Quantum Computing Trends and Prospects

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The Japan Research Institute, Limited.

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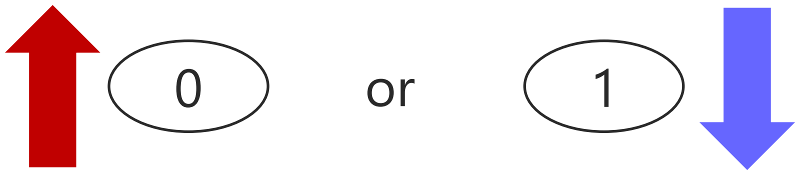
Agenda

What's a Quantum Computer?

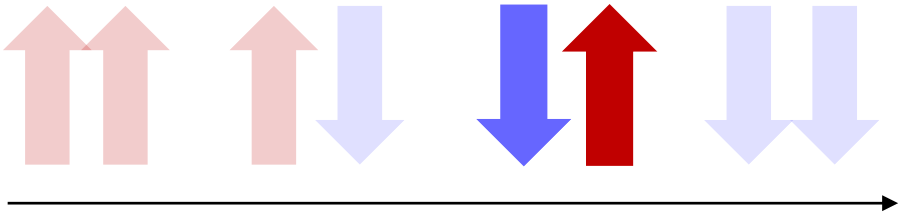
- **A quantum computer works using the principles of quantum mechanics (quantum properties: superposition, entanglement) to information processing.**
- Unlike calculations using a classical binary bit (0 or 1) of classical computers, quantum computers utilize **qubits (quantum bits) that can handle overlapping 0 and 1.**

Classical computers: Bit

In the case of N bits, only one pattern out of 2^N combinations **can be expressed.**

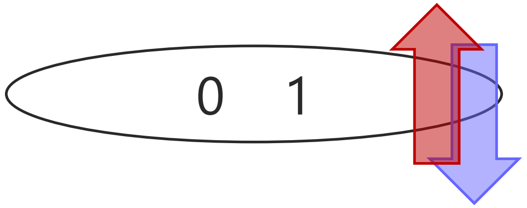


Calculate all combinations sequentially. **It takes a long time when the number of combinations is enormous.**



