Quantum Science and Technology

PERSPECTIVE

Quantum information science and technology in Japan

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Abstract

We review the national projects on quantum information science and technology in Japan over the past 30 years. The main funding agencies for this field have been the Japan Science and Technology Agency, the National Institute of Information and Communications Technology, the Japan Society for the Promotion of Science, and the Cabinet Office of the Government of Japan. The total investment in the quantum information science and technology field from these funding agencies for the past 15 years amounts to US$250 million. A similar amount of investment has been put in parallel by industry. As a result, new science frontiers have been created, and some service prototypes, such as quantum key distribution systems and coherent Ising machines, have been delivered to user premises. Recently, Japan has launched new initiatives to advance quantum information science and technology to the next phase, and to make full use of them for the resolution of societal problems.

1. Introduction

In the past 30 years, we have witnessed the growing interest and rapid progress of quantum information science and technology around the world. In Japan, the early basic research in this field has mainly been supported by a unique program called Exploratory Research for Advanced Technology (ERATO) of the Japan Science and Technology Agency (JST) [1]. In this program, a single principal investigator (PI) explores a research subject of his/her own choice for five years with generous support (US$15 million per five years). The long list of ERATO projects in the area of quantum science includes the quantum magneto flux logic project (1986–1991), the quantum wave project (1988–1993), the electron wavefront project (1989–1994), the quantum fluctuation project (1993–1998), the cooperative excitation project (1997–2002), the mesoscopic correlation project (1999–2004), the quantum computation and information project (2000–2005), the macroscopic quantum control project (2005–2010), the innovative space-time project (2010–2015), and the macroscopic quantum machines project (2016–2021). Figure 1 summarizes the research topics supported by ERATO. These ERATO programs have been very successful not only in creating new science frontiers, such as Josephson qubits, coherent Ising machines (CIMs), and artificial atoms, but also in training young researchers. Many of the key players trained in the ERATO projects have been leading the subsequent national projects.

In Japan, quantum information processing, metrology and sensing have been funded mainly by JST and the Japan Society for the Promotion of Science (JSPS), while quantum communication and cryptography have been funded by the National Institute of Information and Communications Technology (NICT). The strategic promotion for societal deployment of these technologies has been funded by the Cabinet Office of the Government of Japan (CAO), and by the Ministry of Internal Affairs & Communications. These national projects are summarized in figure 2. In the following sections, the main activities of these projects are reviewed.

2. Quantum communication and cryptography (2001–2015)

NICT began the strategic research and development (R&D) programs on quantum communication and cryptography in 2001, which consisted of NICT’s own research and the NICT commissioned R&D to public and
private organizations. The basic research program has been carried out at NICT laboratories, focusing on basic theory and technologies for quantum communication and cryptography. Research results have been transferred to the commissioned R&D for practical technology development.
In the commissioned R&D, quantum key distribution (QKD) technologies were developed from 2001–2015 in a strong collaboration between academia and industry including NEC, Toshiba, MELCO, NTT, Gakushuin University, Tohoku University, Hokkaido University, the Tokyo Institute of Technology, and Nagoya University. High speed QKD systems operating at a 1 GHz repetition rate were developed and deployed in a field testbed, called the Tokyo QKD Network, in 2010, demonstrating one-time pad encryption of video data transmission in a metropolitan scale distance [2]. Since then, the Tokyo QKD Network has provided a platform for updating QKD technologies (security certification technologies and key management architecture) and developing new cryptographic applications including secure IP routers, secure TV conferencing, secure smart phone systems, and secure medical records systems [3, 4]. In 2017, the NEC deployed its QKD system in the premises of the NEC Cyber Security Factory in Tokyo for a long-term reliability test [5], and Toshiba applied its QKD system to encrypt genomic data transmissions through a 7 km installed fiber in Sendai [6]. These field tests lasted for more than three years. The commissioned R&D also covered three core technologies; entangled-photon-based communication, quantum optical control at telecom band, and highly secure optical transmissions.

From 2006–2015, the commissioned R&D was carried out on quantum repeater technologies based on several different schemes (semiconductor quantum dot spins, diamond NV centers, and superconducting circuits) by the National Institute of Informatics, NTT, Tohoku University, Osaka University, the University of Tokyo, and the Tokyo Medical and Dental University.

