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View from the Top

Front-line Researchers

Rising Researchers

Feature Articles: Efforts to Speed Up Practical Application of Quantum Computers

Global Standardization Activities

Information

External Awards

Creating Something New in Growing XR Market by Utilizing Agile Management

Seiji Maruyama
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Abstract

NTT QONOQ was created by NTT DOCOMO, which focuses on communication between people. NTT QONOQ aims to create new experiences that zigzag between real and digital spaces with the hopes to enrich people's minds and energize society, going beyond distance, time, and imagination. We interviewed Seiji Maruyama, president and chief executive officer of NTT QONOQ, who is working toward creating a market for extended reality (XR), about the status of the company's business and his mindset as a top executive.

Keywords: XR, metaverse, remote operation

Entering the XR market in three areas: the metaverse, digital twins, and XR devices

—More than a year has passed since NTT QONOQ was established and you were appointed president and chief executive officer. Could you please tell us how you feel looking back on the past year and the progress of the company's business?

Since NTT QONOQ was launched in October 2022, things have been going well. We have developed a variety of extended reality (XR)* services and established NTT QONOQ Devices, a joint venture with Sharp Corporation. In addition to the approximately 200 employees of NTT QONOQ, the employees of our subsidiaries, and our collaborative partners, we are working together to develop XR technology; and I feel that we have finally formed NTT QONOQ into a company.

We provide various services and solutions in three business areas: the metaverse, digital twins, and XR devices. Although these businesses are supported by XR technology, XR technology is still a developing field. The amount of data in the three-dimensional space that composes the XR space is enormous, and it is essential that communication networks and devices evolve to cope with this. However, current technology has not evolved enough, so what we can do is limited, and we are developing XR products within those limits.

Under the above-described circumstances, we are working with the research and development (R&D) departments of NTT and NTT DOCOMO to promote medium- and long-term technological development. To supplement expertise not available within the NTT Group, we are collaborating extensively with other companies to provide new customer value

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* XR: A generic term for advanced technologies such as virtual reality (VR), augmented reality (AR), and mixed reality (MR).

while adopting agile management by leveraging the advantage of being a small company.

—Regarding the XR business, you will have to compete with major domestic and global companies. In such a competitive market, what strengths does NTT QONOQ bring?

XR technology is still in its infancy, and the XR market is in its growth stage. Meta, Microsoft, Apple, Epic Games, and other major companies are actively investing in the XR business to achieve vertical integration, and the XR market is expected to grow significantly over the next few years. A variety of smaller companies, including startups, have also entered the XR market, and each one is specializing in areas where they can use their strengths to develop their businesses, which is boosting the market.

Under these circumstances, we have two strengths. One strength is that we cover the full range of XR components—from servers and networks to terminals. Our other strength is that we have a wealth of technology and human resources. Originally, each company in the NTT Group developed its own XR business under the NTT XR vision of “transcending the limits of reality to a world where people can experience and share their dreams and thoughts.” To achieve this vision, those technologies and human resources were consolidated to establish NTT QONOQ.

We are exploring various business possibilities by leveraging the NTT Group’s sales base and technological capabilities, while striving to provide value and flexibly, by combining our technologies we can meet customer needs in a speedy manner. Naturally, we are very grateful to NTT Group companies for their support.

Combining the strengths of the NTT Group to take on challenges in a wide-ranging and comprehensive manner

—NTT QONOQ is combining the strengths of the NTT Group to address the XR market in a broad and comprehensive manner. Is there any chance for us to experience its technological capabilities?

Yes. The NTT Group will participate in Expo 2025 Osaka, Kansai, Japan, and I believe this is a great opportunity to showcase technological capabilities of NTT QONOQ and the NTT Group. As one example, NTT will provide the Virtual Expo, which is a virtual reproduction of the Expo’s physical venue, and NTT QONOQ will be in charge of developing the software. The Virtual Expo is part of the future society showcase project at the Expo, which will incorporate cutting-edge technologies and systems into operations at the venue. This service will enable visitors to experience the Expo without actually visiting the venue by reproducing the Expo site and pavilions in a virtual space (the metaverse). Visitors will be able to use their avatars (alter egos) to tour the Virtual Expo and enter the virtual pavilions and experience virtual events.

Before I go on, let me leap back in time. As an elementary-school pupil in rural Kyushu, I went to see the Japan World Exposition, Osaka in 1970. As a boy who loved science, I remember being very excited about the Expo. I feel that the experience influenced me into becoming an engineer. Through the Virtual Expo, I hope that many people will be able to experience similar hopes and dreams like I did.

As I mentioned earlier, XR is an immature technology, and the general public may not have a real sense of what it is. However, experiencing XR will help them realize how interesting XR is and change their impression of the technology. Therefore, to provide an experience of XR technology, we have opened "XR BASE produced by NTT QONOQ" (https://www.nttqonoq.com/xrbase/) at the Electric Town ticket gate of Akihabara Station in Tokyo. Admission to XR BASE produced by NTT QONOQ is free, so please feel free to visit and experience it for yourself.

—Once we experience XR technology, how to apply it to the real world will become more realistic. NTT QONOQ has announced in press releases and through other media that it began offering a variety of XR solutions, correct?

In the metaverse business, we are focusing on representing avatars in a more human-like manner. Specifically, we will enable a human-like response by an avatar in the virtual space platform on the web called "DOOR" by using artificial intelligence (AI). NTT QONOQ offers the "XR Concierge" solution by combining an avatar and dialogue engine equipped with customized conversational AI. Using these technologies and knowledge on the metaverse, we will enable an avatar to respond to users in a user-friendly manner by analyzing the user's emotions and estimating their state of mind. We are collaborating with NTT Group companies to incorporate AI technologies gathered by the NTT Group.

Remote work has become widespread due to the COVID-19 pandemic, and some people say it is difficult to communicate remotely compared to face-to-face. With that concern in mind, we started a service called "NTT XR Lounge." As a small metaverse space containing avatars, NTT XR Lounge is designed to facilitate informal communication such as chatting among team members.

Amidst the labor shortages due to the declining birthrate and aging population in Japan, the augmented reality (AR) field is addressing social issues through remote operation. We offer "NTT XR Real Support" (https://www.nttqonoq.com/realsupport/), a remote-operation support solution using mixed reality (MR) technology, for reducing on-site maintenance in the infrastructure industry and supporting machine operation and on-site maintenance in the manufacturing industry. It is already being used in a variety of fields, including agriculture and fire departments, where it allows the transmission of skilled techniques remotely. We are also investigating applying it in the medical field, such as dentistry, and in the educational field by taking advantage of its ability to represent objects in three dimensions.

XR is active mainly in the industrial sector, and we exhibited our XR solutions at the 7th Smart Factory EXPO Tokyo in January 2023 to help people realize the advantages of our XR solutions. At our booth, we added a new device model compatible with NTT XR Real Support and offered visitors the chance to

experience hands-free MR remote support. We are also developing a lightweight eyeglass-type device, which we plan to launch in 2024.

Intuition is cultivated from experience

—Is the experience you have gained since joining NTT useful in your work as the head of NTT QONOQ?

I became president of NTT QONOQ following my previous job as the senior executive vice president of NTT DOCOMO. After assuming my new position, I have felt a big change because the scales of the two companies are completely different. Since joining NTT, I have worked as an engineer and served as a top executive several times. The experiences I had during that time have been useful in my current position, and I want to talk about one of those experiences I had at DOCOMO PlusHearty, of which I was the president for about two years.

DOCOMO PlusHearty was established to promote employment, primarily for people with severe intellectual disabilities. The company offers cleaning and other services and is about the same size as NTT QONOQ. At that time, I strived to create a good environment and devised ways to make it easier for employees with disabilities to work and make progress in their tasks. The employees took this to heart and worked diligently on various job sites, and we received feedback from our customers that they were very pleased with our employees' work, which made me very happy.

In fact, now I again realize the importance of communication. I think the success of DOCOMO PlusHearty shows the advantages of being a small company—speed of response, quick decision making, and agile management—which allow the voices of the workers in the field to be delivered directly to a top executive, who can then respond quickly.

Because of that experience, I continue to place importance on direct communication with employees at NTT QONOQ. For example, I hold in-house events, such as wine parties and participate in e-sports tournaments, to increase opportunities to communicate directly with front-line employees, and I find those activities meaningful and fun.

Another thing I continue to emphasize is to be unafraid of failure. Of course, we are in business, so it is important to reduce failures; but even so, it is equally or even more important to be willing to take on challenges. If you are afraid of failure, you cannot take on any risks.

As I already mentioned, XR is in uncharted territory, and it is our job to create something new with XR. I remind our employees daily that even if they fail, they should keep trying.

—It sounds like you are taking the helm of NTT QONOQ and leveraging your various experiences. What do you think is required of top executives? And do you have a message for everyone?

First, top executives are the ones who make the final decision. In a large organization, the heads of each department make careful decisions from their respective standpoints, and those decisions are then taken into consideration when a top executive makes their final decision; however, in an organization the size of ours, employees in the field consult directly with a top executive. Therefore, quick decision making is required, which can be difficult, but I try to make decisions on the spot as much as possible.

While it is important to analyze past cases, figures, and failures, it is also important to listen to your heart to confirm the true meaning and gravity. At the final moment of decision making, intuition plays a key role. Intuition may sound irresponsible, but I think it means making instantaneous judgments based on previous experience. In that sense, intuition may be an "unconscious lessons learned from experience."

Top executives should also value the curiosity of not only their employees but also themselves. Curiosity shows us new things and teaches us how to look at things from different angles. We do not know everything about the world. Curiosity is stimulated by talking with people from a wide range of perspectives, and I try to stay curious no matter what position I find myself in.

Considering these experiences, I hope that all of you, especially researchers, will embrace curiosity and engage in your work without fear of failure. They say that failure is the mother of success, but without the accumulation of results and efforts, no awareness can be gained. Considering my experience as an engineer, I believe that the research and development you are engaged in is important and you need to respect your desire to take on this challenge.

To our corporate and consumer customers, XR technology is rapidly evolving. Please try it out and let us know what you think. Your impressions and experiences will help us open new doors. To all our partners, there are limits to what one can do alone, so let's continue to work together.

Interviewee profile

■ Career highlights

Seiji Maruyama joined NTT in 1985. In his career at NTT DOCOMO, he became general manager of the Product Department in 2010, senior vice president and general manager of the Human Resources Management Department in 2016, executive vice president and general manager of the Corporate Strategy & Planning Department, responsible for Mobile Society Research Institute and Preparation for the 2020 in 2018, and senior executive vice president and representative member of the board of directors in 2019. He assumed his current position in October 2022.

Taking the Challenge to Create Novel High-temperature Superconductors and Access New Physical Phenomena by Using a Thin-film Growth Method *sui generis*

Hideki Yamamoto

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Abstract

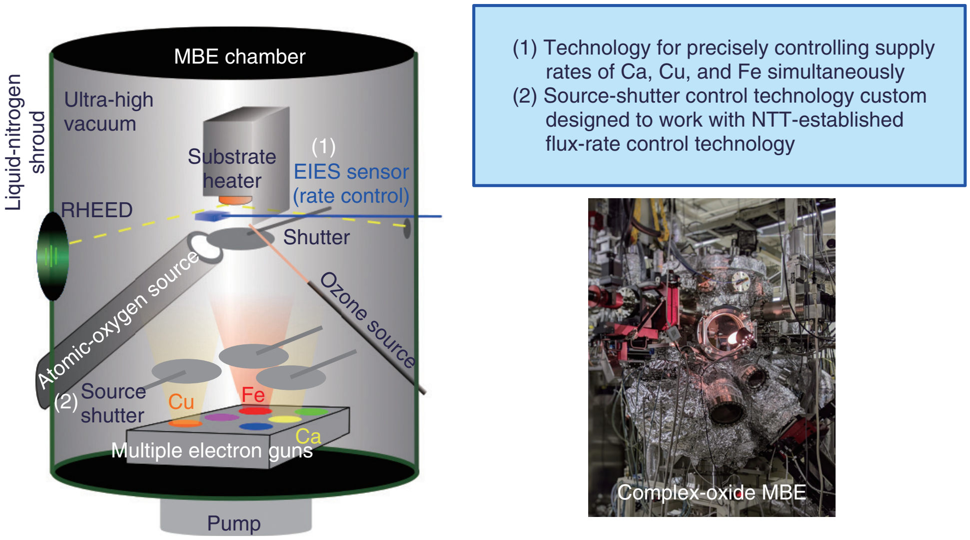
A newly developed elemental source-sequencing technique has further advanced NTT's world-leading complex-oxide-thin-film growth technology, which allows for synthesis of artificial materials consisting of alternating layers of different materials with molecular-layer thicknesses, culminated in the discovery of a new superconductor. Synergetic integration of the thin-film growth technology and process informatics has enabled efficient preparation of the world's highest-quality thin films of oxides in existence, which has led to the observation of new physical properties in an oxide previously unsubstantiated. We interviewed Hideki Yamamoto, a senior distinguished researcher at NTT Basic Research Laboratories, who is conducting research on new materials synthesis and on their physical properties, about the above achievements, his thoughts on superconductors, which are expected to be used in the environmental and energy-related fields, and his attitude as a leader of a world-class research team.

Keywords: superconductor, thin-film growth, artificial superlattice, molecular beam epitaxy

Creating and discovering new materials by using high-quality complex-oxide-thin-film growth technology

—Could you tell us about your current research?

My research theme focuses on creating new materials and elucidating their physical properties. In the three years since my last interview for "Front-line Researchers," our research team made three main accomplishments: (i) discovery of a new copper oxide (cuprate) superconductor through the formation of artificial superlattices; (ii) development of a pioneering and efficient method for growing high-quality thin films; and (iii) substantiation of a magnetic Weyl semimetal state in $SrRuO_3$ (Sr: strontium,



(1) Technology for precisely controlling supply rates of Ca, Cu, and Fe simultaneously
(2) Source-shutter control technology custom designed to work with NTT-established flux-rate control technology

EIES: electron impact emission spectroscopy
MBE: molecular beam epitaxy
RHEED: reflection high-energy electron diffraction

Fig. 1. Technology for growing high-quality complex-oxide superlattices.

Ru: ruthenium, O: oxygen) by using ultra-high-quality thin films.

I'll explain the first accomplishment, discovery of a new cuprate superconductor, in more detail. Superconductivity is a phenomenon in which electrical resistance in a material disappears under certain conditions; as a result, an electric current continues to flow in the material without heat generation or other losses. A material that has this property is called a superconductor. We created a new superconductor using a thin-film growth method we developed. To achieve superconductivity, it had been necessary to cool materials to cryogenic temperatures. Some hydrides have recently been found to exhibit superconductivity at temperatures approaching room temperature: the highest superconducting critical temperature $T_c \approx -25$°C. This discovery suggests the existence of yet-undiscovered materials that can exhibit superconductivity at room temperature. However, such hydrides with high critical temperatures are stable only under ultra-high pressure, about 200 GPa. The materials change their crystal structures under ambient pressure and become non-superconducting. The material family with the second highest T_c is cuprate. The highest T_c in the cuprates is about –130°C, so lower temperatures are required, but cuprate superconductors have the advantage of exhibiting superconductivity under ambient pressure.

There are two approaches to achieve the ultimate goal of discovering materials that exhibit superconductivity at ambient pressure and room temperature: (i) focusing on hydrides that show high T_c under high pressure and searching for materials that can be stabilized under ambient pressure and (ii) focusing on cuprates that exhibit relatively high T_c under ambient pressure and searching for materials that are likely to have higher T_c. Making artificial superlattices of cuprates is in line with the second plan.

The crystal structure of cuprate superconductors is a natural superlattice composed of periodically stacked superconducting layers and charge-reservoir layers. Therefore, a bottom-up technique for material creation, i.e., superconducting layers and charge-reservoir layers are alternately stacked to form an artificial superlattice, has long been considered promising. However, the crystal structure is complex, and each layer has a totally different crystal structure; therefore, a top-down technique for material creation has been used, i.e., natural superlattice structures are synthesized through solid-state reactions via a so-called powder mixing + sintering process. Our oxide-thin-film growth technology, coupled with further technological developments (**Fig. 1**), has reached a level at which we can now create difficult-to-prepare artificial superlattices. Our challenge was to design and prepare an artificial superlattice that combines a

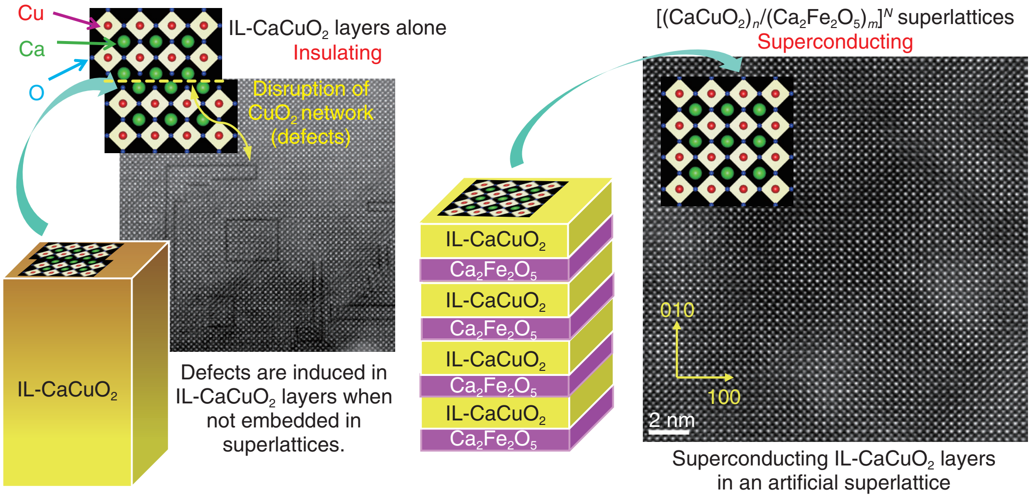


Fig. 2. The reason why $IL-CaCuO_2$ layers exhibit superconductivity when embedded in the superlattice structure.

compound called $IL-CaCuO_2$ (infinite-layer calcium copper oxide) as a superconducting layer and another oxide as a charge-reservoir layer. Since $IL-CaCuO_2$ is a quasi-stable phase, the $IL-CaCuO_2$ layers can only be stabilized on lattice-matched substrate (and lattice-matched charge-reservoir layers) and within a limited growth temperature range (590–600°C) while maintaining strong oxidizing conditions. Accordingly, the material to be combined with $IL-CaCuO_2$ must have growth-condition compatibility and lattice matching with $IL-CaCuO_2$. Through case studies, we found a material that fulfills these requirements, $Ca_2Fe_2O_5$ (calcium iron oxide), and were able to form the $[(CaCuO_2)_n/(Ca_2Fe_2O_5)_m]^N$ superlattices as designed, which showed superconductivity.

An atomic-resolution scanning transmission electron microscope (STEM) equipped with an element-distinctive electron energy-loss spectroscopy (EELS) apparatus enabled direct observation of the atomic arrangements in the superlattices and evaluation of their crystallinity. The capability of visualizing atomic arrangements has been of great help in optimizing the growth conditions for such superlattices composed of materials with different crystal structures.

Our newly discovered and synthesized artificial-superlattice high-T_c superconductor $[(CaCuO_2)_n/(Ca_2Fe_2O_5)_m]^N$ has a T_c below −223°C, which does not reach the highest record for cuprates; nevertheless, we have demonstrated that a new superconductor can be synthesized by stacking two layers with completely different crystal structures. This suggests that the creation of artificial superlattices with even higher T_c by changing the material combined with $IL-CaCuO_2$ is possible. It had not been clear why the $IL-CaCuO_2$ layer, which is responsible for superconductivity in the superlattice, does not exhibit superconductivity by itself; however, through our research, we were able to clarify the mechanism by which the $IL-CaCuO_2$ layer exhibits superconductivity when embedded in the superlattice. As shown on the left side of **Fig. 2**, in bare $IL-CaCuO_2$ layers, the CuO_2 planes, the playground of superconductivity are discontinuous due to the displacement of the atomic arrangement. In contrast, as shown on the right side of Fig. 2, when embedded in the superlattice, the pristine CuO_2 planes are formed.