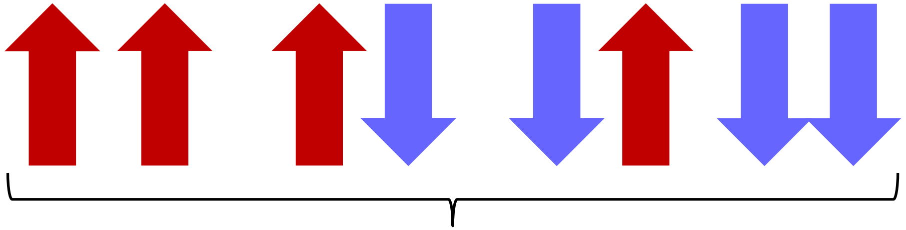
Quantum computers: Qubit

In the case of N bits, **2^N combinations are expressed simultaneously.**



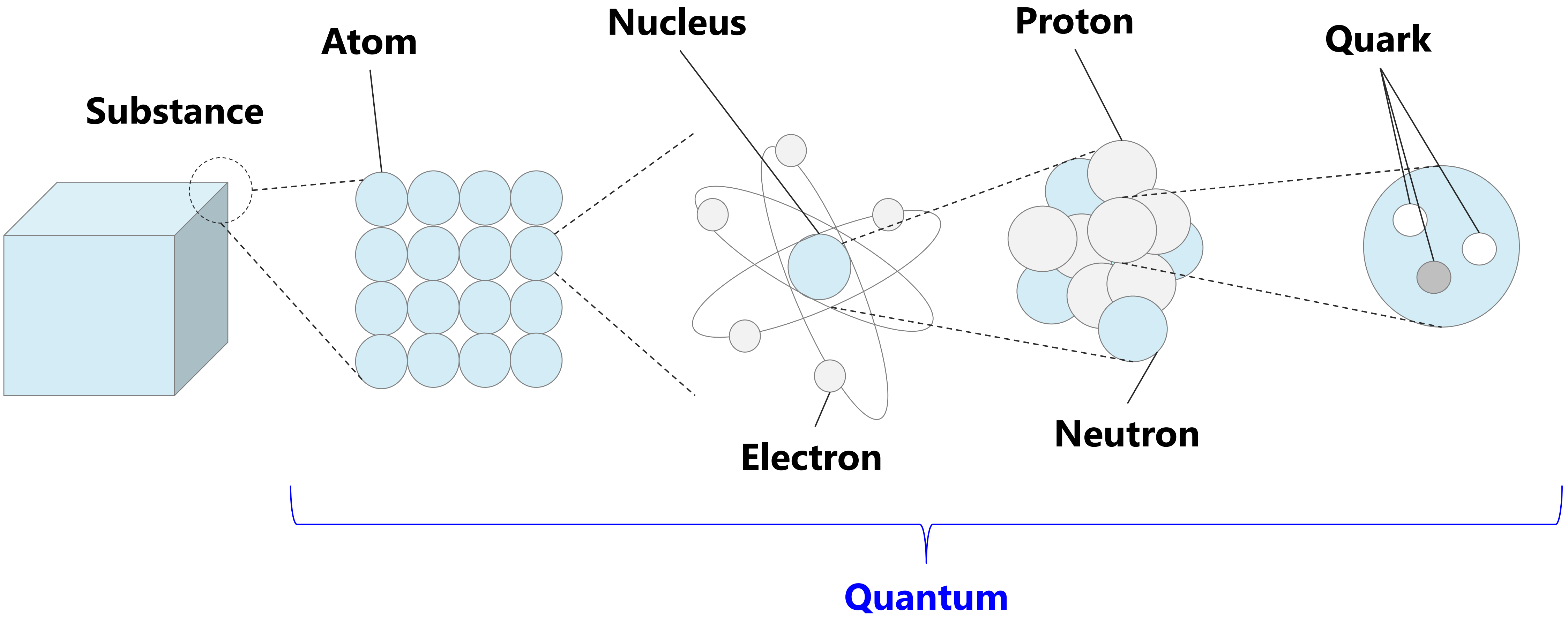
Quantum Superposition

From all combinations, probabilistically search for a definite answer using quantum entanglement.



What's a Quantum?

- In physics, **a quantum is the smallest discrete unit of any physical property**, such as energy or matter.
- Unlike classical mechanics, which deals with macroscopic objects, **quantum mechanics explains phenomena that occur at very small scales, such as electrons, photons, and other subatomic particles.**



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Two Types of Quantum Computers

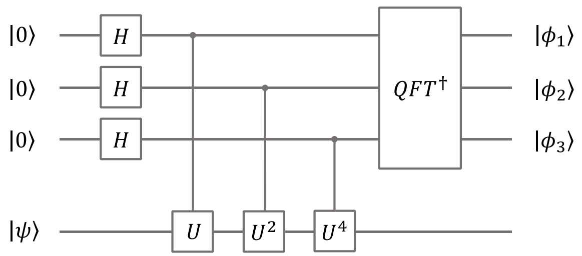
- It is broadly classified into **Universal Gate-Based Quantum Computers** (general-purpose) and **Quantum Annealing** (specialized).
- The quantum annealing have already been put into practical use for optimizing the shift schedule and the allocation of television ads.

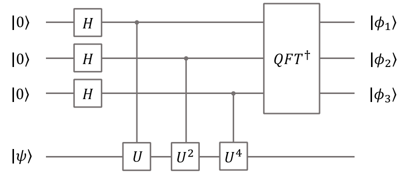
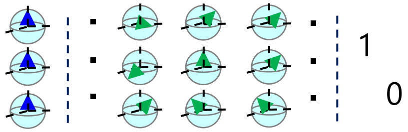
	Universal Gate-Based Quantum Computers		**Quantum Annealing**
Problems	**Solve all types of problems (not all problems are favorable for a quantum computer)**		**Solve combinatorial optimization problems**
Application Status	**NISQ*1 (no error correction)**	**FTQC*2 (with error correction)**	**Practical application in some areas** (shift schedule, the allocation of television ads, etc.)
	Social implementation within a few years?	Social implementation around 2030?	
Development Status	1,000+ qubits (IBM)	N/A (under development)	5,000+ qubits (D-Wave)