A cumulative investment of NICT basic research and commissioned R&D from 2001–2015 reached around US$64 million. Through these efforts, QKD point-to-point links and networks have become reliable systems in a practical environment, and quantum repeater technologies have evolved into a useful toolbox to control quantum information with photons and various matter qubit systems. On the other hand, these projects also revealed many challenges for making QKD a viable solution in the security technology market, and for operating quantum repeaters in meaningful environments.

The function of QKD itself is limited only to point-to-point symmetric key exchange, and its distance and speed are limited. Because of this very fact, the QKD market is still niche. For QKD to find its place in the real world, improving QKD technologies would not suffice. It will be necessary to develop some killer applications to meet real security demands which currently cannot be realized by modern cryptography. This issue has been examined extensively since 2014 in the ImPACT Program of CAO (see section 5).

To put quantum repeaters to a field test, highly efficient coupling between photonic and matter quantum states and fault-tolerant quantum memory and processing systems need to be developed, which require further fundamental research. These issues have been studied extensively since 2015 in a JSPS program on the ‘Science of hybrid quantum systems’, and since 2016 in the JST CREST and PRESTO programs on the ‘Creation of an innovative quantum technology platform based on the advanced control of quantum states’ (see section 3).

3. Quantum information processing, metrology, and sensing (2003–2022)

JST began the national project Core Research for Evolutional Science and Technology (CREST) on Quantum Information Processing in 2003 [7]. This program was conducted for seven years and with a special emphasis on hardware technologies not only on information processing but also metrology and sensing, and 11 research teams were supported with a total investment of US$60 million. The five projects in the first period (2003–2008) worked on quantum information processing with photonic qubits, superconducting qubits, neutral atoms, atomic ensemble, and continuous variables. The three projects in the second period (2004–2009) studied quantum information processing with semiconductor spin qubits, trapped ions and molecular vibration/rotation degrees of freedom. The four projects in the third period (2005–2010) focused on quantum information processing by entangled photons at the telecom band, molecular spin qubits, the optical lattice clock, and quantum simulation tools for many-body systems. During the overlapping period (2003–2008), another basic research program (PRESTO) of JST supported individual junior researchers in the interdisciplinary field of quantum physics and information science [8].

JSPS kicked off its grant-in-aid for scientific research on innovative areas in ‘Quantum Cybernetics’ in 2009, which lasted for five years [9]. In Quantum Cybernetics, the coherent control, retention, and transmission of quantum states in various physical systems were studied with superconducting devices, semiconductor devices, molecules, atoms, ions, and photons. The second program, the ‘Science of Hybrid Quantum Systems’ followed in 2015 and is planned to last for five years [10]. This program aims to create, manipulate, and control quantum hybrid systems based on electronics, spintronics, photonics, and phononics.

In 2016, JST restarted the CREST program on the ‘Creation of an innovative quantum technology platform based on the advanced control of quantum states’, aiming at realizing new quantum information processing and element/system functions that are superior to prior technologies in terms of performance [11]. The program
In 2009, CAO began the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST), aiming to strengthen Japan’s international competitiveness while contributing to the welfare of society through the application of its results. In total 30 projects over various fields were conducted under the direct control by the Council of Science, Technology, and Innovation, including ‘Quantum information technology’. Its total budget was US$30 million over 5 years, which supported the research groups of 33 co-PIs. The areas covered include quantum communication, quantum metrology and sensing, quantum neural networks (QNNs), quantum simulation, quantum computing, and quantum device technologies [13].

The FIRST program disclosed the two important facts in quantum information processing technologies, which greatly influenced the following efforts in Japan. The program discovered that performance limit of circuit-model quantum computers for combinational optimization problems, which are ubiquitous in modern life and appear in important fields such as machine learning, scheduling, resource distribution, routing, sampling, lead optimization and sparse coding. Those problems do not have hidden periods or specific structures, so we must use Grover’s iteration, which is proven to be an optimum algorithm for an unstructured data search. However, such an approach is necessarily slow due to the $\sqrt{2^N}$ dependence of the computational time on the problem size $N$. For instance, the combinatorial optimization of an even modest problem size ($N = 20, 50, 100$ and 150 bits) requires a computational time of $4 \times 10^{-3}$ (s), $6 \times 10^2$ (s), $2 \times 10^{10}$ (s), and $6 \times 10^{17}$ (s), respectively, even if an ideal quantum computer with no decoherence, no gate error, all-to-all connections, and 1 ns gate time.