Drs. Ai Ikeda and Yoshiharu Krockenberger have been the main players in achieving these research accomplishments, which have been published in four scientific papers [1–4], leading to an invited talk in an international conference in 2021. We will be giving two more invited talks in November and December 2023. Dr. Ikeda received the 50th (Spring 2021) Japan Society of Applied Physics (JSAP) Young Scientist Presentation Award and the 14th JSAP Superconductors Division Young Scientist Award for an Excellent Article (March 2023), proving our research has been highly evaluated. Going forward, aiming for a higher T_c superconductor, we will try to establish material-design guidelines by varying the number of $IL-CaCuO_2$ layers in one superlattice cell as well as using empirical rules concerning the types of charge-reservoir layers in materials that exhibit high T_c.

Through such activities, we intend to elucidate the mechanism of high-T_c superconductivity in cuprates. As represented by the study of infinite-layer materials such as IL-$CaCuO_2$, we have reported that the electronic phase diagram, which is the key to comprehending the mechanism of superconductivity in cuprate superconductors, is strongly affected by the integrity of the CuO_2 planes, the playground of superconductivity [5]. Although it is on cuprates that slightly differ from those we have been studying, another research group has recently reported similar results [6], which is of great interest from the viewpoint of comprehending the mechanism of superconductivity.

—Thin-film growth technology is important in terms of creating new materials and elucidating phenomena associated with them, right?

New substances and materials are generally synthesized either by reactions in beakers or flasks or, in the case of oxides, by solid-state reactions in which powders of constituent materials are mixed and fired in a furnace to synthesize bulk materials. In contrast, NTT aims to create new materials through thin-film synthesis—in which atomic beams of constituent elements are supplied and reacted under ultra-high vacuum—using the world's most-advanced multi-source oxide molecular beam epitaxy (MBE) with high-precision control of evaporation rates that we have developed and improved over the years. The following are three key technologies: (i) for evaporating high-melting-point elements (≥ 2000°C) by high-energy-electron irradiation; (ii) for controlling the evaporation rates of multiple elements with high accuracy and in real time by using electron impact emission spectroscopy (EIES); and (iii) for oxidizing materials under ultra-high vacuum conditions by using ozone and atomic oxygen.

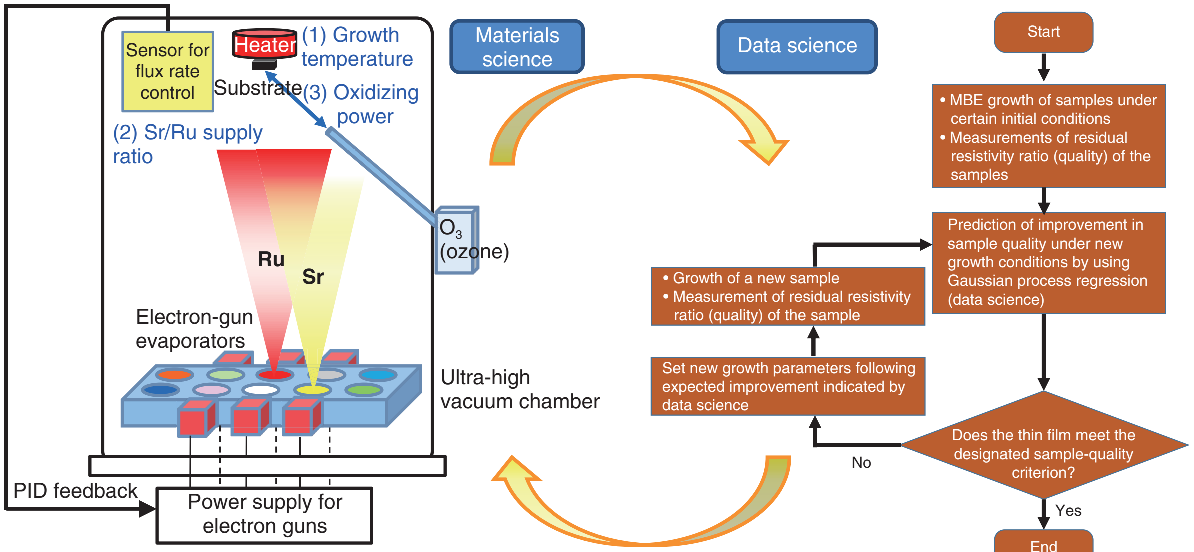
Our thin-film growth technology has been applied to synthesize new materials and prepare high-quality thin films of materials already in existence; however, to prepare the highest-quality thin films, it has been necessary to optimize the growth conditions through several hundreds to a thousand trial-and-error runs. To address this issue, we used process informatics to develop a methodology, algorithm, and program suitable for optimizing the thin-film growth conditions, which enabled us to efficiently prepare the world's highest-quality thin films in less than 50 growth runs (**Fig. 3**). This is the second example of our major accomplishments mentioned at the beginning, i.e., (ii) the development of a pioneering and efficient method for growing high-quality thin films. In addition to establishing the superlattice-formation technology mentioned above, this technology has made rapid progress in the past five years or so thanks to the collaboration between NTT Basic Research Laboratories and NTT Communication Science Laboratories, where Dr. Yuki K. Wakabayashi has been playing a central role.

The development of this method, called machine-learning-assisted molecular-beam epitaxy (ML-MBE), enabled us to demonstrate the magnetic Weyl semimetal state by using ultra-high-quality $SrRuO_3$ thin films, our main accomplishment (iii) mentioned at the beginning. The compound $SrRuO_3$ has been studied extensively from the viewpoints of both physics and applications because both metallic and ferromagnetic states are inherent in it, and it has a perovskite structure like many other complex oxides that have been widely studied in the field of oxide electronics. Since only limited sizes of single crystals of $SrRuO_3$ were obtained until recently due to difficulty in crystal growth, research on physical properties has mainly been conducted using thin-film specimens. We used ML-MBE and successfully prepared the world's highest-quality $SrRuO_3$ thin film. This highest-quality thin film enabled us to demonstrate that $SrRuO_3$ is a novel material in a unique quantum state: metallic, ferromagnetic, and Weyl semimetal states simultaneously occur in it [7–9]. These research outcomes have been published in many papers (approaching 15) first authored by Dr. Yuki K. Wakabayashi.

What is common sense in one field may not be in another, so a team of researchers with various backgrounds can turn something that does not seem common sense into something that is

—Please tell us what you keep in mind as a researcher.

We are currently researching as a team, but as a team manager, I try to take a bird's-eye view when searching for research themes and subjects, and when interpreting experimental results. Regarding research themes, I first set a major theme and then leave the rest to our team members while making sure to respect their autonomy. Of course, I give advice based on my own experience and knowledge, and some problems can be solved based on that experience; however, a dilemma arises if we put too much emphasis on that experience: our ideas and research



Parameters that should be optimized for growth of $SrRuO_3$ thin films: (1) growth temperature, (2) Sr/Ru supply ratio, and (3) oxidizing power. Although all three parameters can be controlled independently, the quality of the thin films is determined by a complex function of the three parameters.

Flowchart of the newly developed machine learning-assisted thin-film growth method.

PID: proportional-integral-derivative

Fig. 3. Synergetic integration of materials science and data science.

will become more and more predictable. I believe that this balance between past-experience-based advice and on-the-fly thinking by individual researchers must be kept in mind to maximize the strengths of a research team consisting of members of different generations. Regardless of generation, what is common sense in one field is often not in another. Fortunately, our team members have various expertise and backgrounds, and pursuing research while discussing among themselves often leads to unexpected ideas and results; thus, what was thought to be not common sense yesterday may become so tomorrow.

I also value the opportunity to talk face-to-face as we research as a team. I spend a lot of time on management-related desk work and in meetings, and it is sometimes difficult to find time to talk directly with the team members, but the limited time I can find conversely highlights the importance of such opportunity. Under the restrictions on laboratory attendance during the COVID-19 pandemic, I prioritized, as much as possible, attendance of the team members involved in experiments and I myself shifted to teleworking. Now that the restrictions have been lifted, I feel that face-to-face discussions in the lab and other places deepen our mutual understanding of the research themes and results. I hope this shift back to face-to-face discussion will lead to new discoveries.

NTT Basic Research Laboratories has an external evaluation committee called the Advisory Board, whose members include prominent researchers, including Nobel Prize laureates. Thus far, we have held twelve Advisory Board Meetings once every two years. In those meetings, the members of the Advisory Board visit the Laboratories to hold discussions and give evaluations and recommendations on our research system, research plans, and progress of research, and related matters. In 2021, during the COVID-19 pandemic, we were forced to hold the meeting online, but one of the members commented on my presentation that “This research effort is unique in the world, and this presentation is now achieving incredible results.” Even though I was distressed because we could not proceed with experiments and research as we wanted and could not make direct discussions due to the pandemic, that comment encouraged me a lot.

—What do you aim to achieve as a researcher in the future?

The discovery of materials that exhibit superconductivity at ambient pressure and room temperature is the ultimate goal of researchers involved in superconductivity. Although there are many possible approaches to discovering and synthesizing such materials, I want to focus on using thin-film growth methods. Although further study and verification are needed to determine the specific composition and crystal structure to target, fortunately, recent advances in theoretical and computational science have made it possible to predict with a high degree of accuracy the stability and electronic structure of materials that have not yet been synthesized. It has also become possible to (i) estimate the phonon structures of yet-undiscovered hypothetical materials and the magnitude of electron-phonon interactions in those materials and (ii) predict the superconducting transition temperature to some extent. We plan to incorporate such an approach while exploiting joint research with other institutions.

Even if a new material is discovered, it usually takes a certain amount of time before it can be put to practical use. However, if a material that exhibits superconductivity at room temperature and ambient pressure were put to practical use, it would be possible to transmit and supply electric power using direct current in a lossless manner, and if that material were used for wiring in circuits, problematic heat generation would be greatly reduced, thereby contributing to resolving environmental and energy issues. As a researcher, I am grateful for being able to conduct research at a time when materials that exhibit superconductivity at temperatures close to room temperature—though under ultra-high pressure—have been discovered, and I want to challenge myself to achieve the ultimate goal, though it will not be achieved overnight.

Streamline your research process and take detours once in a while

—What is your message to younger researchers?

First of all, I want to thank all the team members who have achieved outstanding results one after another, despite the great headwind of the COVID-19 pandemic, and NTT Communication Science Laboratories and other collaborators for their sincere efforts. To next-generation researchers, including those who are not necessarily directly involved in our research, I want to say the following. It is important to improve time performance so that we can achieve results and success in a limited amount of time. It is natural that people tend to focus on this time keeping, but I also want to point out that it is also important to take a detour once in a while. In the aforementioned research on artificial superlattices that exhibit superconductivity, it may sound as if we had taken the shortest route, but, in fact, we took quite a few detours. As a result of those detours, we discovered the unexpected phenomenon, disruption of the superconducting layer due to defects, and we were able to proceed with our research with a deep understanding of the significance of superlattice formation in preventing such disruption. Although the improvement in efficiency of the process for optimizing growth conditions through process informatics may seem to contradict this story, that efficiency improvement has also given us room to take a detour in our research on $SrRuO_3$.

I also recommend that if you get a chance, you should experience a stay abroad. Living abroad means, at least in the short term, your research at that point in time will be interrupted. I think that from the standpoints of work as well as family and personal life, the timing when “everything is in order now and I can stay abroad without any problems or worries” will almost never come around. Today, we can make contact with people from different countries at academic conferences and other gatherings through web-conferencing systems and other means. Even so, I think that the experience of living abroad is still very significant. One example of this significance is to experience firsthand cultural differences and differences in ways of thinking; however, I also feel that experiencing other aspects that cannot be adequately expressed in words is more significant. I went to Stanford University in the USA for eleven months from 2004 to 2005 as a joint researcher. The primary significance was the deep and fruitful discussions I had with local researchers, but that is not all. For example, I was able to form valuable contacts and then expand that network of contacts, which helped us to accept an internship student from the University of Twente in the Netherlands from October 2022 to May 2023. Going abroad may not necessarily lead directly to research results in the short term; in the long term, however, the presence or absence of such experience will make a difference in your range of thinking and approaches to research.

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■ Interviewee profile

Hideki Yamamoto received a B.S., M.S., and Ph.D. in chemistry from the University of Tokyo in 1990, 1992, and 1995. He joined NTT in 1995, and his principal research fields are thin-film growth, surface science, and condensed-matter physics. He was a visiting scholar at the Geballe Laboratory for Advanced Materials, Stanford University, USA (2004–2005). He is currently executive manager of Multidisciplinary Materials Design and Science Laboratory, NTT Basic Research Laboratories. He received the 2nd Young Scientist Presentation Award (1997) from the Japan Society of Applied Physics (JSAP) and the 20th Superconductivity Science and Technology Award (2016) from the Forum of Superconductivity Science and Technology, the Society of Non-traditional Technology. He is a member of JSAP, the Physical Society of Japan, the Japan Society of Vacuum and Surface Science, the American Physical Society, and the Materials Research Society.

Scientific Understanding of the Desire to Touch and Haptic Presentation Methods Based on Cross-modal Perception—Toward New Horizons in Haptic Content That People Really Want to Touch

Yusuke Ujitoko
Distinguished Researcher, NTT Communication Science Laboratories

Abstract

Haptic presentation technologies that can express a sense of touch in a variety of ways are continuing to progress. On the other hand, "What kind of haptic experience do people want?" has not yet been clarified, and as a result, the spread of haptic content in society has not made much progress. Going forward, creating haptic content that people want to experience will require an understanding of the psychological aspects of the sense of touch as in "What do people want to touch?" In this interview, we talked with NTT Distinguished Researcher Yusuke Ujitoko to learn about "scientific understanding of the desire to touch and haptic presentation methods based on cross-modal perception" that aims to popularize haptic content in the future by clarifying the "desire to touch" from large-scale data such as social media and using haptic presentation methods.

Keywords: desire to touch, haptic presentation, cross-modal perception

Clarifying the "desire to touch" from large-scale social media data

—Dr. Ujitoko, what kind of research is involved in obtaining a "scientific understanding of the desire to touch"?

"Scientific understanding of the desire to touch" refers to research that takes a psychological approach to understanding such riddles as "What kind of things do people think they want to touch?" and "Why do they think they want to touch them?" By promoting this kind of research to deepen our understanding of the "desire to touch," which has not been studied much in prior research, could we not provide the knowledge needed to create haptic content that people

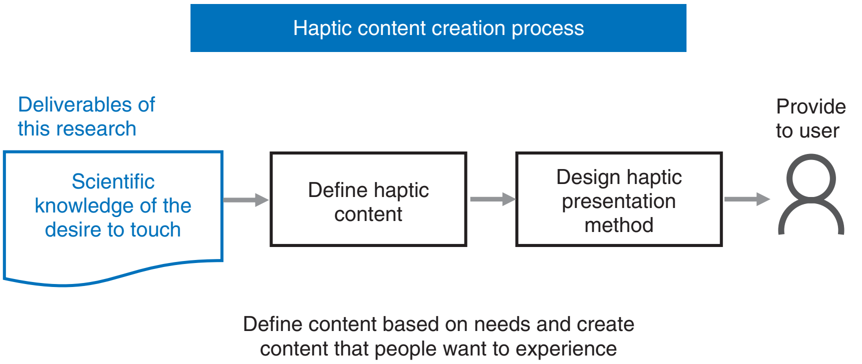


Fig. 1. Process of creating haptic content based on knowledge of the desire to touch.

want to experience?

In contrast to the sense of touch, information presentation technologies involving the sense of sight and sense of hearing have become widely used. Today, the world is overflowing with attractive and compelling music and video content, and each of us can experience content that we want to experience. However, while the research and development of haptic presentation technologies involving the sense of touch have made some progress, the current situation is that haptic content that a person wants to experience has yet to spread in society. I believe that a major reason for this is a lack of understanding as to what kind of haptic experience people want. In the past, investigations into the desire to touch consisted of experiments conducted in laboratories with subjects using actual stimuli. These laboratory experiments, however, could only use a limited number of targets from among those we touch in our daily lives, and could also produce biased results since subjects were conscious of results that the experimenter was seeking. For these reasons, it was difficult to investigate the desire to touch in everyday life.

We collected a large amount of text related to the desire to touch in everyday life stored in social media and aimed to understand the desire to touch in a comprehensive manner from the viewpoint of diverse situations in daily life. By clarifying what people want to touch in what kind of situation as basic research based on large-scale social media data, it would be possible to obtain insights into haptic content that people want to experience and to identify where we should focus our efforts in developing technology based on those insights. For example, if it's understood that the desire to touch cats in one's living room on one's day off is a strong desire, a decision can be made to prioritize the development of technology that presents a feeling of cat fur and paw pads, which may then lead to the creation of content that people want to experience in the future (**Fig. 1**).

—What have been some concrete findings in your research to date on the desire to touch?

In collecting data related to the desire to touch, we found that targets that people would like to touch are extremely limited in number. This was an unexpected result since there are a limitless number of targets that we can touch all around us, which suggests that there would be a wide variety of targets that people would like to touch. In demonstrations presenting the results of certain studies on haptic presentation, the ability to express the feel of all sorts of targets is often regarded to be a strong point and an attractive feature of those studies. Our above result, however, suggests that the ability to reproduce certain types of tactile sensations may be appealing even if the feel of a wide variety of targets cannot be expressed. We also came to understand that the targets that people want to touch are biased on the whole towards living things like people and animals over things. For this reason, I believe that content that can provide communication through remote touching of a loved one or family member or through touching of virtual avatars in the metaverse, or content that can produce a calming effect by touching animals like cats and dogs, may in the future become an integral part of human life. In addition, we found that there is a strong relationship between the target of what a person wants to touch and the way of touching that target. For example, "stroking" and "cat" are strongly related, so when creating "cat touching" content, it may be best to start out by

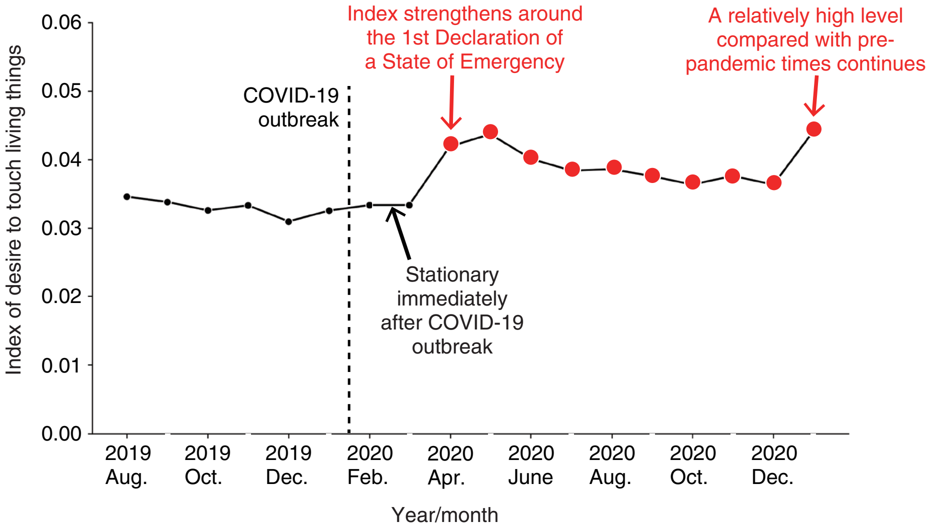


Fig. 2. Change in desire to touch and COVID-19 outbreak.

formulating a policy that places importance on expressing the feel of stroking.

This research began during the spread of COVID-19 when I thought to myself "Could this be research that I could conduct from home?" As it turns out, I also found that the desire to touch was changing during the spread of COVID-19. From around the time of Japan's Declaration of a State of Emergency in response to the COVID-19 outbreak in 2020, I obtained a result suggesting that the phenomenon of "skin hunger," or a craving for the warmth of the skin of living things like people and animals, was appearing among people. I thought that this was likely due to the effects of social distancing and restrictions on going out on the desire to touch (**Fig. 2**). This result led me to conclude that there was a need for technology that could achieve a tactile connection with other people in a remote environment during the COVID-19 pandemic. Similarly, since this research also identified the desire to refrain from touching non-living things like cash or door knobs thought to be a source of infection, I found that technology that could provide a sense of touch even when not actually touching something would be needed during such a pandemic. In addition, a series of our studies revealed that the desire to touch possessed not only static properties but also dynamic properties that change depending on the event. This was a deeply interesting discovery that reflects the complexity of the desire to touch.