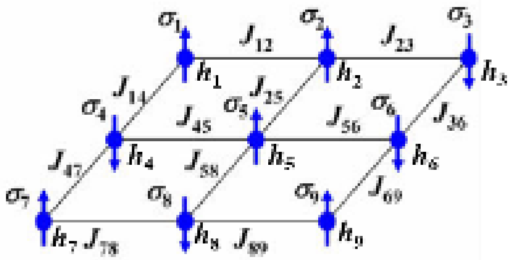
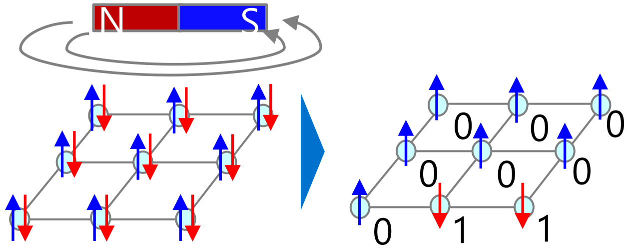
***1** **N**oisy **I**ntermediate-**S**cale **Q**uantum device: small to medium-scale quantum computers with qubits numbering up to several hundred.
***2** **F**ault **T**olerant **Q**uantum **C**omputer: designed quantum computers that can operate error-free, even in the presence of noise or errors.

Two-Method Process

- Although it is common to harness quantum properties, **the way to solve the problems and implamentation are very different** between the universal gate-based quantum computers and the quantum annealing.

<table>
<tr><th></th><th></th><th>Design</th><th>Coding</th><th>Calculation</th><th></th></tr>
<tr>
<td>Gate-Based</td>
<td rowspan="2">Identification of issues and problems</td>
<td>Design new or personalized quantum algorithms for applications.
<table>
<tr><th>Name</th><th>Main application</th></tr>
<tr><td>Shor</td><td>Prime factor decomposition</td></tr>
<tr><td>Grover</td><td>Data Exploration</td></tr>
<tr><td>…</td><td>…</td></tr>
</table>
</td>
<td>Set quantum circuits with qubits and quantum gates: circuit diagram of quantum gate operation that operates on qubits.


</td>
<td>Manipulate quantum gates according quantum circuits.
Quantum Circuits

Quantum Gate Manipulation


</td>
<td rowspan="2">Measurements: Read the results</td>
</tr>
<tr>
<td>Annealer</td>
<td>Formulate the combinatorial optimization problems as Ising models.
Ising Model:
$$H(\sigma) = -\sum_{i<j} J_{ij}\sigma_i\sigma_j - \sum_{i=1}^{N} h_i\sigma_i$$
σ: Variable set $\{\sigma_1, \sigma_2, \cdots, \sigma_N\}$
N: Number of spins (integer)
Each σ_i: Ising spin (variable that takes {1,-1})
J_{ij}: Interaction between spins
h_i: Local magnetic field
</td>
<td>Set the bond strength (J_ij) between each formulated variable and the weight (h_i) of each variable to the quantum computer.

</td>
<td>By applying a magnetic field and slowly weakening it, an optimal solution is obtained (the state changes from superposition to either 0 or 1).


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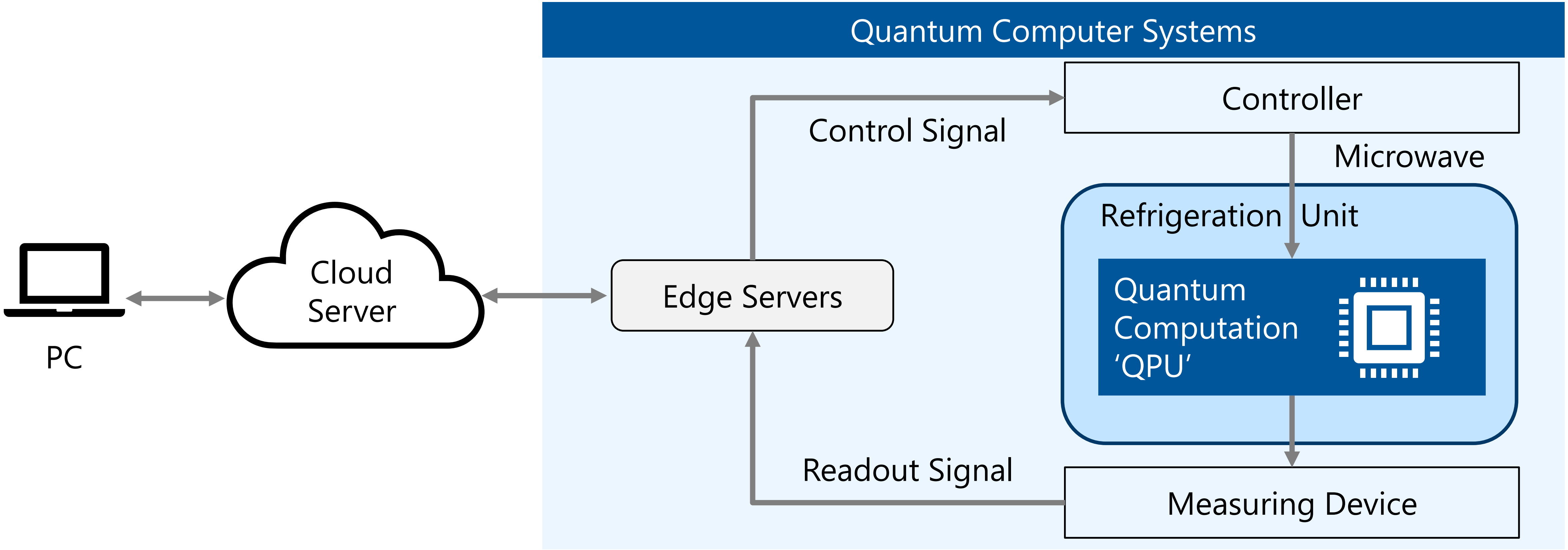
Source: The Japan Research Institute, Limited, Overview and Trends of Quantum Computing (https://www.jri.co.jp/MediaLibrary/file/column/opinion/pdf/11942.pdf)