Modern heuristics such as simulated annealing or breakout local search implemented on standard CPUs need only $10^{-3} - 10^{-2}$ (s) for such small combinatorial optimization problems. Table 1 summarizes those shocking results, which discloses the extreme inefficiency of universal quantum computers even if an enormous overhead due to quantum error correction is not taken into account.

The performances of three heuristic machines for the same problem are also listed in table 1. The quantum approximate optimization algorithm (QAOA) machine combines a circuit-model quantum computer for a simple unitary rotation and a classical digital computer for sophisticated machine learning and is expected to more efficiently solve combinatorial optimization problems [14, 15]. A bottleneck effect in interfacing quantum and classical machines, the so-called I/O slow down problem, is a major challenge in this heuristic approach. The quantum annealing machine utilizes a quantum tunneling effect instead of thermal activation to allow a system to escape from local minima [16, 17]. A heavy overhead in the minor embedding for mapping arbitrary graph structures on sparsely connected Josephson junction qubits is a major drawback in this heuristic approach [18]. Compared to these approaches, the OPO-based QNN with all-to-all connections demonstrated a reasonable performance but is not yet competitive against modern heuristics in classical digital computers [18].

The other fact we recognized during the FIRST program is that a realistic circuit-model quantum computer with finite decoherence and gate error must consume quite a large resource to complete the error-free computational task. For instance, in order to factor a 1024 bit integer number using the Shor’s algorithm, we must implement $10^8 - 10^9$ physical qubits and consume the computational time of a few days, even if the one-bit

### Table 1. Time-to-Solution for NP-hard MAX-CUT Problems.

| Problem size | Universal quantum computation$^a$ | Heuristic | QAOA machine$^a$ | Quantum annealer$^b$ | Quantum neural network$^c$ |
|--------------|----------------------------------|-----------|-----------------|---------------------|---------------------|
| $N = 20$     | $4 \times 10^{-3}$ (s)           |           | 600 (s)         | $1.1 \times 10^9$ (s) | $1.0 \times 10^4$ (s) |
| $N = 50$     | $6 \times 10^2$ (s)              |           | —               | $5.0 \times 10$ (s)  | $3.7 \times 10^3$ (s) |
| $N = 100$    | $2 \times 10^{10}$ (s) (~700 years) |           | —               | $(\sim 10^{17}$ (s)) | $2.5 \times 10^7$ (s) |
| $N = 150$    | $6 \times 10^{17}$ (s) (~208 years) |           | —               | $(\sim 10^{53}$ (s)) | $5.4 \times 10^7$ (s) |

$^a$ Theoretical limit (no decoherence, no gate error, all-to-all connections, 1 ns gate time).

$^b$ Rigetti Computing 19 bit machine (Quantum Approximate Optimization Algorithm, Dec. 2017).

$^c$ D-WAVE 2000Q with sparse connection (Experimental: $N = 20, 50$, Extrapolated: $N = 100, 150$).

$^d$ NTT 2000 CIM with all-to-all connections (Experimental: $N = 20, 50, 100, 150$).

will support 6 projects from 2016–2020, 7 projects from 2017–2021, and 6 projects from 2018–2022 which cover quantum simulators, sensing, imaging, repeaters, and state control with various physical systems. During the overlapping period (2016–2022), PRESTO supported individual junior researchers working on quantum state control and functionalization [12].

### 4. FIRST program by CAO (2009–2013)

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and two-bit gate errors are less than $10^{-3}$ [19]. In a more recent and detailed study, it turns out those numbers for physical qubits and computation time became even worse.

5. ImPACT Program by CAO (2014–2018)

Strategic R&D on quantum information technology was followed by CAO’s new program, called Impulsing Paradigm Change through Disruptive Technologies Program (ImPACT), with a special focus on real-world applications of quantum technologies [20]. The total budget of this 4.5 year program is US$30 million, which supports the research groups of 26 co-PIs. The ImPACT program focuses on a QNN, quantum simulation, and a quantum secure network.