—How are you researching "haptic presentation methods based on cross-modal perception"?

I am now studying haptic presentation methods based on cross-modal perception as technologies that can give people a sense of touch. To give an example of cross-modal perception, when a person is eating red-colored *kakigori* (shaved ice, a summer treat in Japan) that smells like strawberries, a phenomenon occurs in which that person experiences the taste of strawberries despite the fact that *kakigori* is essentially tasteless. What happens here is that perception corresponding to a certain sensation is modulated by input into a different sensory organ. Now, if we were to apply this phenomenon to haptic presentation when touching something with one's finger, we could produce a pseudo sense of touch by simply changing the way in which the finger and target movement is viewed as visual information without any physical haptic stimulation. In research using this technology, I am proposing a haptic presentation method associated with the swipe operation on a display in which the user perceives "heaviness," which should be absent in such a display operation, by limiting the amount of scrolling (**Fig. 3**).

Past haptic presentation devices were often expensive and difficult to carry around, so in actuality, spreading their use in the manner of "one per household" was deemed difficult. In the face of this problem, I considered that applying cross-modal perception to haptic presentation could lead to a device

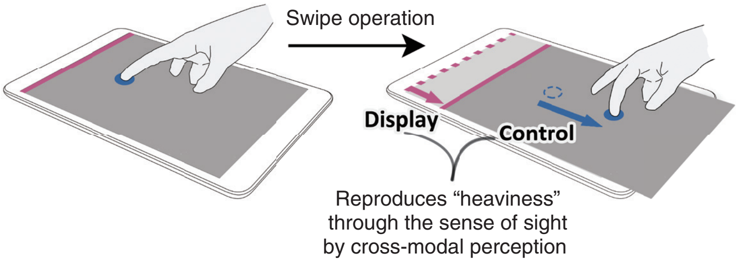


Fig. 3. Example of a haptic presentation method based on cross-modal perception.

based on a simple and inexpensive mechanism.

In my studies of haptic presentation methods based on cross-modal perception, I have not only proposed individual presentation methods but also undertaken the systematization of presentation methods. In this regard, a variety of methods have previously been proposed as haptic presentation methods based on cross-modal perception. For example, various methods have been proposed such as a method that expresses a feeling of heaviness when picking something up and a method that expresses a feeling of roughness when rubbing the surface of an object. In the past, however, knowledge associated with these methods (such as the method itself and its limitations) was presented in separate papers in a fragmentary manner. In such an environment, researchers and developers of haptic content cannot efficiently obtain knowledge. For this reason, I conducted a comprehensive survey on related research from the 2000s up to now and organized haptic presentation methods from viewpoints of tactile feeling, user input, and visual stimulus. This type of work is similar to that of a consultant in terms of the need for conducting a comprehensive survey and organizing information based on meaningful viewpoints. However, this requires working in a way different from that of a researcher, so completing this survey was a challenge for me. This survey clarified the present state of "haptic presentation methods based on cross-modal perception," which have contributed greatly to the field of haptic research. The survey also enabled me to discover topics missing in the field to date.

Creating appealing haptic content and generating a paradigm shift in the haptic field

—What are some difficult points in your current research?

In analyzing the desire to touch using large-scale social media data, it is difficult to determine whether information on the desire to touch can truly be obtained as a result of investigation. As a research theme, the desire to touch crosses into a person's private domain, but on the other hand, social media data constitutes information that the user wants to publically release. So we need to be careful in deciding whether publically released data truly reflects the desire to touch. In addition, there is a bias with respect to user gender or age depending on the social media, so a bias naturally arises in results. In my research, I deal with these problems by comparing the results of collecting large-scale data in online experiments with the results of social media data to clarify as much as possible the bias originating in the method of data collection. In my research to date, I have come to understand the targets of the desire to touch, but I have not yet been able to clearly identify what kind of tactile sensations should be presented in those targets or what kinds of situations are more desirable. My research objectives from here on are to clarify "What kind of tactile sensation is needed in a target that people desire to touch?" and "In what kind of situation is a touching experience needed?"

Another problem in a haptic presentation method based on cross-modal perception is that the degree of feeling differs from one person to the next. In actual demonstrations targeting a variety of people, we have found that the way of feeling changes depending on the person and that the ease of feeling differs according to age. By clarifying the factors that give rise to such differences in the way of feeling, I hope to apply the knowledge gained to calibration techniques in haptic presentations to mitigate individual differences. Moreover, in comparison to past haptic presentation devices that physically stimulate a person's body, a problem in existing haptic presentation methods based on cross-modal perception is that the tactile sensation that can be felt is very weak. To solve this problem, I will combine existing methods with physical stimuli based on simple haptic presentation devices, and from here on, I plan to search for haptic presentation methods based on more powerful means of cross-modal perception.

—What do you think will become possible in the years to come based on your research achievements?

I believe that using the results obtained from the scientific analysis of the desire to touch and from haptic presentation methods based on cross-modal perception should be able to contribute to various elements making up the Innovative Optical and Wireless Network (IOWN) vision proposed by NTT. For example, in Digital Twin Computing, one of the three key elements of IOWN, our results can contribute to making the digital twin itself more appealing by implementing in the cyber world "content that people desire" born from an understanding of the desire to touch. In addition, haptic presentation methods based on cross-modal perception can be used as a mechanism for conveying to a user in the physical world a haptic experience of the user's digital twin in the cyber world. In this way, it will be possible to provide a natural haptic experience without special devices.

—Dr. Ujitoko, what message would you like to leave for researchers, students, and business partners?

I myself have been in this research field related to the sense of touch for some time, but the present situation is that the general public knows little about this research with no clear outlook for the spread of haptic content in society. This can make me feel a bit sad as a researcher. To overcome this state of affairs, what motivates me in my research is a desire to produce results that can support technologies and content that the general public can easily use while pursuing my work in basic research. From here on, as well, I will focus on basic research that could lead to appealing technologies in the future. Furthermore, in contrast to a desire for immediate profits, I hope that the knowledge that I accumulate in relation to the sense of touch will enable someone in the future to gain some valuable insights. To those readers who have an interest in the research that I am pursuing here at NTT Communication Science Laboratories, I would like to say, "Let's work together to create a new future for haptic research!"

■ Interviewee profile

Yusuke Ujitoko received his M.A.Sc. degree from the Graduate School of The University of Tokyo in 2016 and joined Hitachi, Ltd. the same year. He received his Ph.D. degree from the Graduate School of The University of Electro-Communications in 2020 and joined Nippon Telegraph and Telephone Corporation (NTT) the same year. He has been an NTT Distinguished Researcher since 2022. He is engaged in research that aims to clarify the characteristics of human haptic perception and control haptic presentation using those characteristics. He is a recipient of the IEEE World Haptics 2021 Best Video Presentation, IEEE Haptics 2020 Best Paper Second Honorable Mention, and other awards.

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

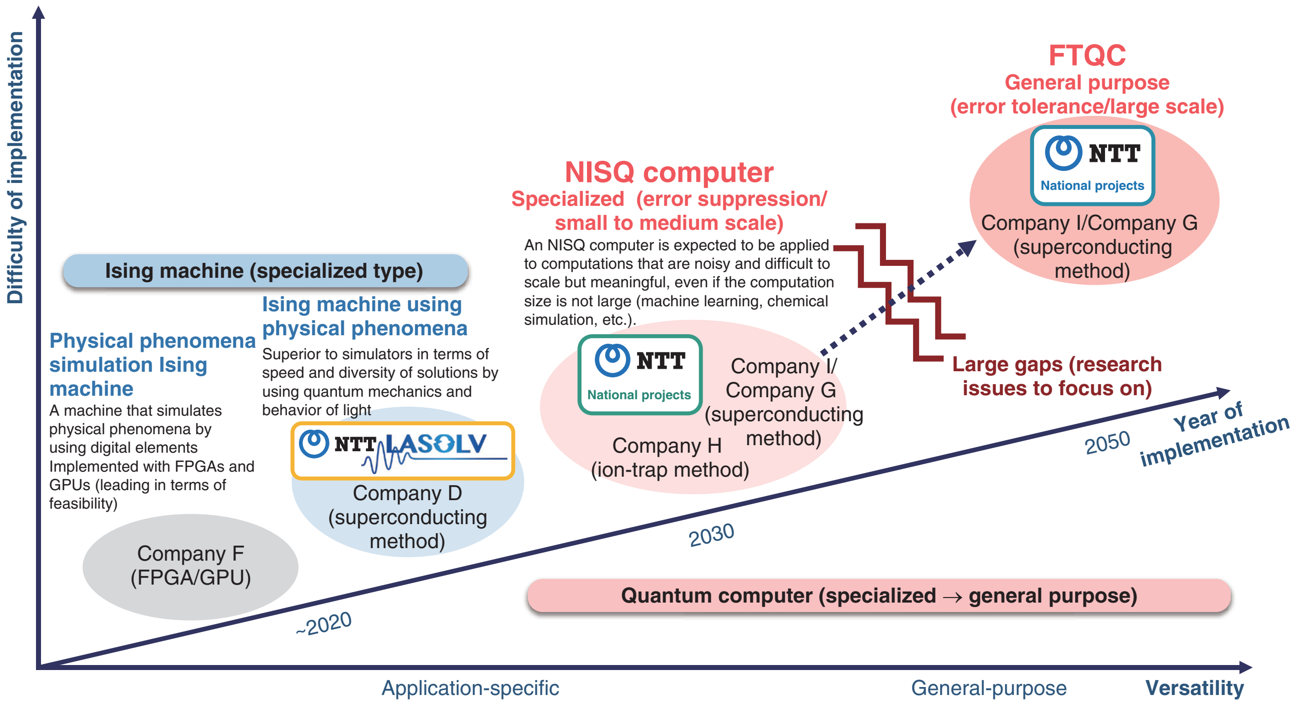
Various types of hardware have been proposed for implementing Ising machines and quantum computers. A research-and-development competition to establish a mechanism for controlling various types of hardware that enable quantum computing and executing meaningful applications, that is, establishing a quantum-computing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



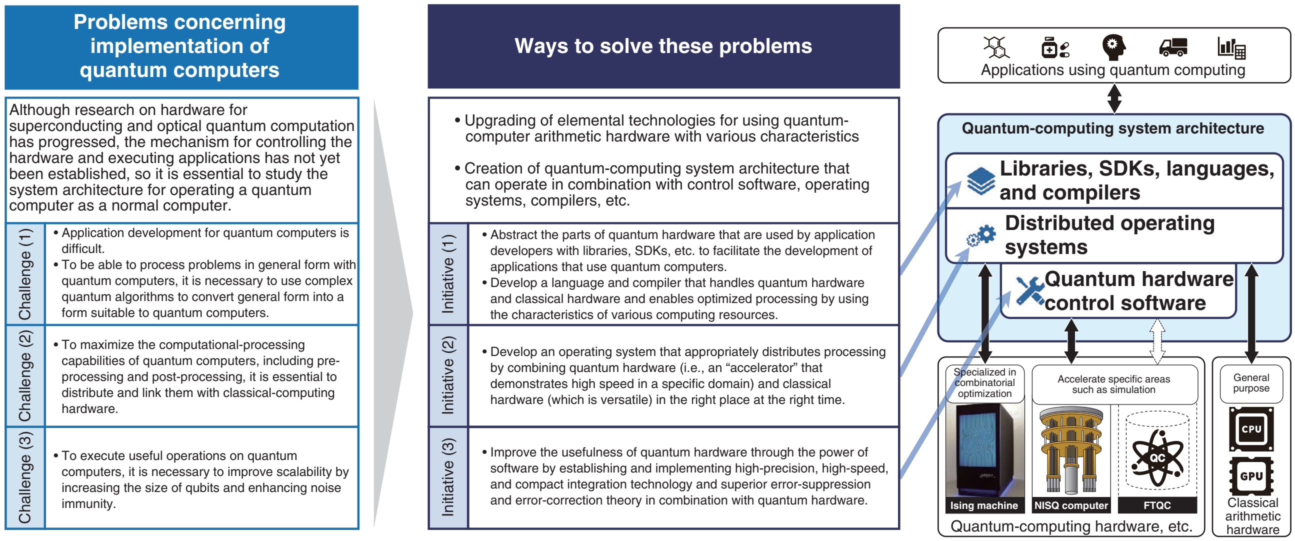
A machine that simulates physical phenomena by using digital elements Implemented with FPGAs and GPUs (leading in terms of feasibility)

Superior to simulators in terms of speed and diversity of solutions by using quantum mechanics and behavior of light

An NISQ computer is expected to be applied to computations that are noisy and difficult to scale but meaningful, even if the computation size is not large (machine learning, chemical simulation, etc.).

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

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



Problems concerning implementation of quantum computers

Although research on hardware for superconducting and optical quantum computation has progressed, the mechanism for controlling the hardware and executing applications has not yet been established, so it is essential to study the system architecture for operating a quantum computer as a normal computer.

Challenge (1)
- Application development for quantum computers is difficult.
- To be able to process problems in general form with quantum computers, it is necessary to use complex quantum algorithms to convert general form into a form suitable to quantum computers.

Challenge (2)
- To maximize the computational-processing capabilities of quantum computers, including pre-processing and post-processing, it is essential to distribute and link them with classical-computing hardware.

Challenge (3)
- To execute useful operations on quantum computers, it is necessary to improve scalability by increasing the size of qubits and enhancing noise immunity.

Ways to solve these problems

- Upgrading of elemental technologies for using quantum-computer arithmetic hardware with various characteristics
- Creation of quantum-computing system architecture that can operate in combination with control software, operating systems, compilers, etc.

Initiative (1)
- Abstract the parts of quantum hardware that are used by application developers with libraries, SDKs, etc. to facilitate the development of applications that use quantum computers.
- Develop a language and compiler that handles quantum hardware and classical hardware and enables optimized processing by using the characteristics of various computing resources.

Initiative (2)
- Develop an operating system that appropriately distributes processing by combining quantum hardware (i.e., an "accelerator" that demonstrates high speed in a specific domain) and classical hardware (which is versatile) in the right place at the right time.

Initiative (3)
- Improve the usefulness of quantum hardware through the power of software by establishing and implementing high-precision, high-speed, and compact integration technology and superior error-suppression and error-correction theory in combination with quantum hardware.

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.

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Sumitaka Sakauchi

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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.

A Computing System for Supporting Application Development Using Ising Machines

Kazuhiro Miyahara and Junji Teramoto

Abstract

One of the problems that conventional computers, such as those based on central processing units, cannot solve is the combinatorial optimization problem, the solution to which is a pattern from among a huge number of combinations of patterns that satisfies a certain condition. Operating on the basis of a new principle, an Ising machine is a computer that specializes in solving this problem. However, there are many challenges to using an Ising machine, such as converting real-world problems into a format that the Ising machine can handle. Research and development of a software development kit and computing system that overcome these challenges are introduced in this article.

Keywords: Ising machine, LASOLV™, combinatorial optimization problem

1. Combinatorial optimization problems and Ising machines

Combinatorial optimization problems, namely, finding the best solution from a large number of alternatives, are difficult to solve and require long computation time even with today's computers. For example, the traveling salesman problem (finding the most-efficient order in which to visit multiple destinations) and the graph-coloring problem (ensuring that adjacent areas of a given map are painted with different colors under the constraint of a limited number of colors) are typical combinatorial optimization problems that become more difficult as the scale of the problem increases.

Research on an Ising machine that solves such problems on the basis of a new approach, namely, using a model representing the properties of magnetic materials, is progressing. An Ising machine is a computer that specializes in solving a combinatorial optimization problem called the Ising-model ground-state search problem. As a statistical-mechanics model, an Ising model describes a network of magnets (each with a property called "spin"), as shown in **Fig. 1**. The spin σ_i can be either up (+1) or down (–1). If J_{ij} and h_i represent spin-spin interaction and magnetic-field strength, respectively, the ground state is the state in which the second-order polynomial Ising model H, defined by the following equation, is minimized.

$$H = -\sum_{i<j} J_{ij}\sigma_i\sigma_j - \sum_i h_i\sigma_i$$

The combination of spins that satisfies this equation is the solution to the ground-state search problem.

Although there are many different types of combinatorial optimization problems, it has been theoretically proven that they can all be transformed into such an Ising-model ground-state search problem. Given this fact, various companies, such as D-Wave Systems [1] and Fujitsu [2], have developed Ising machines and are using them to solve various combinatorial optimization problems. Likewise, NTT laboratories are developing a laser-based coherent Ising machine [3] called LASOLV™.

2. Software development kit to facilitate the use of Ising machines

To use an Ising machine, it is necessary to represent the problem to be solved in the form of an Ising

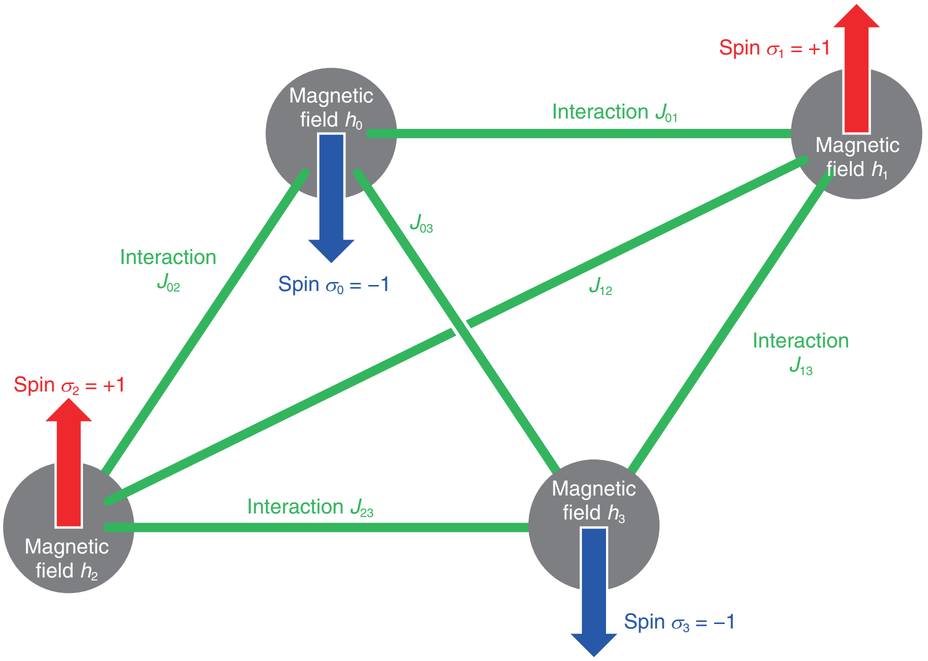


Fig. 1. Ising model.

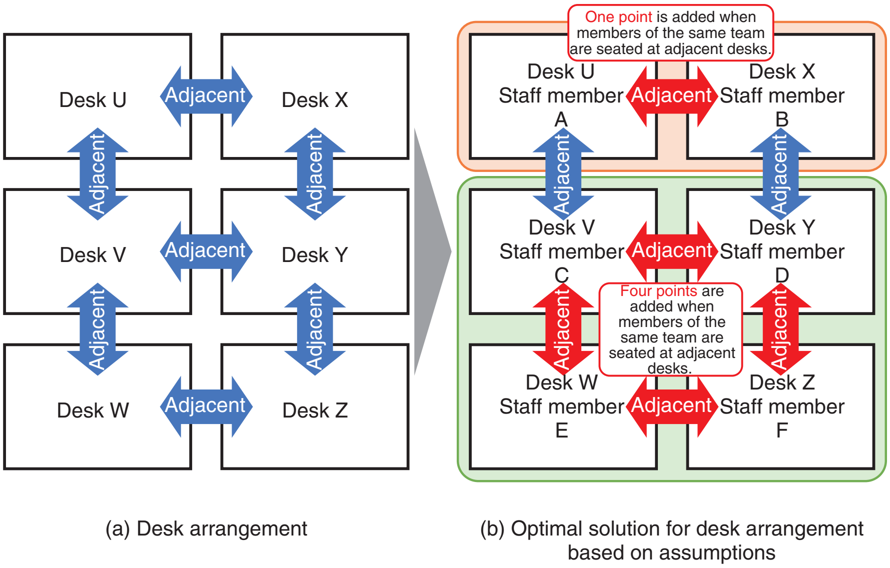
model that can be input to the Ising machine. To express the problem with the Ising model, it is necessary to (i) correlate the value taken by the spin (+1 or –1) and the meaning of the solution to the problem and (ii) create a polynomial that corresponds to the desired solution when the value of the Ising model is minimized. The reason for correlating that minimum value to the desired solution is that the Ising machine is a calculator that finds the value of spin at which the input Ising model is minimized. The task of devising the Ising model becomes more complicated in proportion to the complexity of the problem, which increases the difficulty of using the Ising machine. NTT Computer and Data Science Laboratories is developing a software development kit (SDK)—called cimsdk—that greatly simplifies the process of devising Ising models. The conventional process for devising an Ising model is explained as follows with a simple problem as an example.