Overview of Quantum Computer Systems

- **Quantum computation is performed on a quantum chip (QPU*1). Programming, generation of microwave signals, measurements, etc. are performed using current classical computers.**
- In the case of the superconducting quantum computing, a huge cooling system is required. Therefore, quantum computers **are usually used via the cloud computing**.

*1 Quantum Processing Unit.



How to make a Qubit

- There are many ways to create a qubit. **Superconducting and trapped ion quantum computers have progressed, but there are performance trade-offs among them**.

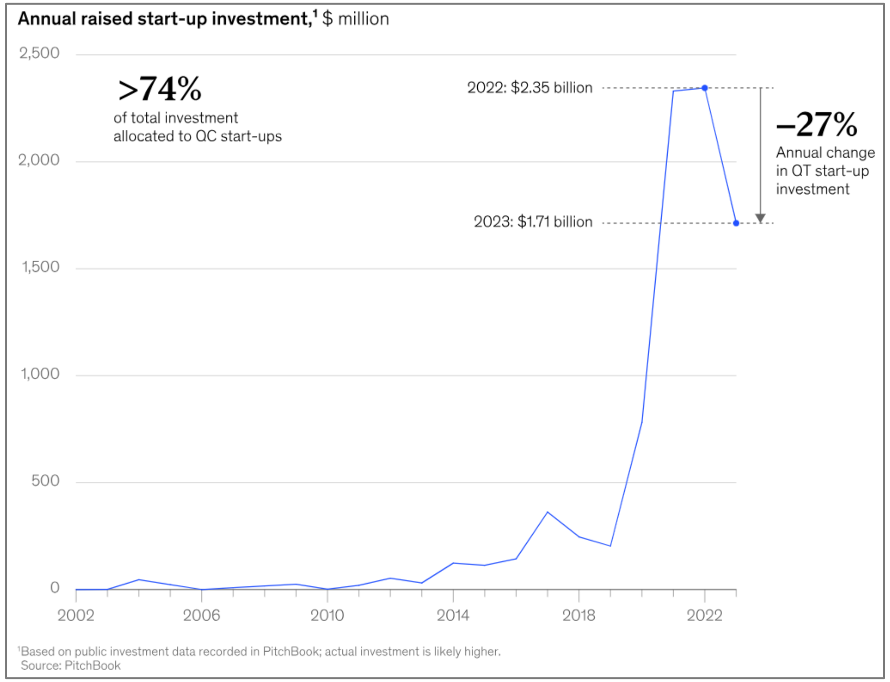
	(Artificially realized qubits)		(Making qubits with natural physical systems)		
	Superconductors	**Semiconductors (Silicon)**	**Trapped Ion**	**Neutral Atoms (Cold Atoms)**	**Photonics**
Principle	Calculations for electronic circuits in a superconducting state using microwaves, etc.	Electrons in a thin semiconductor film have spins that represent 0 or 1.	Ions are confined in a vacuum and calculated using laser light.	Laser cooling is used to control and calculate the motion of neutral atoms.	Information is placed on photons, optical circuits are created, and calculations are made.
Development Status	**Development and sales of actual equipment**	Prototype development	**Development and sales of actual equipment**	Prototype development	Prototype development
Operating Environment	Extremely low temperatures (mK*1)	Extremely low temperatures (K*1)	Vacuum	Vacuum	Room temperature*2
Number of Qubits	1,121 (IBM)	12 (Intel)	56 (Quantinuum)	N/A*3	N/A*3
Power Consumption*4	25~140kW	21kW	2kW	7~20kW	4kW
Strengths (○) / Weaknesses (×)	○ Can be integrated × Needs cooling to around 0K*1 × Wiring problem (there is a limit to the number of qubits that can be wired)	○ Can be integrated ○ Coherence time*5(long) ○ Semiconductor technology can be applied × Difficult to control qubits	○ Coherence time*5(long) ○ High gate fidelity*6 ○ Fully connected × Gate operation time	○ Coherence time*5(long) ○ Expandability × Gate operation time	○ Gate operation time (short) ○ Less susceptible to environmental noise × Noise due to photon loss
Sample – Enterprise	IBM, Google, Rigetti, Fujitsu, IQM, Anyon, D-Wave, NEC	Intel, Equal1, HITACHI, blueqat, C12	Quantinuum, IONQ, AQT, Universal Quantum, Qubitcore	Pasqal, QuEra, Infleqtion, Atom Computing, NanoQT	PsiQuantum, Xanadu, OptQC, NTT
Sample – Academia	UC Berkeley, RIKEN, OSAKA University, TUS, USTC	RIKEN, AIST, UNSW	Duke, Maryland (UMD), NIST, University of Innsbruck, OIST	MIT, Harvard University, Institute for Molecular Science	University of Tokyo, TU Delft USTC