A unique feature of the ImPACT program is the unification of quantum information technology with other technologies in relevant fields, which might be an inevitable process to produce meaningful real-world applications. Such a unification is exemplified in the following two cases.

5.1. Quantum neural network

Researchers with different backgrounds such as statistical physics, quantum optics, electrical engineering, and computer science are working closely to develop the hardware and software for the QNN. QNN is a platform of special-purpose computers. Four quantum optical systems for solving various hard optimization problems constitute the QNN. Those four systems are a CIM for solving NP-hard Ising problems, whose performance is summarized in table 1, a coherent SAT solver for solving NP-complete k-SAT problems, a coherent XY machine for solving continuous optimization problems, and a coherent crypto-machine for solving those problems on encrypted codes.

The QNN system opened for cloud service in November 2017 so that users around the world could experience its computational capabilities. For example, users can find solutions to large-scale maximum-cut problems on complete graphs with up to as many as 2000 nodes.

One interesting future direction is to clarify the origin and limitation of the computational power of QNN. The QNN has many different aspects such as an analog neural network [21], computing at criticality [22], and a quantum Darwinism machine [23]. We hope that understanding the roles of those concepts in the QNN will be one of the fascinating research themes in the global quest of quantum-to-classical crossover.

Finally, Japan’s future perspectives on quantum information processing are summarized in table 2. In the past 30 years, the research on quantum computing has been focused on a circuit-model quantum computer, in which an entire computational task is carried out by the unitary rotation of pure state vectors in a closed system. This scheme of quantum computing is a powerful approach for problems with hidden periods or special structures but is poorly suited for problems without such internal structures. A dissipation quantum computer is a novel concept in which the self-organization process at criticality in an open quantum system is utilized as a computational resource. This scheme of quantum computing may find applications for problems without any internal structures such as combinatorial optimization, machine learning, and compressed sensing.

5.2. Quantum secure network

Today various cryptographic functions (authentication, signature, key exchange, encryption, secret computation, and so on) are required to protect critical data securely. These functions are realized by public key cryptography, symmetric key cryptography, hash functions, secret sharing, and so on. Can QKD find its place as an essential part in the crypto-technology field?

In today’s world, state secrets, corporate secrets, and personal data on daily activities, medical records, and genomic information, and more are stored in data centers for a very long time. These critical data are prime targets of malicious attacks with powerful computers, and also continue to be jeopardized by large disasters.

| Table 2. Japan’s future perspectives on quantum information processing. |
|---------------------------------------------------------------|
| **Unitary quantum computation**                                      | **Dissipative quantum computation**                  |
| Principles | Unitary rotation of state vectors in isolated quantum systems | Self-organization in open quantum systems with excitation from and dissipation to environments |
| Proposals | Deutsch (1985): Quantum parallelism Shor (1994): Factoring and discrete logarithm | Zurek (2003): Quantum Darwinism, Quantum chaos Verstraete, Wolf and Cirac (2009): Universal quantum computation by dissipation |
| Merits | Transparent physics Universality proven | Robust against noise and gate error |
| Demerits | Sensitive to noise and gate error | Complicated physics Universality not-proven |
| Applications | Problems with hidden periods or structures (Public key crypto-systems) | Problems without hidden periods nor structures (Combinatorial optimization) |
Although post-quantum public key cryptography is expected to resist quantum computer attacks, there is no understanding of the very long-term resistance.

Secret sharing between multiple data servers has been known to enable an information-theoretic-secure storage, provided that the data servers are connected via perfectly private channels. QKD can provide a means to realize such private channels. Even if some data servers are corrupted, the original data can be restored from the remaining servers. Hence, combining secret sharing and QKD can provide a killer application to secure distributed data storage in the long-term [24]. Secret sharing allows multiparty secret computation. However, secret sharing and QKD cannot ensure the integrity of data. The integrity protection can be realized by modern cryptography (digital signatures and commitments) because their hash values (a kind of fingerprint of the original data) can be renewed, and thus the validity of the original data can be prolonged for any length of time. Post-quantum public key cryptography is well suited to this purpose. All these technologies were combined in the Tokyo QKD Network. This system is referred to as the long-term integrity and confidentiality protection system (LINCOS) [25]. LINCOS is a symbolic example of integrating post-quantum public key cryptography and QKD, and it is now put to the field test for demonstrating data backup of medical records.