In this example of an office department, six staff members (given as A, B, C, D, E, and F) are to be assigned to six desks (given as U, V, W, X, Y, and Z).

The six desks are positioned, as shown in **Fig. 2(a)**. It is assumed that one desk must be assigned to one staff member (Assumption 1). It is also assumed that staff members A/B and C/D/E/F are teamed up for the same job, so they must be assigned adjacent desks. In this process, one point is added to a points total when each staff-member pair on the same team is assigned adjacent desks, and the goal is to maximize the total number of points (Assumption 2). Based on Assumptions 1 and 2, the assignment shown in **Fig. 2(b)** is one of the solutions giving the maximum number of points. The following Ising-model representation of this example problem is considered.

First, the correspondence between the +1 and –1 spins and the meaning of the solution to the problem are considered. One spin is assigned to each of the 36 possible combinations of 6 staff members and 6 desks, and the following meaning is associated with each spin: "+1 means that a certain staff member was assigned to a certain desk" and "–1 means that the staff member was not assigned to that desk." The spins are represented by variable $x_{A,U}$, where A represents the staff member and U represents the desk. For example, $x_{B,X}$ is interpreted as follows: "If x is +1, staff member B was assigned to desk X; if x is –1, staff B was not assigned to desk X. For the 36 spins prepared in this way, the following expressions for Assumptions 1 and 2 are considered.

Assumption 1 (i.e., one desk per staff member) is supposed to express spin as described earlier. In other words, "only one of the six desks is assigned to each staff member" or "only one of the six staff members



(a) Desk arrangement

(b) Optimal solution for desk arrangement based on assumptions

Fig. 2. Example desk arrangement and optimal solution.

is assigned to each desk.” For example, the assumption “only one of the six desks is assigned for staff member A” can be expressed by the quadratic polynomial $(\sum_{desk\in\{U,V,W,X,Y,Z\}} x_{A,desk} + 4)^2$. The value of this quadratic polynomial is minimized when only one of $x_{A,U} – x_{A,Z}$ is +1 and the remaining five variables are –1. The fact that only one desk is assigned to a staff member corresponds to the fact that the value of the quadratic polynomial is minimized. The other staff members and desks can be represented by a similar quadratic polynomial with a single assignment.

Assumption 2 (i.e., 1 point is added for each staff member of the same team seated at adjacent desks) is considered with the following example of a team composed of staff members A and B. One point is added if staff members A and B are respectively assigned to desks U and X. Assumption 2 is expressed as the quadratic polynomial $(x_{A,U} + 1)(x_{B,X} + 1)/4$. When +1 and –1 are respectively substituted for $x_{A,U}$ and $x_{B,X}$, this quadratic polynomial is +1 only when $x_{A,U}$ and $x_{B,X}$ are +1; otherwise, it is 0. Since this condition would result in no points being awarded for opposing desk assignments and/or combinations of non-team staff members on adjacent desks, the number of points awarded can be expressed as a quadratic polynomial by adding up the values given by the quadratic polynomials for all combinations. It should be noted that the Ising machine derives the solution that minimizes the Ising model. In other words, it is necessary to minimize the value taken by the Ising model as the points added due to the desk adjacency increase, so the plus or minus signs of these quadratic polynomials are inverted, and these quadratic polynomials are added together.

The Ising model for this example is shown in **Fig. 3**, which is constructed by adding up the above-devised quadratic polynomials. Even in the case of such a simple example, the Ising-model formula/equation is relatively complex.

In contrast, the Ising model constructed using the functions of cimsdk is shown in **Fig. 4**. It can be understood that the Ising model can be generated without considering what value each polynomial takes when it satisfies what, which was a necessary condition when devising the equations in Fig. 3.

For practical problems, more spins and more complex assumptions are required, so the task of devising an Ising model becomes much more complicated. Practical problems may deal with integers, and it may be necessary to combine multiple spins taking either +1 or –1 and treat them as a single integer. If it is necessary to express conditions related to three or more spins at the same time, it will be necessary to handle third-order or higher polynomials; however, the Ising model can only handle second-order polynomials, so the polynomial order must be reduced.

Regarding the work of devising such a complicated Ising model, cimsdk provides a function for automatically converting various spins (such as integers

Quadratic polynomials of this example

Assumption 1

$$\sum_{staff\in\{A,B,C,D,E,F\}}\left(\sum_{desk\in\{U,V,W,X,Y,Z\}} x_{staff,desk}+4\right)^2 + \sum_{desk\in\{U,V,W,X,Y,Z\}}\left(\sum_{staff\in\{A,B,C,D,E,F\}} x_{staff,desk}+4\right)^2$$

Only one of the six desks is assigned for each staff member.

Only one of the six staff members is assigned to each desk.

Assumption 2

$$-\sum_{(d1,d2)\in\{(U,V),(V,W),(U,X),(V,Y),(W,Z),(X,Y),(Y,Z)\}}\frac{(x_{A,d1}+1)(x_{B,d2}+1)+(x_{B,d1}+1)(x_{A,d2}+1)}{4}$$

One point is added for each adjacent staff member of team A/B.

$$-\sum_{(d1,d2)\in\{(U,V),(V,W),(U,X),(V,Y),(W,Z),(X,Y),(Y,Z)\}}\ \sum_{s1\in\{C,D,E,F\}}\ \sum_{s2\in\{C,D,E,F\},s2\neq s1}\frac{(x_{s1,d1}+1)(x_{s2,d2}+1)+(x_{s2,d1}+1)(x_{s1,d2}+1)}{4}$$

Reversed signs due to the desk adjacency increase

One point is added for each adjacent staff member of team C/D/E/F.

Fig. 3. Ising model representing the desk-arrangement problem.

```
staffs = ["A", "B", "C", "D", "E", "F"]
teams = [{"A", "B"}, {"C", "D", "E", "F"}]
desks = ["U","V", "W", "X", "Y", "Z"]
neighbor_desks = [
    {"U", "V"}, {"V", "W"}, {"X", "Y"}, {"Y", "Z"},
    {"U", "X"}, {"V", "Y"}, {"W", "Z"},
]
x = {}
for s, d in itertools.product(staffs, desks):
    # Declare variables that take +1 or -1
    x[s, d] = cimsdk.boolean((s, d))

# Variables for summing up the values given by Ising model
input = 0

# Assumption 1: The Ising model is automatically created by declaring the “choose_one” function.
for s in staffs:
    input += cimsdk.choose_one(x[s, "U"], x[s, "V"], x[s, "W"], x[s, "X"], x[s, "Y"], x[s, "Z"])
for d in desks:
    input += cimsdk.choose_one(x["A", d], x["B", d], x["C", d], x["D", d], x["E", d], x["F", d])

for t in teams:
    for s1, s2 in itertools.combinations(t, 2):
        for d1, d2 in itertools.product(desks, 2):
            # Assumption 2: Declaring an associative array of values automatically creates the Ising model.
            input -= cimsdk.translate_dict(
                (x[s1, d1], x[s2, d2]),
                {
                    (-1, -1): 0,
                    (-1, +1): 0,
                    (+1, -1): 0,
                    (+1, +1): +1 if {d1, d2} in neighbor_desks else 0,
            })
```

Fig. 4. Ising model constructed using cimsdk.

and their related conditions) to the Ising model. This function makes it easy for people without expertise in Ising models or Ising machines to benefit from the fast solutions given by the Ising machine.

The unique strengths of cimsdk in comparison with similar SDKs from other companies are three-fold: (i) the ability to combine multiple conditions unrestrictedly, (ii) the ability to express mathematically definable logical structures as is, and (iii) the ability to automatically generate the corresponding Ising model from an arbitrary associative array. We plan to expand the number of spins and conditions for automatic conversion to an Ising model, thereby broadening the range of practical problems that can be handled by cimsdk.

3. Application development and execution using LASOLV™ computing system

Another problem with using an Ising machine is that it is difficult for it to complete the application because it is a computer specialized for solving the Ising-model ground-state search problem. To execute processes, such as data pre-processing and post-processing using cimsdk, for classical computers to have an advantage, a heterogeneous system that combines an Ising machine with various computing devices, such as classical computers, is required. The cost and installation location of an Ising machine pose difficulties compared with those of a personal computer or a general server, so it is difficult to have a large number of Ising machines available. Therefore, as is the case with supercomputers, a means of sharing a small number of Ising machines among several users is required. NTT Computer and Data Science Laboratories has therefore been developing the LASOLV™ Computing System (LCS) as a platform for efficient use of Ising machines such as LASOLV™ [4]. In addition to providing a development environment that facilitates application development such as cimsdk, LCS has functions for controlling user jobs and scheduling them so that multiple users' jobs do not overlap while efficiently coordinating and using nodes that perform calculations on central processing units and Ising machines.

By developing applications using cimsdk on LCS, we are also developing applications that use the capabilities of LASOLV™. To cite an example, we conducted a joint demonstration in conjunction with Mitsubishi Heavy Industries, Ltd. to use an Ising machine for personnel-assignment planning [5]. The company is responsible for inspecting and repairing power plants and other facilities worldwide. In response to this responsibility, workers with skills tailored to various inspection items must be dispatched, and personnel-assignment plans must account for complex parameters such as the number of workers, consecutive working days, and overtime hours. Conventionally, it took about one month for a skilled planner to manually formulate a personnel-assignment plan for 26 plants to be inspected by 141 workers within a period of 64 days to find a candidate solution for the plan that satisfies constraints such as the skills possessed by the workers. The scale of this task is tremendous, namely, 3.48×10^{13329} combinations. By using the latest version of LASOLV™, which can calculate 50,000 spins at once, we demonstrated that a solution can be obtained in a very short time. This high solution speed is expected to make it possible to formulate personnel-assignment plans with multiple patterns and revise the plans as needed to accommodate infectious-disease countermeasures and other circumstances.

4. Future developments

Our efforts concerning SDKs to facilitate application development and computing-system development while taking into account the characteristics of Ising machines were introduced. Practical application of quantum computers—as well as Ising machines—will increase the importance of SDKs and other libraries that account for their characteristics, and the need for computing systems with greater heterogeneity will grow. At NTT Computer and Data Science Laboratories, we will define the ideal computing-system architecture that uses advanced technologies, such as quantum computers and advance research, on that architecture.

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Design and Development of Superconducting-quantum-computer System

Yasunari Suzuki

Abstract

To scale up quantum computers to a practical size and provide them as a service, the abstraction of computing systems with a large number of quantum bits is a key step towards practical quantum computing. As a milestone to this goal, NTT, RIKEN, and collaborators launched a quantum computing service with 64 quantum bits in March 2023. In this article, NTT's efforts in this development to control a large-scale quantum computer and make it a cloud service are described. The configuration of the cloud service and future prospects of quantum computing are also explained.

Keywords: quantum computing, superconducting qubits, computer architecture

1. Introduction

By using superposition states of quantum matter, quantum computers are expected to enable high-speed computing and new types of information processing. However, superposition states are vulnerable to environmental noise and can easily change to another superposition state; therefore, quantum computing research and development (R&D) has focused on the development of devices with long lifetime of the superposition state, exploration of efficient error-correcting codes to reduce quantum noise, and analysis of quantum algorithms and its computational-performance limits.

Quantum computing has become a reality as these basic technologies have been established, and designing and developing a large-scale quantum computer that combines the research results of these technologies have been active. NTT, in collaboration with RIKEN and others, developed a quantum computer using superconducting quantum bits (qubits)*1 and launched the first quantum-computer cloud service in Japan in March 2023. NTT has worked on the development of technology to abstract, calibrate, and automate the control of qubits and provide quantum computing as a cloud service. This superconducting quantum computer and the efforts being made to demonstrate practical quantum computing are discussed in this article.

2. Superconducting qubits

Since the matter around us obeys quantum mechanics, any two distinct states can theoretically be treated as a qubit. However, there are a limited number of systems in which we can realistically maintain the superposition state for a long time. Superconducting qubits, which use the two lowest-energy states of superconducting circuits as qubits, are promising as highly scalable quantum physical systems because they can be integrated on a substrate and maintain a long lifetime of several hundred microseconds to milliseconds.

A photograph of integrated qubits on a chip is shown in **Fig. 1**. The circular pattern in the enlarged image on the left corresponds to a single qubit. The qubits are arranged two-dimensionally on the chip

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*1 Superconducting qubit: A physical system that uses a circuit in a superconducting state to represent the 0, 1 state of a qubit. It is known to be controllable with high fidelity while ensuring integration and considered a leading candidate for creating a scalable quantum computer.

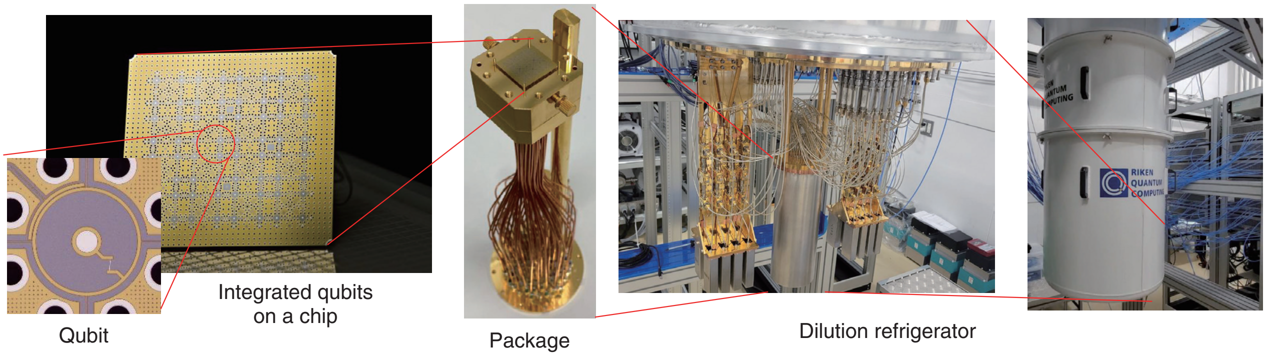


Photo courtesy of Institute of Physical and Chemical Research (RIKEN)

Fig. 1. Appearance of superconducting quantum computer.

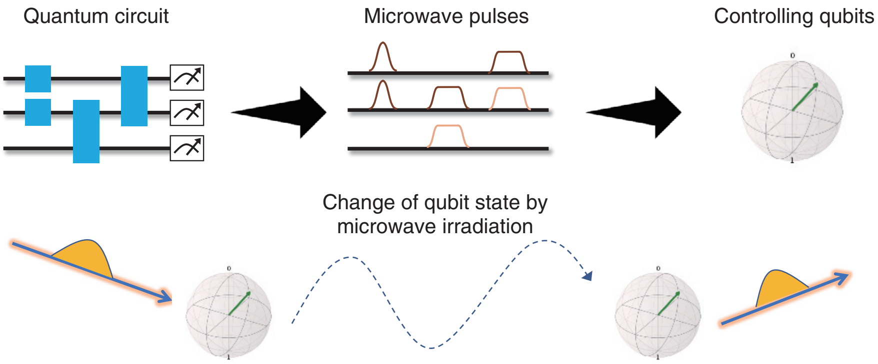


Fig. 2. Control of superconducting qubits.

and wired to the outside via the package. Since the superposition state of superconducting qubits is sensitive to thermal noise, the chip is cooled to tens of millikelvin by placing it in a dilution refrigerator.

The superconducting circuit shown in Fig. 1 is a medium that stores information and does not have the ability to compute on its own. For this reason, as shown in **Fig. 2**, microwave pulses are sent to the qubits to control them. A typical quantum-computing program is written in a representation similar to a logic circuit, called a quantum circuit. There are two types of operations on a qubit in a quantum circuit: (i) unitary operations, which change the quantum state of the qubit without obtaining information about it, and (ii) readout operations, which obtain the state of the qubit as either 0 or 1. Both operations involve qubit control with multiple microwave pulses, the shapes of which are optimized for the characteristics of the qubit and the type of operation [1]. For readout operations, in addition to microwave controls, the shape of the response microwave pulse is analyzed to discriminate whether the qubit state is 0 or 1.

These microwave controls are experimentally implemented as follows. First, the waveform of the microwave pulse is designed as digital data with classical computers in accordance with the characteristics of the quantum-circuit elements and qubit characteristics. These data are then transferred to control electronics installed at room temperature, which converts the digital signal to an analog signal that is output in the form of a microwave. The microwaves are transmitted through wires to the qubits in the dilution refrigerator. The state of qubits can be read out from the signal returned from the qubit. Thus, the returned analog waveform is converted to digital data using the electronics, and the state of qubits is discriminated with a binary classifier. By subjecting the qubits arranged in a chip to the above-described processing,

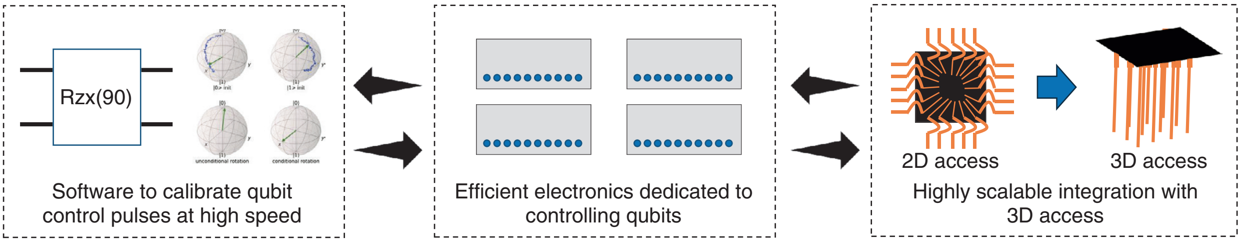


Fig. 3. Fundamental technologies supporting scalability.

it is possible to execute the desired computations and obtain results.

3. Controlling qubits

To perform quantum operations on qubits, we need to design the pulse shape of the microwaves required to control the qubits as well as the binary classification function for the readout operation. The optimal pulse shape depends on qubits' properties such as lifetime and energy gaps. Since these properties differ from qubit to qubit, the control signal must be designed for each qubit. The characteristics of the qubits can be roughly estimated at the chip-design stage, but the exact value cannot be determined without measurements on fabricated qubits. Therefore, the following two procedures must be established to carry out quantum computing with qubits. First, clarify the characteristics of the qubits through multiple measurements after cooling them in a dilution refrigerator. Second, in accordance with those characteristics, create optimal pulse shapes for each type of operations and classification functions for the readout operation. The series of experiments that ensure that the manufactured qubits can be used for computation is called "calibration."

We can calibrate qubits by hand as long as the number of qubits is small. However, as the number of qubits increases, it is not practical to design and calibrate them in an ad-hoc manner. Thus, we have made efforts to abstract large-scale quantum computing, experimentally reveal the challenges that impede scalability, and address them one by one. The three fundamental technologies that support the scalability of quantum computing shown in **Fig. 3** are explained hereafter.

The first challenge in scaling quantum computers is the problem of qubit wiring. Qubits are typically arranged two-dimensionally on the chip and individually wired from the periphery of the chip so that control signals can be transmitted to the individual qubits. However, with this arrangement, the number of necessary wires increases quadratically with respect to the chip width, while the number of wires that can be routed to qubits increases linearly to the chip width; as a result, wiring becomes more difficult when the circuit scale increases. To solve this problem, RIKEN proposed a highly scalable method, with which the control wires are three-dimensionally connected to the chip (Fig. 1), and in collaboration with Fujitsu, National Institute of Advanced Industrial Science and Technology (AIST), and National Institute of Information and Communications Technology (NICT), RIKEN has integrated qubits by using this wiring method [2].