*1 The Kelvin (symbol: K) is the base unit of temperature, and absolute zero (0 K) is equivalent to -273.15 °C. Since the superconducting system operates in an environment of about 10 mK (-273.14 °C) and the semiconductor method operates in an environment of about 100 mK (-273.05 °C) ~ 1.5 K (-271.65 °C), the semiconductor method is expected to reduce the size of the dilution refrigerator compared to the superconducting method. *2 PsiQuantum's single-photon method requires a large refrigerator to cool the photodetector. *3 Although general-purpose calculations are not possible, the neutral atom method: 289 qubits (QuEra, dedicated to one type of combinatorial optimization problem) and the optical method: 216 qubits (Xanadu, dedicated to Gaussian boson sampling) have been developed. *4 Source: Pasqal, 'Quantum Computing in the Roadmap to Greener Calculations'. In addition, it should be noted that the value fluctuates depending on the component in which each method operates and the number of qubits, and that it is difficult to make a simple comparison with current classical computers because the problems that can be solved by current quantum computers are not small-scale and practical problems. *5 A measurement of how long a qubit can maintain its quantum state. If the coherence time is short, the quantum state is disrupted, noise is generated, etc., and the calculation accuracy decreases. *6 Fidelity is an index of how close two quantum states are, and represents the correctness of the calculation of a quantum circuit.

Investment in Quantum Technology

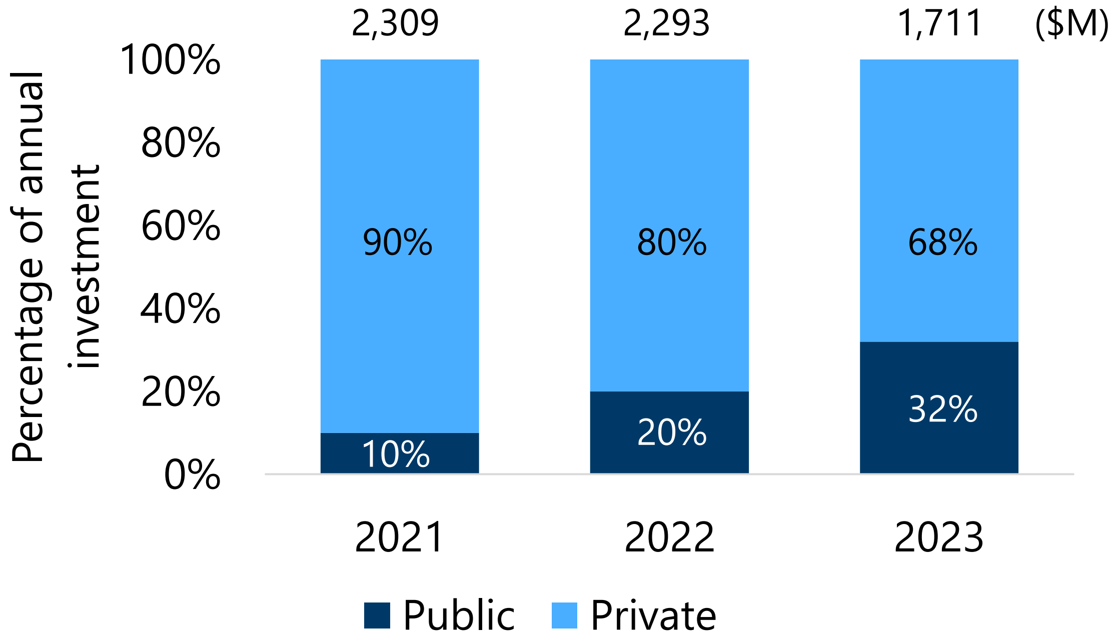
- **In 2019, after Google's announcement of quantum supremacy, investment in quantum technology became very active.** The decline peaked in 2022, but this is said to be largely due to the decline in global investment and the attention to generative AI.
- In contrast to the private sector, **public investment in 2023 increased compared to 2022.** It accounts for one-third of the total.