6. New Japanese initiatives

New Japanese initiatives were launched in 2018 to advance quantum information science and technology to the next phase. The Ministry of Education, Culture, Sports, Science, and Technology started an initiative called ‘Q-LEAP’. This covers the three pillars of quantum simulation and computation, quantum sensing, and ultrashort pulse lasers, investing US$200 million over 10 years, which is managed by JST. The first pillar consists of a flagship project on a superconducting quantum computer and 6 basic research projects on hardware and software for quantum simulation and computation. The second pillar consists of a flagship project on solid state quantum sensors and 7 basic research projects on quantum sensing technologies and applications. The third pillar consists of a flagship project on advanced laser innovation and 4 basic research projects on atto-second pulse laser technologies and applications.

JST recently kicked off two big projects on the applications of atomic physics. One is on quantum inertial sensor technologies based on gyroscopes with matter waves, which began in 2017 and will last for 10 years and is funded with US$37 million. The other is on ultrahigh precision time measurement technologies leading to a new time-business by using a space-time information platform with a cloud of optical lattice clocks, which began in 2018 and will last for 9.5 years and is funded with US$37 million. These activities contribute greatly to the standardization of space time. Optical lattice clocks will be a central topic in re-defining ‘Second’ by Comité International des Poids et Mesures in 2019.

In 2018, the New Energy and Industrial Technology Development Organization began funding projects on quantum annealing technologies with superconducting parametron devices, and on common software platform for Ising machines.

In CAO’s Cross-ministrial Strategic Innovation Promotion Program Phase II, which has a total budget is US$300 million per year, ‘Photonics and Quantum Technology for Society 5.0’ was selected as one of 12 subjects. ‘Society 5.0’ was defined in the fifth Science and Technology Basic Plan of Japan as a future society that Japan should aspire to. It follows the hunting society (Society 1.0), the agricultural society (Society 2.0), the industrial society (Society 3.0), and the information society (Society 4.0). Society 5.0 is a human-centered society that balances economic advancement with the resolution of social problems by a system that highly integrates cyberspace and physical space, i.e. cyber physical system (CPS). ‘Photonics and Quantum Technology for Society 5.0’ consists of three pillars; (1) CPS-type laser processing for smart manufacturing based on advanced integration of simulators and laser material processing systems with novel laser technologies; (2) photonic quantum communication to develop quantum secure cloud technology by integrating quantum cryptography, secret sharing, and secret computation into a network; (3) photonic and electronic information processing to develop software and middleware to solve combinatorial optimization problems for smart manufacturing. The teams will contribute to the standardization of quantum cryptography such as in the European Telecommunications Standards Institute and the International Telecommunication Union-Telecommunication Standardization Sector.

The Ministry of Internal Affairs and Communications started a five year project on ‘Satellite Quantum Crypto-technology,’ aiming to establish core technologies to realize a secure backbone for a future satellite communications network. Special emphasis is put on the development of long-distance and high-rate crypto-technologies for small-size and low-cost satellites as well as unmanned aerial systems.
7. Summary and outlook

Some Japanese inventions such as quantum dots, superconducting qubits, quantum annealing, optical lattice clocks, and so on provide the foundations for today’s quantum revolution. A long series of strategic funding and R&D promotion on quantum science and technology created new science frontiers, and well-engineered system technologies including a new computing machine 'CIM' and a secure storage network 'LINCOS', which have been put to prototype service tests.

In these R&D activities, Japan has also faced intrinsic bottlenecks in a pipeline from research laboratories through corporate business divisions to marketplaces. Concentrating on the improvement of quantum technologies does not suffice at all. Cross-disciplinary efforts to hybridize all of the necessary technologies for building up final deliverables are essential, as seriously pursued in the FIRST and ImPACT programs of CAO, involving various potential users in government, public and private sectors. These efforts are, in turn, making an impact on computer science, cryptography, and communication technologies, creating new frontiers in these fields, which might be referred to as quantum-inspired science and technology.

What we have seen so far might be only part of huge possibilities that quantum would inspire. Our challenges in new initiatives are just at a starting point in a long journey to revolutionize all aspects of information science and technology.

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