The second challenge is to improve the efficiency of electronics. To control qubits with as few wires as possible, it is necessary to multiplex and transmit microwave signals with multiple frequencies and waveforms with a single wire. If expensive measurement equipment is used for each qubit to achieve this control, the scalability of the quantum computer becomes impractical in terms of cost and size as the number of qubits increases. The developed superconducting quantum-computer system uses the electronics optimized for controlling qubits developed under the leadership of Osaka University and others.

The third challenge is to write software to efficiently control and calibrate the qubits. As mentioned above, the method of manually characterizing qubits is known, but it is impractical to manually calibrate a large number of qubits. Since the characteristics of qubits and their controllers change over time, the quantum computer cannot be operated accurately if calibration takes too long. NTT and RIKEN have constructed a platform for controlling multiple electronics in parallel and systematically measuring qubits. Using this platform, NTT and RIKEN have also written software and protocols for automating the parallel and accurate calibration of multiple

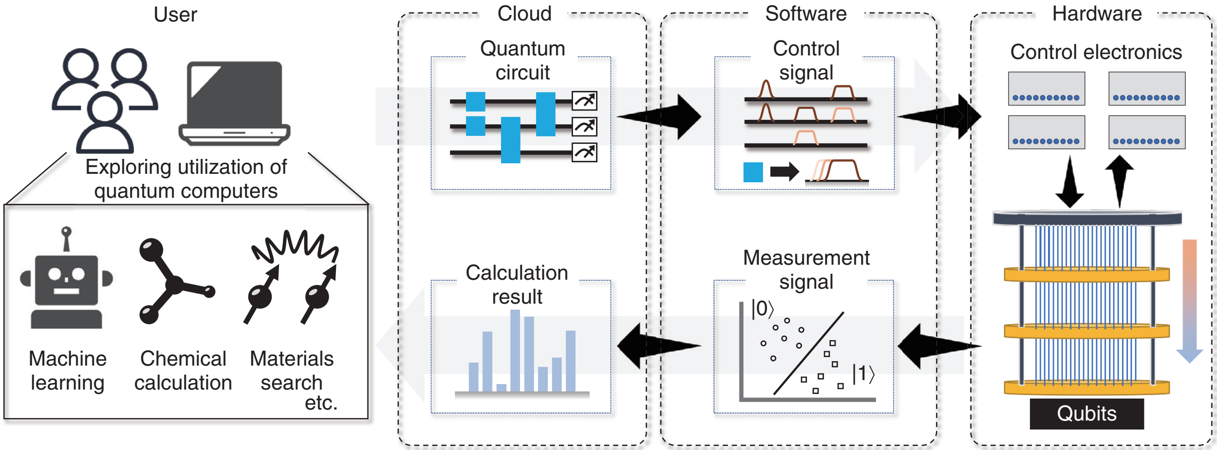


Fig. 4. Overview of our cloud service.

qubits.

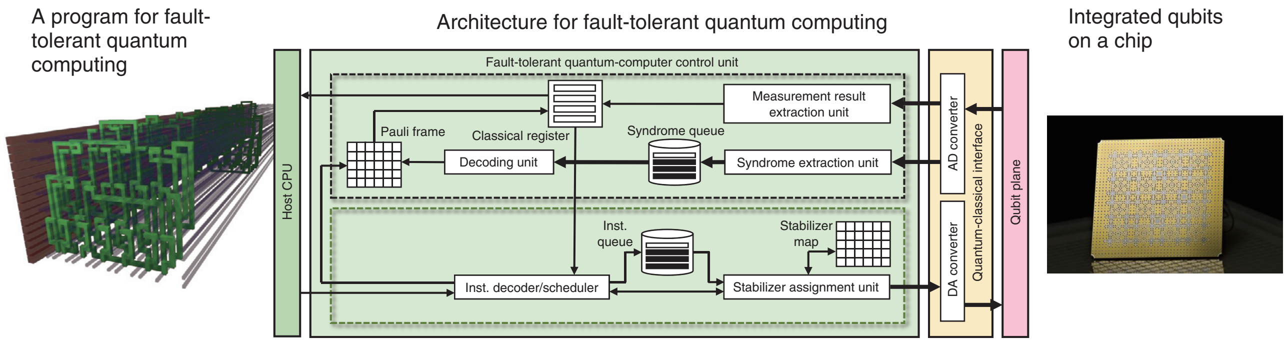
4. System abstraction and operation

The above-mentioned superconducting quantum-computer system provides the fundamental technologies to control the integrated qubits. However, to operate this system continuously as a cloud service, we need to accumulate the knowledge to maintain its stable operation. We also must create a framework for providing the service to users. The above-mentioned platform for measuring qubits works well when the qubits are manufactured ideally. In practice, however, calibration often fails for a variety of reasons. Causes of this failure range from human error, such as wrong wiring, to manufacturing problems, which cause the characteristics of the qubits to deviate so much from the designed values that they cannot be controlled. As the system is scaled up, the more difficult it becomes to identify the type and location of the cause of failure, and practical operation of the quantum computer becomes difficult. The software that oversees the entire system is therefore expected to not only operate the system in a normal state but also accurately report the cause of any anomalies at the earliest possible stage. Since there are countless types of abnormal cases, it is not easy to completely automate this procedure. Even so, NTT and RIKEN have accumulated knowledge during the development period and built a software system to efficiently find typical factors.

To provide this quantum-computing system as a service, it is also necessary to establish a web service to make it easier for users to use quantum computers. In the current design of the control software, the lowest-level representation of the program that controls the qubit is the waveform information of the microwave that controls the qubit. This representation is convenient to experimentally investigate the characteristics of qubits, but it is not realistic for users to describe their computing tasks with pulse shapes. The developed quantum computer platform provides two methods: a job-description method for directly designing the shape of a pulse for the developers of quantum computers and a method for specifying a program in the description of a quantum circuit for the users of cloud service. To provide quantum computing as a cloud service, Osaka University, RIKEN, and NTT collaborated to build the system shown in **Fig. 4**. Through this system, the user sends a program described in quantum circuits at the front end, the back-end service executes calculations using qubits with the latter method, and the measurement values, which identify measurement data, are returned to the user.

5. Future developments

Although the current cloud service is a milestone in the integration of qubits, many obstacles still have to be overcome before a practical quantum computer can be implemented. As shown in **Fig. 5**, NTT is developing technologies for a fault-tolerant quantum computer in parallel for future practical applications. The largest problem with today's quantum computers is their large noise. The best currently available



AD: analog to digital
CPU: central processing unit
DA: digital to analog

Fig. 5. Technologies for developing a fault-tolerant quantum computer.

qubits have about 0.1% error probability per gate operation, so it is impossible to reliably run large-scale quantum algorithms. It is therefore necessary to develop a technology to encode qubits using quantum-error-correction technology*2 that will execute repetitive error correction during computation and reduce the effective error rate [3]. If quantum-error-correction technology is developed, the errors and variations in the characteristics of qubits can be absorbed to some extent; accordingly, it will be possible to design and build a highly scalable quantum computer.

NTT is collaborating with various research institutes to establish a computer architecture for quantum error correction [4–8]. When we build an architecture under the assumption of error correction, the basic instruction set is defined by the characteristics of the error-correcting code rather than the device. Therefore, new compilers and software targeting fault-tolerant quantum computers are also needed. NTT constructed a compiler for long-term fault-tolerant quantum computing and proposed methods for optimizing it and software for evaluating it [9, 10]. The left side of Fig. 5 shows the actual designed program displayed as a three-dimensional graph during compiler optimization.

NTT's next goal is to integrate these system stacks we have built thus far with qubits to demonstrate a fault-tolerant quantum computer. To create a system that incorporates error correction and can process instructions at high speed as a computer, the fusion of physics and computer science is more essential than ever before. NTT will study the design of computers on the basis of cooperative design that integrates software and hardware in these cross-cutting fields. In doing so, we will lead the world in envisioning the future of practical quantum computers.

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Quantum Error Mitigation and Its Progress

Suguru Endo

Abstract

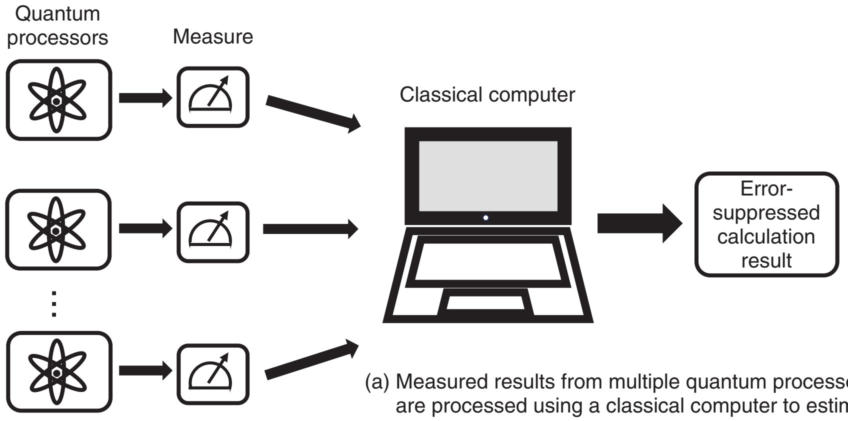
Current quantum hardware is significantly affected by computation errors. Error reduction is thus required to obtain meaningful results from quantum computers. Quantum error mitigation (QEM) methods, which are a class of hardware-friendly error-reduction methods not relying on the encoding of quantum information, are being actively researched. In this article, I review the major QEM methods. I then introduce the recent progress in QEM technologies proposed by our research group. First, I review the worlds' first quantum sensing method incorporating QEM. I then review the generalized quantum subspace expansion method, quite a general unified framework of QEM.

Keywords: quantum computing, quantum error mitigation, post-processing of measurement results

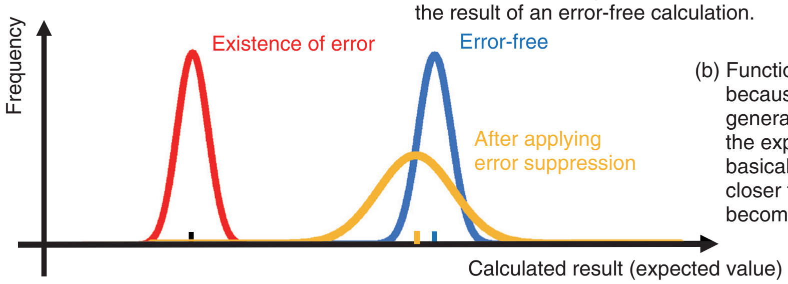
1. Quantum error mitigation

A pressing challenge for quantum computers is suppressing the effects of computational errors due to the loss of quantum coherence. Quantum error mitigation (QEM) is a relatively recent concept proposed for mitigating computation errors while keeping the hardware load to a minimum [1]. QEM is often compared with quantum error correction (QEC). In QEC, multiple physical quantum bits (qubits) are used to represent a single logical qubit. This redundancy is used to detect computational errors, and errors are actively corrected on the basis of this information. However, because the number of qubits in quantum hardware is at most several hundred qubits, QEC reduces the effective number of qubits. QEC thus cannot make the best of the computation power of near-term quantum devices. Therefore, QEM was introduced as a set of methods that can reduce computational errors without reducing the effective number of qubits by avoiding the use of redundancy. Progress related to QEM implementation has been remarkable. In a recent paper, IBM claimed the world's first accomplishment of a practical task with a 127-qubit quantum processor [2]. This breakthrough shows that QEM has an extremely useful role. The exponential-extrapolation error mitigation method I proposed [3] also shows extremely high performance. There are a variety of other QEM methods. In QEM, the correct result of a calculation is generally estimated by post-processing the output from multiple quantum circuits using a classical computer. A conceptual diagram of QEM is shown in **Fig. 1(a)**.

QEM cannot fundamentally suppress errors in the quantum state. However, it can mitigate errors in the expectation values of observables. **Figure 1(b)** illustrates the function of QEM. Because many quantum algorithms that are expected to be implemented in current quantum computers and first-generation fault-tolerant quantum computation use the expectation values of observables, QEM is considered to be highly useful. It should be noted that the cost of QEM is an increase in measurement shots; an exponentially greater number of measurements in accordance with the frequency of computational errors in quantum hardware is required. Intuitively, this is because QEM has the effect of amplifying the expectation values of observables that generally decays exponentially with respect to the number of quantum gates and the gate error rate. The variance of calculation results thus increases exponentially. Mathematical proof related to the exponential increase in the number of measurements have been shown in several papers, including



(a) Measured results from multiple quantum processors are processed using a classical computer to estimate the result of an error-free calculation.



(b) Function of QEM. Calculation results have a distribution because in quantum mechanics, measurement results are generally random and statistical errors are introduced when the expectation values of observables are calculated. QEM basically brings the expectation values of observables closer to the correct value. However, statistical error becomes greater and more measurements are required.

Fig. 1. Conceptual diagram of QEM.

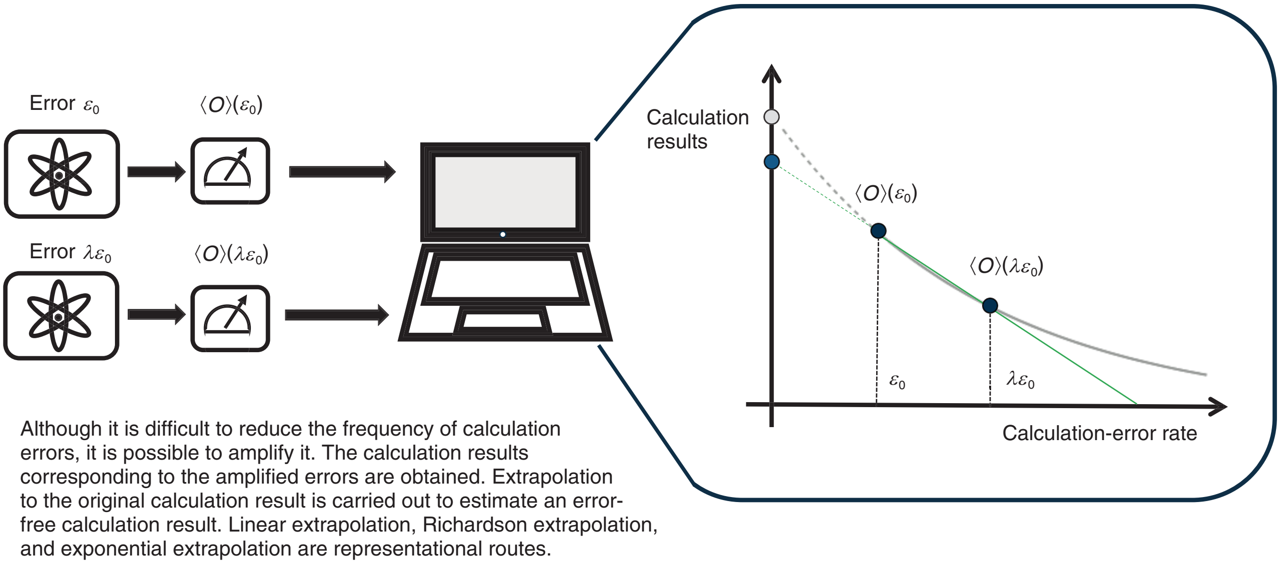
that by our research group [4], using a quantum information-theoretic approach. In the following section, I discuss the major QEM methods: extrapolation [3, 5], quasi-probability (also called probabilistic error cancellation [3, 5]), virtual distillation [6], and subspace expansion [7].

I then describe our research groups' latest achievements, a quantum sensing method incorporating QEM [8] and quite a general unified framework of QEM called the generalized quantum subspace expansion method [9]. For readers who wish to simply have an overview of QEM, it is sufficient to understand the extrapolation methods. For those who wish to learn more, I encourage you to read the other sections. Referring to the review paper I wrote [1] when needed will provide an in-depth understanding of QEM.

1.1 Extrapolation methods

As the name suggests, extrapolation methods estimate the ideal error-free calculation result by extrapolating multiple measurement results [3, 5]. They are simple yet powerful methods used in many experiments. An overview of extrapolation methods is shown in **Fig. 2**. The horizontal axis shows the error rate and the vertical axis shows the result (the expectation value of an observable). Of course, we cannot freely reduce the error rate, but it is relatively easy to increase calculation errors. For example, it is possible to increase the frequency of errors by slowly carrying out gate operations or by carrying out extra gate operations. By extrapolating the original calculation result and calculation results associated with increased error rates, the ideal error-free calculation result is then estimated. When extrapolation methods were first proposed, they used Richardson extrapolation with linear and polynomial functions [5]. Observing that calculation results generally decay exponentially with the frequency of calculation errors, I proposed extrapolation using an exponential function [3]. The exponential extrapolation showed extremely good performance in an actual experiment [2]. However, extrapolation methods cannot guarantee computation accuracy and can be said to be relatively heuristic.

The number of measurements, a cost factor in QEM, can be easily understood with extrapolation methods. Considering linear extrapolation as an example, for calculation error rate ε_0, we express the experimentally obtained average value of the observable as $\langle O(\varepsilon_0)\rangle$ and that with twice the error rate as $\langle O(2\varepsilon_0)\rangle$. From extrapolation, the error-mitigated result can be written as $O_{\text{est}} = 2\langle O(\varepsilon_0)\rangle - \langle O(2\varepsilon_0)\rangle$.



Although it is difficult to reduce the frequency of calculation errors, it is possible to amplify it. The calculation results corresponding to the amplified errors are obtained. Extrapolation to the original calculation result is carried out to estimate an error-free calculation result. Linear extrapolation, Richardson extrapolation, and exponential extrapolation are representational routes.

Fig. 2. Overview of extrapolation methods.

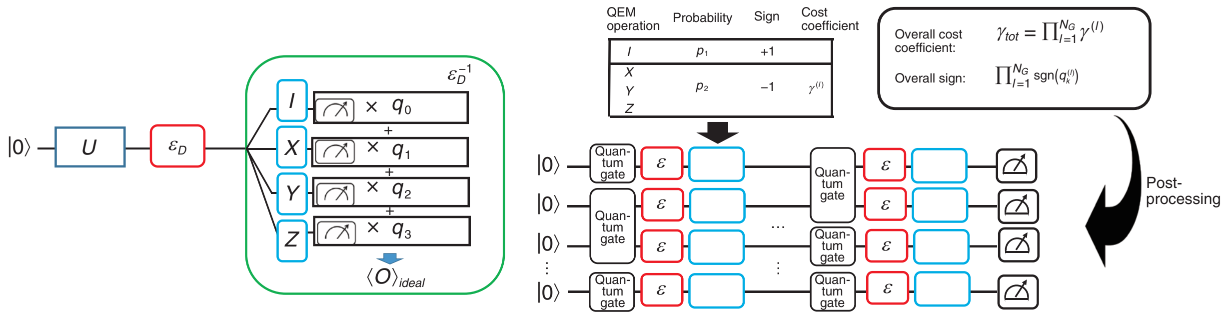
When calculating variance, if no correlation is assumed between $\langle O(\varepsilon_0)\rangle$ and $\langle O(2\varepsilon_0)\rangle$, we obtain $\mathrm{Var}[O_{est}] = 4\mathrm{Var}[\langle O(\varepsilon_0)\rangle] + \mathrm{Var}[\langle O(2\varepsilon_0)\rangle]$. This shows that the variance is amplified after applying QEM and that more measurements are needed to obtain the correct calculation result.

1.2 Quasi-probability method

The quasi-probability method counteracts the effect of gate noise by effectively constructing the inverse of the noise based on the noise model obtained through noise characterization techniques, such as process tomography or gate set tomography [3, 5]. We denote the quantum process corresponding to the noise as $\mathcal{E}$ (it may be easier to think of it as the quantum mechanical version of a transition matrix) and its inverse map as $\mathcal{E}^{-1}$. While $\mathcal{E}^{-1}$ can be mathematically constructed, it is not generally a "physical process" and cannot be directly operated on a quantum computer. By constructing $\mathcal{E}^{-1}$ by a set of operations $\{B_k\}_k$ for QEM that we can execute with fewer calculation errors, we can decompose $\mathcal{E}^{-1}$ as $\mathcal{E}^{-1} = \sum_k q_k B_k$. Usually, we assume that $\{B_k\}_k$ are single qubit operations.

For example, when we consider the depolarizing noise of error probability p to be $\mathcal{E}_D(\rho) = \left(1 - \frac{3}{4}p\right)\rho + \frac{p}{4}(X\rho X + Y\rho Y + Z\rho Z)$, its inverse map is $\mathcal{E}_D^{-1}(\rho) = \left(1 + \frac{3p}{4(1-p)}\right)\rho - \frac{p}{4(1-p)}(X\rho X + Y\rho Y + Z\rho Z)$. Here, $q_0 = \left(1 + \frac{3p}{4(1-p)}\right)$, $q_1 = q_2 = q_3 = \frac{p}{4(1-p)}$, $B_0(\rho) = \rho$, $B_1(\rho) = X\rho X$, $B_2(\rho) = Y\rho Y$, $B_3(\rho) = Z\rho Z$. Because $\sum_k q_k = 1$, and $\mathcal{E}^{-1}$ is generally not a physical process resulting in q_k being a quasi-probability that can be negative, this method is called the quasi-probability method. A negative probability cannot be directly implemented, but the expected value "same as the case of sampling using negative probability" can be effectively calculated by post-processing of the measurement results. Consider a simple 1-qubit system as an example, which is conceptually shown in **Fig. 3(a)**. The ideal quantum state is $\rho_{ideal} = U|0\rangle\langle 0|U^\dagger$. However, because of depolarizing noise $\mathcal{E}_D$, the actual quantum state is $\rho_{noisy} = \mathcal{E}_D(\rho_{ideal})$. Expressing the observable to be measured as O, because the noiseless expectation value is $\langle O_{ideal}\rangle = q_0\mathrm{Tr}[\rho_{noisy}O] + q_1\mathrm{Tr}[X\rho_{noisy}XO] + q_2\mathrm{Tr}[Y\rho_{noisy}YO] + q_3\mathrm{Tr}[Z\rho_{noisy}ZO]$, the expectation value of the observable can be measured by adding together the measurement outcomes of quantum states ρ_{noisy}, $X\rho_{noisy}X$, $Y\rho_{noisy}Y$ and $Z\rho_{noisy}Z$ with the appropriate weight of quasi-probability. Even if a quasi-probability with a negative value exists, a non-physical inverse map can be constructed by multiplying a negative sign to measurement outcomes and performing post-processing.

It is important to implement the inverse map in a quantum circuit with multiple qubits for practical purposes. Consider when a quasi-probability method is applied to the noise $\mathcal{E}_l$ ($l = 1,2,\ldots N_G$, where N_G is the number of gates) of multiple quantum gates. The conceptual diagram is shown in **Fig. 3(b)**. We



(a) Quasi-probability method for 1-qubit system. The average of the observables measured for the quantum state, with Pauli operator added, is multiplied by the quasi-probability and added to form an inverse map of the overall calculation error.

(b) QEM is executed randomly after the quantum gate containing the computational error. This figure shows an example of depolarizing noise, where the QEM operation becomes a Pauli operation. The measurement result is multiplied by the cost coefficient and sign, and the average of the outcomes gives the error-mitigated result.

Fig. 3. Overview of the quasi-probability method.

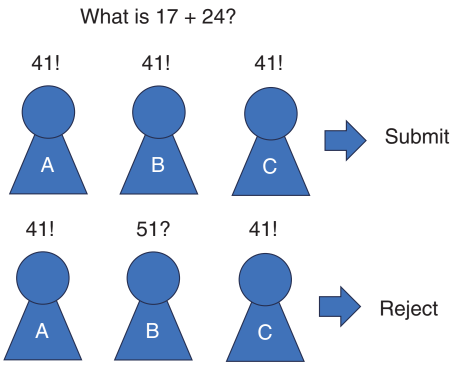
construct an inverse map for each error: $\mathcal{E}_l^{-1} = \sum_k q_k^{(l)} B_k = \gamma^{(l)} \sum_k p_k^{(l)}\, \mathrm{sgn}\big(q_k^{(l)}\big) B_k$ ($\sum_k p_k^{(l)} = 1$, $p_k^{(l)} > 0$, $\gamma^{(l)} = \sum_k |q_k^{(l)}| > 1$, $\mathrm{sgn}\big(q_k^{(l)}\big) = q_k^{(l)}/|q_k^{(l)}|$, where $\gamma^{(l)}$ is the cost coefficient. After each quantum gate (or before, depending on the formulation), operation B_k is generated with probability $p_k^{(l)}$, and the products of sign $\prod_{l=1}^{N_G} \mathrm{sgn}\big(q_k^{(l)}\big)$ and cost coefficient $\gamma_{tot} = \prod_{l=1}^{N_G} \gamma^{(l)}$ are multiplied to the measurement result. By repeating this, the average of the result gives the error-mitigated result. Because the variance of the calculated result is approximately amplified by γ_{tot}^2 compared with the case without error mitigation, an exponentially large number of measurements according to the number of gates is required.

Although a suitable error-characterization method has not been proposed when the quasi-probability was first proposed, I found that gate-set tomography is an efficient error-characterization method for this method [3]. I also discovered a set of operations $\{B_k\}_k$ for QEM that allows for removal of arbitrary computational errors [3]. I have also shown that the quasi-probability method can be applied not only to gate models but also temporally continuous noise models such as those described by the Lindblad master equation $\frac{d}{dt}\rho = -i[H, \rho] + \sum_k (2\, L_k \rho L_k^\dagger - L_k^\dagger L_k \rho - \rho L_k^\dagger L_k)$, extending QEM to analog quantum systems [10].

1.3 Virtual distillation method

Virtual distillation executes QEM by preparing multiple copies of a noisy quantum state ρ_{noisy}, executing entanglement measurements between them and post-processing the results using a classical computer. This enables us to simulate the error-suppressed quantum state as if we distill a noiseless quantum [6]. An example of the "classical" counterpart of this method is as follows: we ask several students to solve the same problem, e.g., elementary school students who often get erroneous results for simple arithmetic problems. Only when all the calculation results are the same is the answer submitted; otherwise, the results are discarded (**Fig. 4**). The more students involved in calculating the result, the higher the percentage of the correct answer. However, the probability of success (i.e., the probability of all students calculating the right answer) decreases exponentially with the number of students.

With virtual distillation, we can calculate the expected value of the physical quantity corresponding to the distilled quantum state $\rho_{vd} = \frac{\rho_{noisy}^n}{\mathrm{Tr}[\rho_{noisy}^n]}$, where n is the number of copies of the noisy quantum state. When we have the spectral decomposition $\rho_{noisy} = \sum_k p_k\, |\psi_k\rangle\langle\psi_k|$ ($p_0 \geq p_1 \geq \ldots$), it is expected that the eigenstate corresponding to the largest eigenvalue is a good approximation of the ideal quantum state when the noise is small. Now, as n increases, ρ_{vd} asymptotically approaches $|\psi_0\rangle$. The contribution of $|\psi_k\rangle$ ($k = 1, 2, \ldots$) is suppressed exponentially with respect to n. However, the number of required measurements increases exponentially with n. The advantage



An intuitive classical explanation of the virtual distillation method. Calculation accuracy is increased by having several participants solve the same problem. The result is rejected if even one of them produces a different result.

Fig. 4. Overview of virtual distillation method.

of this method is that it can mitigate errors with high accuracy if the errors are stochastic, even without information about the error model. However, coherent errors caused by rotation errors of quantum gates and the insufficient expression capability due to the lack of depth of ansatz quantum circuits in variational quantum eigensolver cannot be mitigated with this method, no matter the increase in the number of copies.

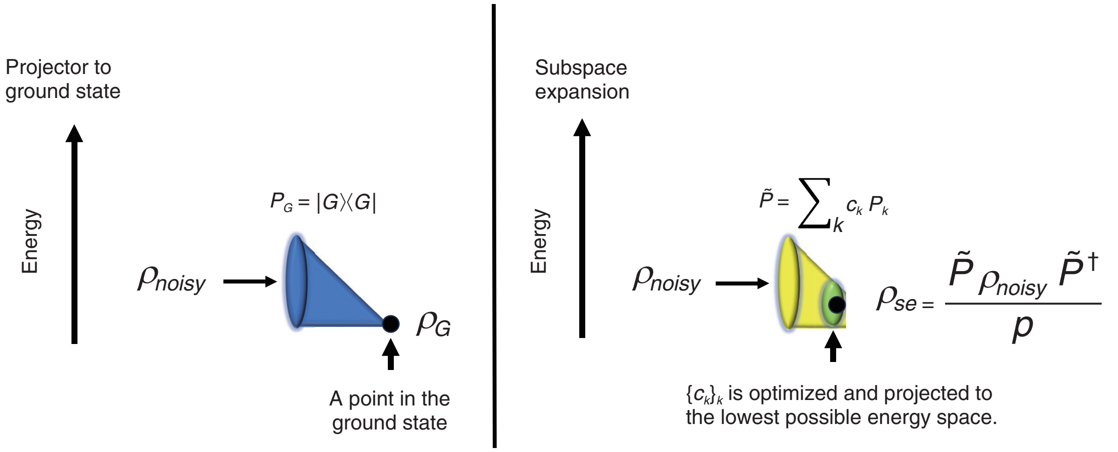
1.4 Subspace expansion method

The subspace expansion method constructs a projector (strictly speaking, this operator does not satisfy the mathematical properties of a projector but is called one here for convenience) [7]. Consider a case in which the actual quantum state immediately before measurement differs from the ideal quantum state because of noise. For example, the variational quantum eigenvalue solver is a method for determining the ground state $\rho_G = |G\rangle\langle G|$ of molecules, etc; however, the actual quantum state may be another quantum state ρ_{noisy} because of errors. If we can construct the projector onto the ground state $P_G = |G\rangle\langle G|$, an error-free quantum state can be obtained as $\frac{P_G\, \rho_{noisy}\, P_G}{p_G} = \rho_\text{G}$ with p_G being the projection probability (**Fig. 5(a)**). However, because $|G\rangle$ is an extremely large quantum state in reality, the expression of P_G cannot be obtained in the first place, and the projection cannot be executed accurately. We thus seek to construct a projection operator (which strictly speaking, does not satisfy the mathematical properties of a projection operator but called one here for convenience) that can project the noisy state onto a space with the lowest possible energy. Using Pauli operators P_k to express such a projection operator as $\tilde{P} = \sum_k c_k\, P_\text{k}$ (where c_k is a complex number), we optimize $\{c_k\}_k$ using a classical computer so that the energy of the projected quantum state $\rho_{se} = \frac{\tilde{P}\, \rho_{noisy}\, \tilde{P}^\dagger}{p}$ (where p is the projection probability) can be minimized (**Fig. 5(b)**). What P_k to choose is arbitrary. Methods for constructing P_k from, for example, excitation operators of a molecule's spin-orbitals, have been proposed [7]. This method can suppress coherent errors to a certain extent but is known to be unsuitable for suppressing stochastic errors such as bit flips.

2. NTT's latest achievements

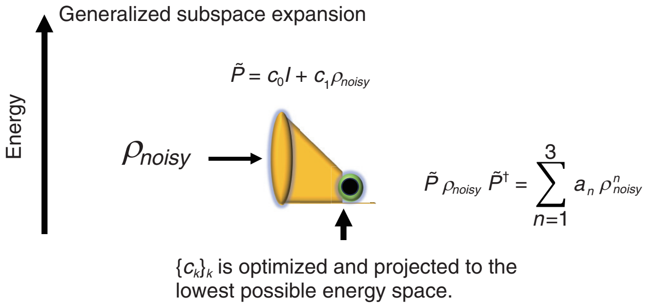
2.1 Application of QEM to quantum sensing

NTT has developed the world's first framework for quantum sensing incorporating QEM. Quantum sensing is an active area of research in the field of quantum information that uses quantum states to efficiently probe fields such as magnetic fields one wishes to measure. This is done by interacting the quantum states with the field followed by the readout. The process is repeated and the results are accumulated to estimate the value of the magnetic field. What is important about quantum sensing is that when quantum entangled states are used as probes, quantum advantageous scaling can be achieved depending on the number of qubits N. However, if the noise fluctuates at each time of measurement, systematic errors occur in the accumulated value and estimated



(a) If the projector to the ground state is operated onto the noisy state ρ_{noisy}, it will become the ground state. However, this cannot be carried out.

(b) In the subspace expansion method, however, a projector that transfers the state to the lowest energy space possible is constructed by optimizing $\{c_k\}_k$.



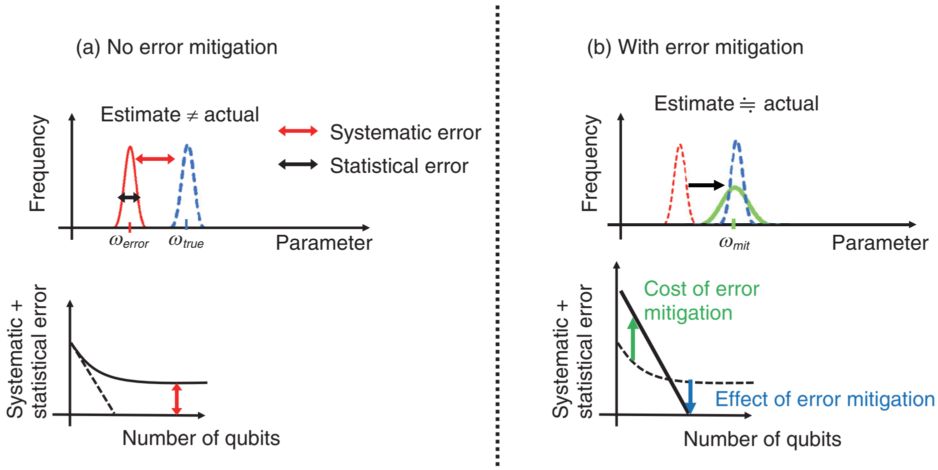
(c) $\tilde{P}$ is extended by not only Pauli operators and their products but also by general operators that include states to construct a projector that transfers the state to the lowest energy space. Thus, extremely general error-mitigated quantum states that completely include the one achieved with virtual distillation and the generalized subspace method can be realized.

Fig. 5. Overview of subspace expansion methods.

magnetic-field value, and quantum advantages cannot be achieved (**Fig. 6(a)**). Our research group has shown that even when noise fluctuates each time the quantum device is executed, virtual distillation can act as a "filter" that removes such noise and accurately mitigates systematic errors [8]. We have also shown that quantum advantageous scaling can be restored (**Fig. 6(b)**).

2.2 Generalized subspace expansion method

Our research group proposed the generalized subspace expansion method, which is quite a general QEM method, which includes subspace expansion and virtual distillation as special cases [9]. I stated above that in subspace expansion, the projection operator $\tilde{P} = \sum_k c_k P_k$ can be optimized so that energy is minimized. The essence of the generalized subspace expansion method is extending P_k to extremely general operators. More specifically, quantum states (and more complex operators that include them) are used as P_k. For example, taking $P_0 = I$, $P_1 = \rho_{noisy}$, the projected state is $\tilde{P}\,\rho_{noisy}\,\tilde{P}^\dagger = |c_0|^2\,\rho_{noisy} + (c_0 c_1^* + c_0^* c_1)\rho_{noisy}^2 + |c_1|^2 \rho_{noisy}^3$, and the expected value of the observables corresponding to an error-mitigated quantum state expanded by a series of powers of a noisy quantum state can be obtained. We call this method the power subspace method (**Fig. 5(c)**). Our research group also proposed the fault-subspace method that uses the essence of extrapolation methods [5] in the construction of projectors. Unification of



When systematic errors exist, increasing the number of qubits in quantum sensing does not achieve quantum advantageous scaling of estimation of parameters of interest.

When QEM is carried out, statistical errors increase due to error mitigation. However, systematic errors can be suppressed, so quantum scaling can be recovered.

Fig. 6. Effect of QEM (virtual distillation) on quantum sensing.

the power subspace method and fault-subspace method is also possible. The generalized subspace expansion method inherits the advantages of both subspace expansion and virtual distillation methods and can mitigate both coherent errors and stochastic errors with high accuracy. Therefore, far more accurate QEM is made possible compared with subspace expansion or virtual distillation alone.

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Toward Early Fault-tolerant Quantum Computing

Yuuki Tokunaga

Abstract

This article introduces new approaches to develop early fault-tolerant quantum computing (early-FTQC) such as improving efficiency of quantum computation on encoded data, new circuit efficiency techniques for quantum algorithms, and combining error-mitigation techniques with fault-tolerant quantum computation.

Keywords: quantum computer, fault-tolerant quantum computation, early fault-tolerant quantum computing

1. Noisy intermediate-scale quantum computers and fault-tolerant quantum computers

Noisy intermediate-scale quantum (NISQ) computers, which do not execute quantum error correction, do not require overhead for encoding. However, because errors inevitably accumulate, there is a limit to computation size. Fault-tolerant quantum computers (FTQCs) carry out computation on encoded qubits, so they have overhead for the encoding and require quantum computers of at least a certain size. The gap between NISQ computers and FTQCs due to the amount of overhead is shown in **Fig. 1**. Is this gap unavoidable? Decades ago, many researchers would consider the answer to be in the negative. However, our team has recently demonstrated a new, unprecedented method to overcome this gap. Motivation to overcome this gap has also led to a research trend that started at around the same time worldwide. These efforts, collectively called early fault-tolerant quantum computing “early-FTQC”, have become a worldwide research movement. In this article, I introduce efficiency-improvement methods and novel efforts for early-FTQC.

2. Possibilities and limitations of NISQ computers

In the article “Design and Development of Superconducting-quantum-computer System” [1] in this issue, a superconducting quantum computer that is currently operated as a cloud service in Japan is introduced. What is the extent of computation possible with a quantum computer of this scale? This quantum computer’s processor chip has 64 qubits. Under ideal conditions, it is considered to be capable of performing computations that cannot be done with current large-scale classical computers. In fact, Google published a paper in 2019 demonstrating a computation task using a processor with 53 qubits and the resulting quantum statistical effects, which would be difficult to classically simulate [2]. However, it is difficult to say that this computation task is useful. After the publication of the paper, several works were published arguing that even with classical computers, faster computation than expected is possible.

Variational quantum eigensolver, a heuristic method for quantum computing that focuses on the efficient computation in the NISQ era has the potential to produce fast and useful computation by exploiting the characteristics of the quantum state, which classical computers do not have. However, there are issues that must be addressed. Because the variational quantum eigensolver is a heuristic method, it is not easy to show the theoretical proof of high-speed and high-precision computation. Realistic noise and error problems also occur when conditions are not ideal. Current quantum computers typically have an error

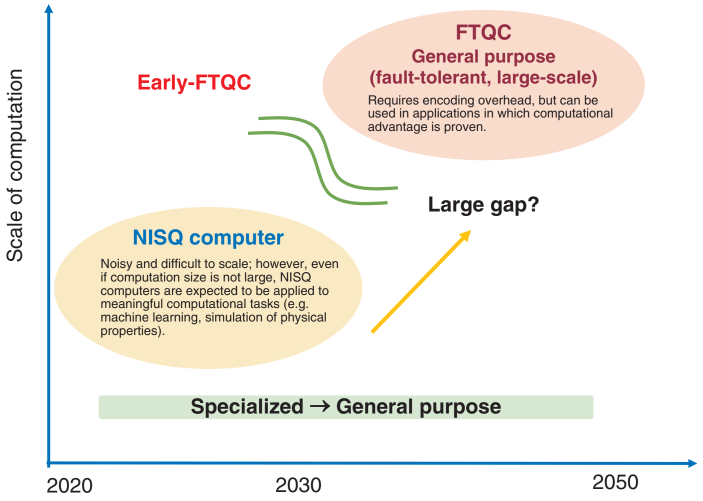

Fig. 1. Gap between NISQ computers and FTQCs.

rate of about 0.1 to 1% for a single gate operation. Roughly speaking, the total error rate increases with the number of gates, so 1000 gate operations would be difficult to achieve without error countermeasures. As introduced in the article “Quantum Error Mitigation and Its Progress” [3] in this issue, quantum error mitigation (QEM) is a class of techniques used to handle errors in the NISQ era. In the noisy computation described above, computational results are buried in errors. With QEM, the correct computational result is extrapolated by executing quantum computations several times to obtain multiple results and statistically estimating the errors. However, the greater the number of errors, the more difficult estimation becomes, and the greater the cost of repeatedly executing computations and performing measurements. In fact, the estimation becomes exponentially more difficult with the increase in errors, so there is a limit to the scale of computation for which QEM is practical. However, in June 2023, IBM published a paper discussing the use of a 127-qubit superconducting quantum computer to solve a condensed matter-physics problem that is difficult to handle with classical computation by ingeniously deploying QEM [4]. This achievement shows that the possibility of executing useful quantum computation that surpasses the capabilities of classical computation in the NISQ era continues to be pursued. Discussion is still ongoing about whether classical computation can handle such problems faster.

3. Improving FTQC efficiency

Is it the case, then, that quantum computers cannot overcome noise and errors and scale up further? It is known that error-correcting codes can also be applied to quantum computers. A fault-tolerant quantum computer (FTQC) can execute quantum computation on encoded qubits. An FTQC requires overhead, and the number of qubits needed is considered to be 1000 to 10,000 times that without encoding. As research and development of FTQC-architecture-based efficient encoding and decoding systems and compilers have just begun, improvement in efficiency is highly expected. We carried out several research projects to date on such improvements, and two are introduced as follows.

The first project is on improving the efficiency of the computational process on encoded data. The standard method of quantum error correction is encoding with what are called surface codes. These codes work relatively efficiently with nearest-neighbor interactions between qubits arranged in a two-dimensional lattice and have a high fault-tolerant threshold. A promising method for executing quantum computation with surface code is lattice surgery. As shown in **Fig. 2**, we have shown that improving the efficiency of lattice surgery can be treated as a scheduling problem of computational paths in three dimensions, which takes into account the time axis of the computation, and have achieved several promising improvements in efficiency [5].

The second project is on improving the circuit

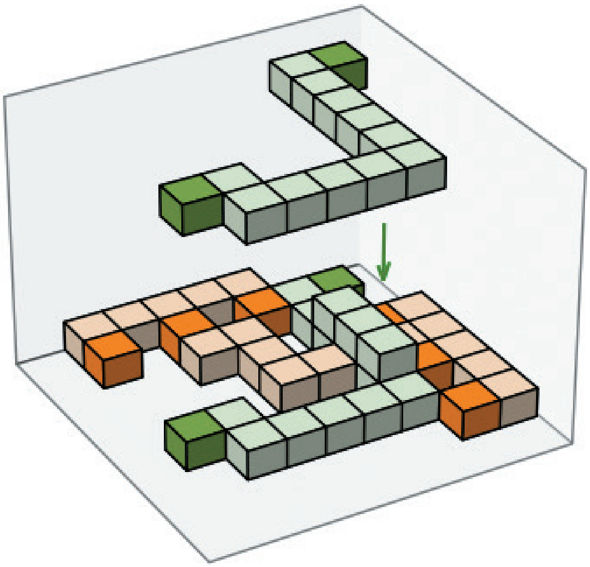

Fig. 2. A scheduling problem of lattice surgery on FTQC.

efficiency of quantum algorithms. The task for determining the eigenenergy of the Hamiltonian in quantum chemistry and condensed matter physics by quantum phase estimation, a key quantum algorithm, is a representative approach of FTQC, showing quantum supremacy in practical problems. Compared with previous methods, qubitization [6, 7] converts the Hamiltonian into a form for which quantum-phase estimation is executable with fewer resources. To execute quantum-advantageous computation in the early-FTQC era, it is necessary to optimize the circuit elements in this qubitization. We reduced the number of *T*-gate operations, which incur computational costs in FTQCs. Specifically, we succeeded in reducing the number of *T*-gates in a quadratic polynomial manner for circuits for the Schwinger model [8].

4. Early-FTQC

In the previous section, FTQCs and efforts to improve their efficiency were introduced. There are limits to improving the computation efficiency of an FTQC, and some overhead is inevitable. What costs are then incurred to run a useful FTQC? **Figure 3** illustrates the FTQC regime. The horizontal axis represents the number of logical operations executed on the encoded quantum state. A logical operation including the overhead of computing on the encoded data is counted as one operation. The vertical axis represents the error rate of logical operations, i.e., the probability that an error will occur for each logical operation, which cannot be corrected despite using quantum error correction. The greater the number of logical operations and lower the logical error rate, the greater the scale of an FTQC can be run. The region to the left of the green line in this figure indicates the region where the scale of computation is tractable enough for classical simulation. The green line is curved at the top because a higher error rate makes it even easier to carry out classical simulation. The region to the right of the brown line represents long-term FTQCs. In this region, we can run algorithms in which the quantum advantage can be demonstrated for meaningful applications. The region between the green and brown lines is what we call early-FTQC [9]. This is the region from the boundary satisfying logical quantum supremacy to the boundary of long-term FTQCs. We believe that heuristic quantum algorithms exist in this region, and it is the region where an FTQC will be first run. Quantum algorithms used in the early-FTQC regime share many traits with NISQ algorithms. The major difference from NISQ era is that because early-FTQC have acquired fault tolerance, they will continue to execute larger computations as quantum computers are scaled up. In other words, as the size of the quantum computer increases, the potential for better computation increases.

Are there ways to further hasten the achievement of early-FTQC? The efficiency-improvement methods described in the previous section are of course significant and effective. Another proposal is rewriting the circuit for algorithms to reduce the number of qubits by incorporating the classical post-processing procedure [10]. Our team has also presented a novel method of applying QEM, considered to be a class of techniques for the NISQ era, to hasten the achievement of early-FTQC [9].

This method adapts a quasi-probability method, a QEM technique mentioned above, to an FTQC. Unlike quasi-probability methods for the NISQ era, we do not mitigate physical errors but logical errors. As shown in **Fig. 4**, recovery operations for error correction in an FTQC are carried out using fundamental quantum operations called Pauli operations. Because Pauli operations are simple, they can be efficiently carried out in batches as the final classical post-processing procedure. In many cases, quasi-probability-based QEM can also be carried out using Pauli operations, so it can be incorporated into the classical post-processing procedure. In some cases, it cannot be carried out with Pauli operations. In this case, the

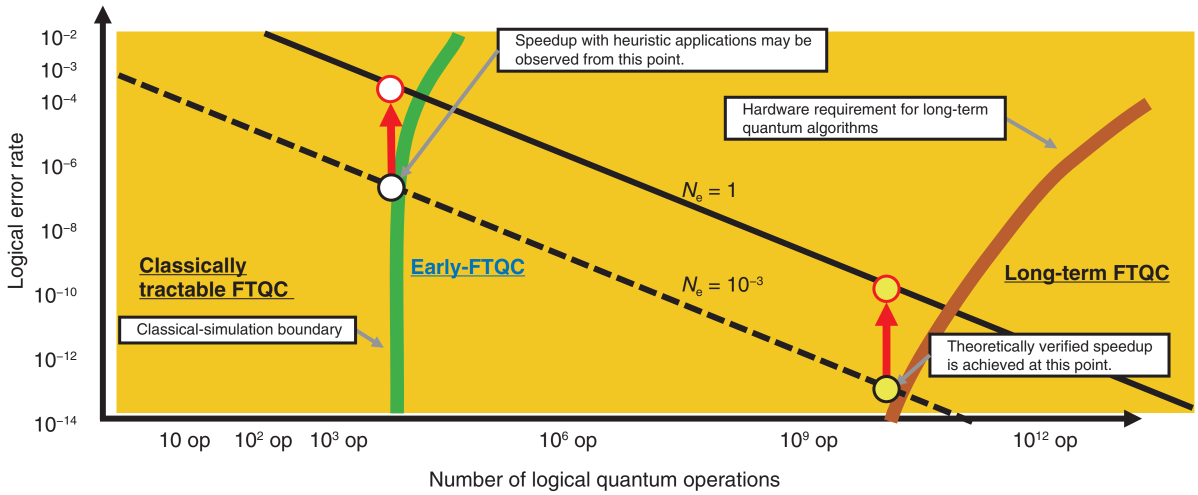

Fig. 3. FTQC regime.

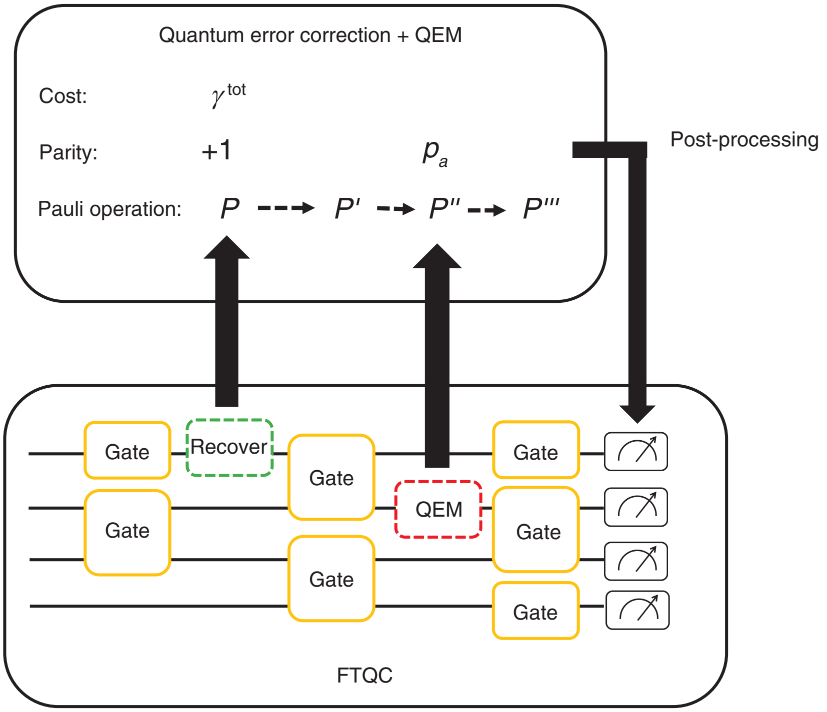

Fig. 4. Application of QEM to an FTQC.

process is carried out physically (see [9] for details).

What becomes important is the cost of QEM. Because the variance of results increases as the amount of errors increases, we need the cost of repeating computations to statistically estimate errors and obtain the correct result. Because there is no error-correction function in NISQ computers, the amount of errors increases as the quantum-computation size increases. Because QEM cost increases exponentially, there is a practical limit to the computation size for which QEM can be used. An FTQC is equipped with error correction, so a region where

QEM can be used within reasonable parameters always exists when computation size increases. In an FTQC, the code distance and overhead are normally set so that the number of errors remaining in the computation results to obtain the correct result is sufficiently smaller than 1 (the line $N_e = 10^{-3}$ in Fig. 3). If QEM is applied to an FTQC, the number of errors can be relaxed to about 1 (the line $N_e = 1$ in Fig. 3), code distance can be shortened, and overhead needed for error correction can be reduced. As indicated with the red arrows in Fig. 3, the region of early-FTQC is expanded (the region of long-term FTQC is also similarly expanded.) In fact, we have shown that by using QEM, the number of qubits required for an FTQC can be reduced by about 80%. In other words, using the same number of qubits, quantum computation size can be increased 1000-fold in terms of the number of quantum operations due to the effect of QEM.

5. Further development of early-FTQC

Early-FTQC has been progressing with various implications. Early-FTQC in a broader sense has also been investigated so far. Early-FTQC described in the previous section meant the initial stages of an FTQC and efforts to hasten the achievement of FTQCs. However, the concept of early-FTQC as a "partial" FTQC, occupying the intermediate stage between a NISQ computing and full-fledged FTQC, has recently emerged. For example, a partial FTQC architecture was proposed in which circuit elements called Clifford gates, which have small encoding overhead, are error corrected, while the rotating gate circuit elements, which are known to incur large overhead for error correction in quantum computation, are not error corrected [11]. In this case, errors accumulate in the rotation gates, so quantum-computation size is limited by this characteristic. However, compared with NISQ computers, this architecture is believed to enable larger quantum computation. We have also proposed a virtual quantum-error-detection protocol that seeks an intermediate procedure between QEM and quantum error correction [12]. Research and development such as that to bridge the gap between NISQ computers and FTQCs have begun. If it becomes possible to freely choose the appropriate error-correction capability and connect a NISQ computer and FTQC, it will be possible to continue to develop quantum computers that perform better than before as computation size increases without incurring gaps from encoding overheads. This new era may soon be a reality.

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Trends in Security Standardization at ITU-T SG17

Kan Yasuda

Abstract

The International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) Study Group (SG) 17 is a de jure organization that deals with security. Another such organization is the International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) Joint Technical Committee (JTC) 1/Subcommittee (SC) 27. This article introduces the efforts of ITU-T SG17 and outlines trends in security standardization by comparing them with JTC 1/SC 27.

Keywords: security standardization, ITU-T SG17, ISO/IEC JTC 1/SC 27

1. ITU-T SG17 (Security)

The International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) Study Group (SG) 17 deals with general security issues. While other SGs handle security issues specific to their respective fields, SG17 is responsible for the overall security study of ITU-T.

ITU-T SG17 has a long history of dealing not only with security but also with fundamental technologies for security, including directories, object identifiers, and technical languages. One of the classic recommendations of ITU-T SG17 is X.509, which defines a standard format for digital certificates. Also well known are the Abstract Syntax Notation One (ASN.1) and object identifiers.

As of July 2023, ITU-T SG17 has five Working Parties (WPs) and twelve Questions (Qs). Each Q belongs to one of the WPs. The composition of these WPs and Qs is dynamic. Qs are added and merged as discussions evolve and technology advances. (That is why they are numbered in skips.) The scope of a particular Q may be expanded. WPs and Qs may be reconfigured at regular intervals. Next year marks a milestone, and a major reorganization may take place. The current structure of WPs and Qs is shown in **Fig. 1**.

2. JTC 1/SC 27 (Information security, cybersecurity and privacy protection)

I now discuss the International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) Joint Technical Committee (JTC) 1/Subcommittee (SC) 27 as a comparison. This de jure organization also deals with general security issues, particularly methods, techniques and guidelines related to information security, cybersecurity, and privacy protection. Although its role is similar to that of ITU-T SG17 in that it is also responsible for security that affects the entire JTC 1, it does not deal with standardization of underlying technologies such as directories or technical languages. (It does make use of them, though.)

Within JTC 1/SC 27, there are five working groups (WGs), each of which is responsible for a different topic. An overview is given in **Fig. 2**. Although the WGs in JTC 1/SC 27 have been added or renamed, they are basically static and the scope of their work has not changed significantly.

3. Comparison of the two organizations

Corresponding to the respective organizational structures of ITU-T SG17 and JTC 1/SC 27, the Japanese domestic committees have different structures. The domestic committee corresponding to ITU-T

- WP1 Security strategy and coordination
  - Q1 Security standardization strategy and coordination
  - Q15 Security for/by emerging technologies including quantum-based security
- WP2 5G, IoT and ITS security
  - Q2 Security architecture and network security
  - Q6 Security for telecommunication services and Internet of Things
  - Q13 Intelligent transport system security
- WP3 Cybersecurity and management
  - Q3 Telecommunication information security management and security services
  - Q4 Cybersecurity and countering spam
- WP4 Service and application security
  - Q7 Secure application services
  - Q8 Cloud computing and Big data infrastructure security
  - Q14 Distributed Ledger Technology (DLT) security
- WP5 Fundamental security technologies
  - Q10 Identity management and telebiometrics architecture and mechanisms
  - Q11 Generic technologies (such as Directory, PKI, Formal languages, Object Identifiers) to support secure applications

5G: fifth-generation mobile communications network
IoT: Internet of Things
ITS: intelligent transport system
PKI: public key infrastructure

Fig. 1. Composition of WPs and Qs in ITU-T SG17 (as of writing).

- WG 1 Information security management systems (ISMS)
  - ISMS ISO/IEC 27000 standards, etc.
- WG 2 Cryptography and security mechanisms
  - Encryption algorithms ISO/IEC 18033 series, etc.
- WG 3 Security evaluation, testing and specification
  - Evaluation criteria for IT security ISO/IEC 15408 series, etc.
- WG 4 Security controls and services
  - IoT security and privacy — Guidelines ISO/IEC 27400 etc.
- WG 5 Identity management and privacy technologies
  - Privacy framework ISO/IEC 29100 etc.

Fig. 2. Areas of responsibility and representative standards of WGs in JTC 1/SC 27.

SG17 conducts technical discussions on all matters; however, there is no subcommittee corresponding to each international WP. (There is of course an assignment of responsibilities within the domestic committee.) There is also a domestic committee corresponding to JTC 1/SC 27, but this committee does not conduct technical studies. The technical discussions are primarily conducted by their domestic subcommittees, which range from WG 1 to WG 5, corresponding to each of the international WGs. Considering the aforementioned differences, namely the dynamic and static organizational structures of ITU-T SG17 and JTC 1/SC 27, it can be said that how the Japanese domestic committees are organized makes sense.

Regarding technical fields, ITU-T SG17 and JTC 1/SC 27 obviously share many common subjects, but there are also many subjects that complement each other. For example, in the area of public key cryptography, ITU-T SG17 defines the standard format and verification algorithms for the public key infrastructure (PKI), while JTC 1/SC 27 defines the cryptographic algorithms and digital signature schemes used in the PKI. Both are essential for the use of public key cryptography. Of course, there are many deeply related subjects regarding guidelines and frameworks for security management and network security; therefore, ITU-T SG17 and JTC 1/SC 27 have liaisons in both directions and work closely to promote their standardization activities.

4. Trends in security standardization

The larger numbered Qs in ITU-T SG17 are relatively new technologies. Examples include Q14 distributed ledger technology (DLT) and Q15 quantum key distribution (QKD). For DLT, a temporary body called ITU-T FG DLT (Focus Group on Application of Distributed Ledger Technology) was active from 2017 to 2019. The recommendations issued by the body have now been taken over by the respective SGs of ITU-T. JTC 1/SC 27 also discussed DLT for a while, and in 2016 a permanent body called ISO/TC (Technical Committee) 307 (Blockchain and DLTs) was established. This body is currently promoting the standardization of DLTs.

The situation is similar for quantum information technology, where a temporary body, ITU-T FG-QIT4N (Focus Group on Quantum Information Technology for Networks), was active from 2019 to 2021. In JTC 1/SC 27, the standardization of QKD is underway in WG 3, and ISO/IEC 23837 series, which defines implementation security requirements and evaluation methods for QKD, is expected to be published soon. However, quantum information technology covers a wide range of areas, certainly not restricted to QKD, and there is a view that a dedicated body is needed to handle the whole area (e.g., TC 307, which is devoted to handling DLT in general), and it is possible that a new permanent organization should be established within ISO/IEC in the future.

In addition to DLT and quantum information technology, another new technology is artificial intelligence (AI). It is not yet clear how AI security is going to be handled and standardized in these organizations.

Finally, I would like to mention post-quantum cryptography (PQC). It is believed that if a large-scale quantum computer is put into practical use, many current cryptographic algorithms, especially many of the public-key cryptographic algorithms, should become insecure. Therefore, there is an active movement to standardize cryptographic algorithms that can be used securely even if a large-scale quantum computer is put into practical use, i.e., quantum computer resistant cryptography. Technically speaking, we see that PQC is not part of quantum information technology but belongs to the conventional “electronic” information technology. In other words, PQC can be implemented and used on current electronic computers. One might have heard that the National Institute of Standards and Technology is running a competition for the standardization of PQC. Now that a part of the competition is over and the selection of cryptographic algorithms has progressed, WG 2 of JTC 1/SC 27 is accelerating its work on PQC. Rather than creating a new standard, at least initially, they plan to start standardization by amending to existing parts of standards or establishing new parts of existing standards. It is natural to expect that these renewed standards should then affect accordingly those set of ITU-T SG17 recommendations, which are related to public key cryptography.

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He received a Ph.D. in mathematical sciences from the University of Tokyo in 2003. He has been working for NTT and involved in security standardization since 2004. He was the head of Delegate of Japan for JTC 1/SC 27/WG 2 from 2016 through 2020. He has been the vice chair of Japan ITU-T SG17 committee since 2022.

Event Report: NTT Communication Science Laboratories Open House 2023

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Masafumi Matsuda, Naotoshi Abekawa,
Chihiro Watanabe, Tomoki Ookuni, Toyomi Meguro,
and Hiroyuki Fujinaga

Abstract

On 1 and 2 June, NTT Communication Science Laboratories (CS Labs) hosted the Open House on-site for the first time in four years. We presented 6 talks and 16 exhibits of our latest research efforts in information and human sciences at the event, attracting more than 400 visitors over the two days. We also featured videos of the talks and exhibits on the Open House 2023 website, which received over 3000 views in 20 days after the event.

Keywords: information science, human science, artificial intelligence

1. Overview

Since the founding of NTT Communication Science Laboratories (CS Labs), we have been engaged in research centered on the pursuit of science that can deepen our understanding of humans and the creation of technologies that approach and exceed human abilities to achieve heart-touching communication between people and between people and machines. We hold the Open House annually for people to experience our latest research results. However, for the three years from 2020 to 2022, the event was not held on-site due to the COVID-19 pandemic. Instead, we showcased videos of talks and exhibitions of our research on the Open House website [1].

This year, we held the Open House on-site for the first time in four years, and as a new trial, we held the event at a new venue QUINTBRIDGE, an open-innovation facility of NTT WEST. We introduced a reservation system to ensure the safety and comfort of all participants, and thankfully, the number of reservations reached a maximum of 500 in less than two weeks after the start of reservations. Unfortunately, the second day of the event was hit by heavy rain due to a typhoon; however, approximately 420 people from various companies, research institutions, and universities attended the event at the site. As we did last year, we made videos of the talks and exhibitions available on the Open House website, which were viewed more than 3000 times in 20 days after the event.

2. Keynote speech

Dr. Futoshi Naya, vice president and head of CS Labs, presented a speech entitled “Design a world where everyone can flourish by deciphering the future of people, society, and the Earth – Communication science that connects the past, present, and future through diverse knowledge and technologies –”, in which he

Photo 1.   Keynote speech by Dr. Futoshi Naya.

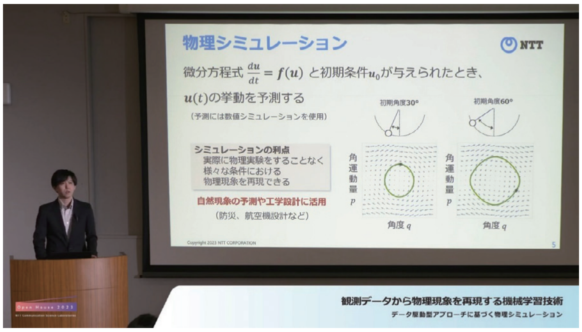


Photo 2.   Research talk by Dr. Yusuke Tanaka.

introduced some of the CS Labs' recent efforts in research centered on human science and brain science for a deep understanding of people and research on media processing and machine learning that approaches and surpasses human capabilities from the perspective of deciphering individuals, society, and the Earth (**Photo 1**).

He first gave an overview of the mission and research areas of CS Labs, and outlined individual research projects, classifying them into three categories: attempts to read "individuals," "society," and "the Earth": mind-reading technology to decipher the latent state of mind from people's unconscious physical movements and physiological reactions as attempts to decipher individuals; understanding the well-being of individuals and society in the COVID-19 pandemic and beyond as attempts to decipher society; and simulation of complex physical phenomena using new machine-learning technology that uses vast amounts of observation data as attempts to decipher the Earth.

He concluded his speech by describing the direction of our future research based on the concept of 'designing the future' and declared that we would continue our research to design a better future world where everyone can shine at any time in their own way.

3. Research talks

The following four talks highlighted recent significant research results and high-profile research topics. Each talk presented some of the latest research findings with a background and overview of the research field.

3.1 "Machine learning that reproduces physical phenomena from data – Physics simulation based on a data-driven approach –": Dr. Yusuke Tanaka, Innovative Communication Laboratory

Dr. Yusuke Tanaka introduced machine-learning techniques for accurately reproducing physical phenomena from observed data using physical laws as prior knowledge. While machine-learning models are highly expressive for potentially representing complex physical phenomena, obtaining an appropriate model that accurately reproduces the target physical phenomena from the vast search space of models is challenging. To solve this problem, he proposed a technique for automatically constructing machine-learning models from data that satisfy one of the most fundamental physical laws, the energy conservation law, by incorporating the theory of Hamiltonian dynamics (a formulation of analytical mechanics) into Gaussian processes (a model of machine learning). He also envisioned the application of this technique to weather forecasting and improving the accuracy of engineering designs for aircraft and automobiles (**Photo 2**).

3.2 "Dilemma between quantum speedup and computational reliability – Overcoming errors by efficient verification methods for quantum computing –": Dr. Yuki Takeuchi, Media Information Laboratory

Dr. Yuki Takeuchi introduced the dilemma that quantum superposition, a fundamental principle of quantum mechanics, makes verifying calculation results on quantum computers difficult and showed a way to avoid this dilemma. While ordinary computers represent information using bits that take the value 0 or 1, quantum computers use quantum bits (qubits)

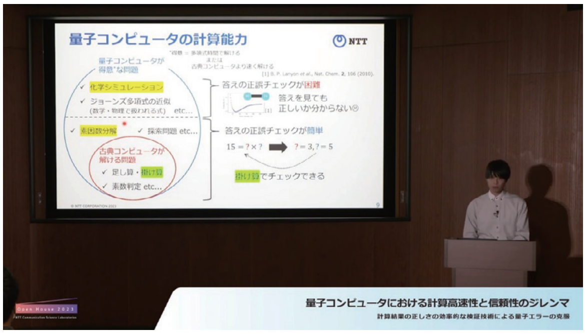


Photo 3. Research talk by Dr. Yuki Takeuchi.

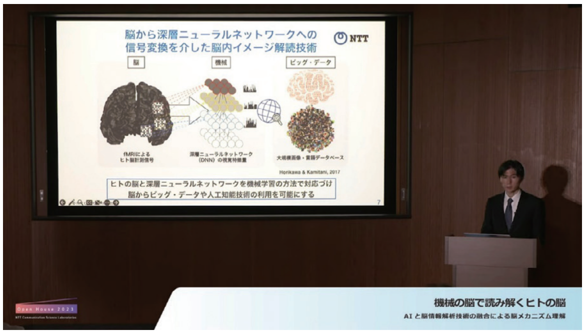


Photo 4. Research talk by Dr. Tomoyasu Horikawa.

that take the state of a probabilistic superposition of 0 and 1. The use of qubits enables high-speed parallel processing that is difficult to reproduce using ordinary computers; however, calculations using qubits are vulnerable to errors because the results can change significantly with minute changes in probability values, and their complexity makes it difficult to verify the results of calculations using ordinary computers. To address this issue, Dr. Takeuchi proposed new verification methods using small-scale quantum devices. He also suggested that the proposed methods could enable quantum computers to be cloud-based and used worldwide via the Internet (**Photo 3**).

3.3 "Decoding the human brain through machine brains – Unraveling brain mechanisms through integration of AI and neural information analysis techniques –": Dr. Tomoyasu Horikawa, Human Information Science Laboratory

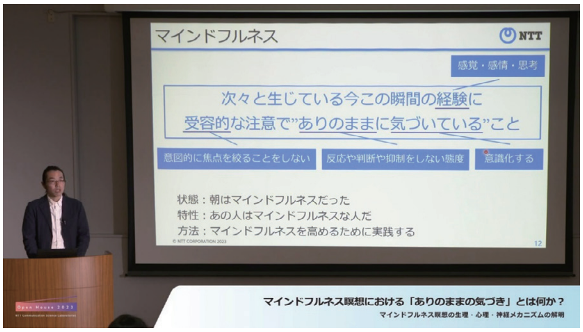
Dr. Tomoyasu Horikawa gave an overview of research on brain decoding, which decodes latent information in the human mind from brain activity, and introduced approaches based on the latest artificial intelligence (AI) technology for understanding the brain mechanism that generates the human mind. For instance, by associating fMRI (functional magnetic-resonance imaging) signals representing brain activity with latent states of deep neural networks (DNNs), an AI technology that has attracted much attention, he showed the similarity between brain activity and DNN behavior and the possibility of reconstructing images that humans see or imagine from brain information. He concluded his talk by mentioning the possibility of reconstructing senses other than sight, such as hearing and touch, from brain activity if AI technology and brain information analysis technology were further linked (**Photo 4**).

3.4 "What is the lucid awareness in the mindfulness meditation? – Investigation of the physiological, psychological, and neural mechanisms of mindfulness meditation –": Dr. Masahiro Fujino, Human Information Science Laboratory

Dr. Masahiro Fujino introduced the definition of mindfulness, which is attracting attention to achieve well-being, and then explained how mindful meditation affects our mind and body from the perspective of physiological, psychological, and neural mechanisms. People are said to be "mindful" if they recognize their own present experience as it is. Mindfulness meditation is one method for achieving mindfulness and consists of two meditation techniques: focused attention meditation and open monitoring meditation. In this talk, Dr. Fujino showed how open monitoring meditation influences the achievement of mindfulness by measuring its effects on autonomic nervous activity, hormone secretion, attention control processes, and brain activity. He also mentioned that the results could help develop more effective methods for achieving mindfulness (**Photo 5**).

4. Research exhibitions

The Open House 2023 featured 16 exhibits displaying CS Labs' latest research results. We categorized them into four areas: Science of Machine Learning, Science of Communication and Computation, Science of Media Information, and Science of Humans. Each exhibit was presented



マインドフルネス

感覚・感情・思考

次々と生じている今この瞬間の経験に
受容的な注意で”ありのままに気づいている”こと

意図的に焦点を絞ることをしない

反応や判断や抑制をしない態度

意識化する

状態：朝はマインドフルネスだった
特性：あの人はマインドフルネスな人だ
方法：マインドフルネスを高めるために実践する

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12

マインドフルネス瞑想における「ありのままの気づき」とは何か？
マインドフルネス瞑想の生理・心理・神経メカニズムの解明

Photo 5. Research talk by Dr. Masahiro Fujino.

Photo 6. On-site research exhibition.

on-site by researchers from CS Labs (**Photo 6**) and showcased a short overview video on the event web page. The following list, taken from the event website, summarizes the research exhibits in each category.

4.1 Science of Machine Learning

- Zeta functions in the interaction of light and matter
  - Discovering the mathematics of quantum Rabi models –
- Is that quantum computer really working correctly?
  - How to verify quantum computations by circuit partitioning –
- Machine learning that reproduces physical phenomena
  - Gaussian process model incorporating energy conservation law –
- We transport numerous guests comfortably and flexibly
  - A shuttle bus operation plan for both visitors and operators –

4.2 Science of Communication and Computation

- Dialog processing techniques for reading the situation
  - Multimodal situation recognition for everyday conversations –
- Here, a moderately challenging problem for you!
  - VAE [variational autoencoder]-based individually optimized problem recommendation –
- Choose the best translation from diverse candidates
  - Generating diverse translation with perturbed kNN-MT [k-nearest-neighbor machine translation] –

4.3 Science of Media Information

- MagneShape: A pin-based display using magnetism
  - Non-electrical control of magnetic pins shows various shapes –
- AI that attends to the sounds you want to listen to
  - Deep learning based selective hearing of arbitrary sounds –
- Listening to topics of interest
  - ConceptBeam: Technology for separating signals by meaning –

4.4 Science of Humans

- The attentional control of mindfulness meditation
  - Meditation reduces inhibition of peripheral visual stimuli –
- How should we interact softly from afar?
  - Realizing a highly compliant remote-operated robot –
- Reading minds from eyes
  - Pupil responses and microsaccades reveal cognitive functions –
- What makes people’s impression for artworks different?
  - Art impressions differ based on language and attributes –
- Precompetitive physiological states determine the game
  - Snowboarders’ physiological states, motion, and performance –
- Auditory perception in autism spectrum disorder
  - Auditory-information processing underlying unique perception –

5. Special lecture

We invited Dr. Akira Takagi, director of Hearing and Speech-language Center, Shizuoka General Hospital and professor of the Shizuoka Graduate University of Public Health, to CS Labs to give a special lecture entitled "Spoken language acquisition through electrical stimulation" and conduct a discussion with CS Labs researchers.

Humans use various modes of communication, such as spoken, written, and signed language; however, spoken language is considered the most efficient mode of communication in terms of body structure and physiology. Auditory perception is necessary for humans to acquire spoken language, but more specifically, humans will only fully develop spoken language if they are provided with auditory stimulation by age three, which is the sensory period. In human hearing, sound vibrations are converted into electrical signals in the Organ of Corti of the inner ear, and only then are sounds transmitted to the brainstem. However, even if the Organ of Corti is congenitally absent or its electrical signals are feeble, humans can fully acquire spoken language if they receive a cochlear implant, a device providing electrical signals to the inner ear, by the time of the sensory period. Cochlear implants have been used worldwide since 1985 when the US Food and Drug Administration approved a 22-channel cochlear implant for adults over 18 for trial use. In this talk, Dr. Takagi explained the efforts of cochlear implantation in Japan and worldwide and introduced the speech and language acquisition process of cochlear-implant recipients using videos and data. At the end of the talk, he suggested that research on how sensory integration is formed during the brain's receptive period could contribute to future brain cognitive science and AI research.

6. Concluding remarks

The Open House 2023 was the first on-site event in four years, and many people could see the latest research results from CS Labs through on-site exhibits and videos on the special website. CS Labs' researchers were also inspired by direct communication with visitors to the event. As a new trial this year, we used the NTT WEST open-innovation facility QUINTBRIDGE, and we believe that this environment facilitated very active communication. We would like to express our sincere thanks to everyone who helped make this event possible.

Reference

[1] Website of NTT Communication Science Laboratories Open House 2023, http://www.kecl.ntt.co.jp/openhouse/2023/index_en.html

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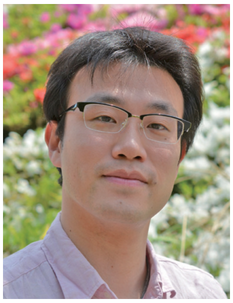

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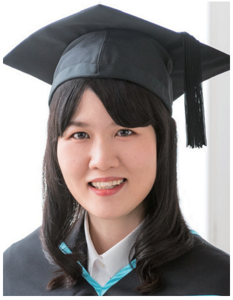
He received a B.E. from Tokyo Metropolitan University in 2003, M.E. from Tokyo Institute of Technology in 2005, and Ph.D. from Kyoto University in 2014. He joined NTT in 2005. From 2015 to 2016, he was a visiting researcher at Institute of Cognitive Neuroscience, University College London. His research interests include human sensorimotor control, especially visuomotor control and motor-learning mechanisms. He is a member of the Society for Neuroscience, the Japan Neuroscience Society, the Japanese Neural Network Society, and IEICE.



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Research Scientist, Interaction Research Group, Innovative Communication Laboratory and Research and Planning Section, NTT Communication Science Laboratories.

She received an M.E. in engineering from Tohoku University, Miyagi, in 2008 and joined NTT Communication Science Laboratories the same year. Her research interests include spoken dialogue systems and social skill training. She was the COLING 2010 Best paper finalist at the International Conference on Computational Linguistics (COLING) in 2010 and received the JSAI Annual Conference Award from JSAI in 2014.

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Assistant Section Chief, Research and Planning Section, NTT Communication Science Laboratories.

He received a B.A. in business administration from Saga University in 1998 and joined NTT the same year, where he was mainly engaged in sales and business support. He joined NTT Science and Core Technology Laboratory Group in 2013, worked at NTT Information Network Laboratory Group, and has been working at NTT Communication Science Laboratories since 2021.

External Awards

2023 HPCI Software Awards, Encouragement Award in Development Category

Winner: The development group of SALMON consisting of Shunsuke Yamada, National Institutes for Quantum Science and Technology, Kansai Institute for Photon Science; Yuta Hirokawa, Preferred Networks, Inc.; Kenji Iida, Hokkaido University Institute for Catalysis; Jun-ichi Iwata, Quemix Inc.; Shinji Noda, ACADEMEIA Inc.; Tomohito Otobe, National Institutes for Quantum Science and Technology, Kansai Institute for Photon Science; Shunsuke Sato, Center for Computational Sciences, University of Tsukuba; Yasushi Shinohara, NTT Basic Research Laboratories/School of Engineering, The University of Tokyo; Takashi Takeuchi, RIKEN Cluster for Pioneering Research (CPR); Mizuki Tani, School of Engineering, The University of Tokyo; Mitsuharu Uemoto, Department of Electrical and Electronic Engineering, Faculty of Engineering, Kobe University; Kazuhiro Yabana, Center for Computational Sciences, University of Tsukuba; Atsushi Yamada, Research organization for Information Science and Technology
Date: May 19, 2023
Organization: High Performance Computing Infrastructure Consortium (HPCI)

The development group of the first-principles calculation code SALMON (Scalable Ab-initio Light-Matter simulator for Optics and Nanoscience, https://salmon-tddft.jp/), which is developing the field of computational science such as large-scale calculations, was selected as a developer or organization whose software was recognized as particularly useful among the software that contributed to HPCI.

ICASSP 2023 Outstanding Reviewer Recognition

Winner: Hiroshi Sawada, NTT Communication Science Laboratories
Date: June 21, 2023
Organization: The 2023 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP 2023)

Best Paper Award

Winners: Shimpei Shimizu, NTT Network Innovation Laboratories; Takayuki Kobayashi, NTT Network Innovation Laboratories; Takushi Kazama, NTT Network Innovation Laboratories/NTT Device Technology Laboratories; Takeshi Umeki, NTT Network Innovation Laboratories/NTT Device Technology Laboratories; Koji Enbutsu, NTT Device Technology Laboratories; Ryoichi Kasahara, NTT Device Technology Laboratories; Yutaka Miyamoto, NTT Network Innovation Laboratories
Date: September 13, 2023
Organization: The Institute of Electronics, Information and Communication Engineers (IEICE) Communications Society

For "Channel Arrangement Design in Lumped Amplified WDM Transmission over NZ-DSF Link with Nonlinearity Mitigation Using Optical Phase Conjugation."
Published as: S. Shimizu, T. Kobayashi, T. Kazama, T. Umeki, K. Enbutsu, R. Kasahara, and Y. Miyamoto, "Channel Arrangement Design in Lumped Amplified WDM Transmission over NZ-DSF Link with Nonlinearity Mitigation Using Optical Phase Conjugation," IEICE Trans. Commun., Vol. E105-B, No. 7, pp. 805–813, 2022.

ComEX Best Letter Award

Winners: Doohwan Lee, NTT Network Innovation Laboratories; Yasunori Yagi, NTT Network Innovation Laboratories; Hiroyuki Shiba, NTT Network Innovation Laboratories
Date: September 13, 2023
Organization: IEICE Communications Society

For "Multishape Radio: New Approach to Utilizing the Physical Properties of Electromagnetic Waves."
Published as: D. Lee, Y. Yagi, and H. Shiba, "Multishape Radio: New Approach to Utilizing the Physical Properties of Electromagnetic Waves," IEICE Communications Express (ComEX)., Vol. 11, No. 9, pp. 571–576, Sept. 2022.

Distinguished Contributions Award

Winner: Shuto Yamamoto, NTT Network Innovation Laboratories
Date: September 13, 2023
Organization: IEICE Communications Society

For contributions as a secretariat in IEICE Technical Committee on Optical Communication Systems.

JIP Specially Selected Paper

Winners: Kazuki Nomoto, Waseda University; Takuya Watanabe, NTT Social Informatics Laboratories; Eitaro Shioji, NTT Social Informatics Laboratories; Mitsuaki Akiyama, NTT Social Informatics Laboratories; Tatsuya Mori, Waseda University
Date: September 15, 2023
Organization: Information Processing Society of Japan

For "Understanding the Inconsistencies in the Permissions Mechanism of Web Browsers."
Published as: K. Nomoto, T. Watanabe, E. Shioji, M. Akiyama, and T. Mori, "Understanding the Inconsistencies in the Permissions Mechanism of Web Browsers," Journal of Information Processing (JIP), Vol. 31, pp. 620–642, 2023.