Start-up Investment



Source: McKinsey & Company, "Steady progress in approaching the quantum advantage", April 24, 2024

Public Funding



Source: Based on McKinsey & Company, "Quantum Technology Monitor", April 2024

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Players in Quantum Computers

- **In regions such as North America, Europe, Japan, and China**, there are numerous leading hardware development companies, and we are also observing an increase in software development.

Hardware

North America

Superconductors
IBM( ) Google ( ) D-Wave( )
Amazon( ) Rigetti( ) Anyon( )
SEEQC( ) Bleximo ( ) Nord Quantique( )
Qolab( )

Semiconductors
Intel( )

Trapped Ion
IonQ( ) Quantinuum( )

Photonics
PsiQuantum( )
Quantum Computing Inc. ( )
Xanadu( )

Neutral Atom
QuEra( ) Infleqtion( )
Atom Computing( )

Topological
Microsoft( )

Europe

Superconductors
Oxford Quantum Circuits( ) QuantWare( )
Alice & Bob( ) IQM( )

Trapped Ion
Universal Quantum( ) Oxford Ionics( )
AQT(Alpine Quantum Technologies)( )

Photonics
ORCA Computing( )
QuiX Quantum( )

Semiconductors
Quantum Motion( )
Equal1( ) C12( )
eleQtron( ) NQCG( )

Neutral Atom
Pasqal( ) planqc( )

Asia & Oceania

Superconductors
Fujitsu( ) NEC( )
Tencent( ) Huawei( )
Origin Quantum( )

Semiconductors
Hitachi( ) blueqat( )
Silicon Quantum Computing( ) Diraq ( )

Neutral Atom
NanoQT( )

Trapped Ion
Qubitcore( )

Diamond (NV Center)
Fujitsu( ) Quantum Brilliance( )

Photonics
OptQC( ) TuringQ( )

Ultra-cooling technology
Oxford Instruments( ) BlueFors( )
Ulvac Cryogenics( )

Control equipment
Keysight Technologies( ) QuEL( ) Qblox( )

Software

North America
QC Ware( )
SandboxAQ( )
Strangeworks( )
Qubit Engineering( )
QSimulate( )
1QBit( )
ProteinQure( )

Europe
Riverlane( ) Rahko( )
Phasecraft( )
HQS Quantum Simulations( )
QuantFi( )
Qubit Pharmaceuticals( )
ParityQC( ) Multiverse Computing( )
Terra Quantum( )

Asia & Oceania
blueqat( ) QunaSys( ) Classiq( ) Q-CTRL( )
Fixstars( ) Quanmatic( ) Qedma( )
Jij( ) Quemix( ) Horizon Quantum Computing( )

Cloud Service

North America
AWS( ) Microsoft( ) IBM( )
Google( ) Rigetti( ) Equinix( )
NVIDIA( ) QC Ware( ) Xanadu( ) D-Wave( )

Asia & Oceania
Fujitsu( ) NEC( ) Hitachi( )
Toshiba( ) Fixstars( )

Europe
Atos( )

*1 The above diagram may not include all the players, but it is noteworthy that there are companies offering integrated services from hardware to software, and each development company provides its own cloud services.

Source: Based on The Japan Research Institute, Limited. Hideyuki Mase / Yoshihiro Mino. Fully understanding Quantum Computing. Nikkei Business Publications, 2023, p.76-77

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Typical Quantum Algorithms

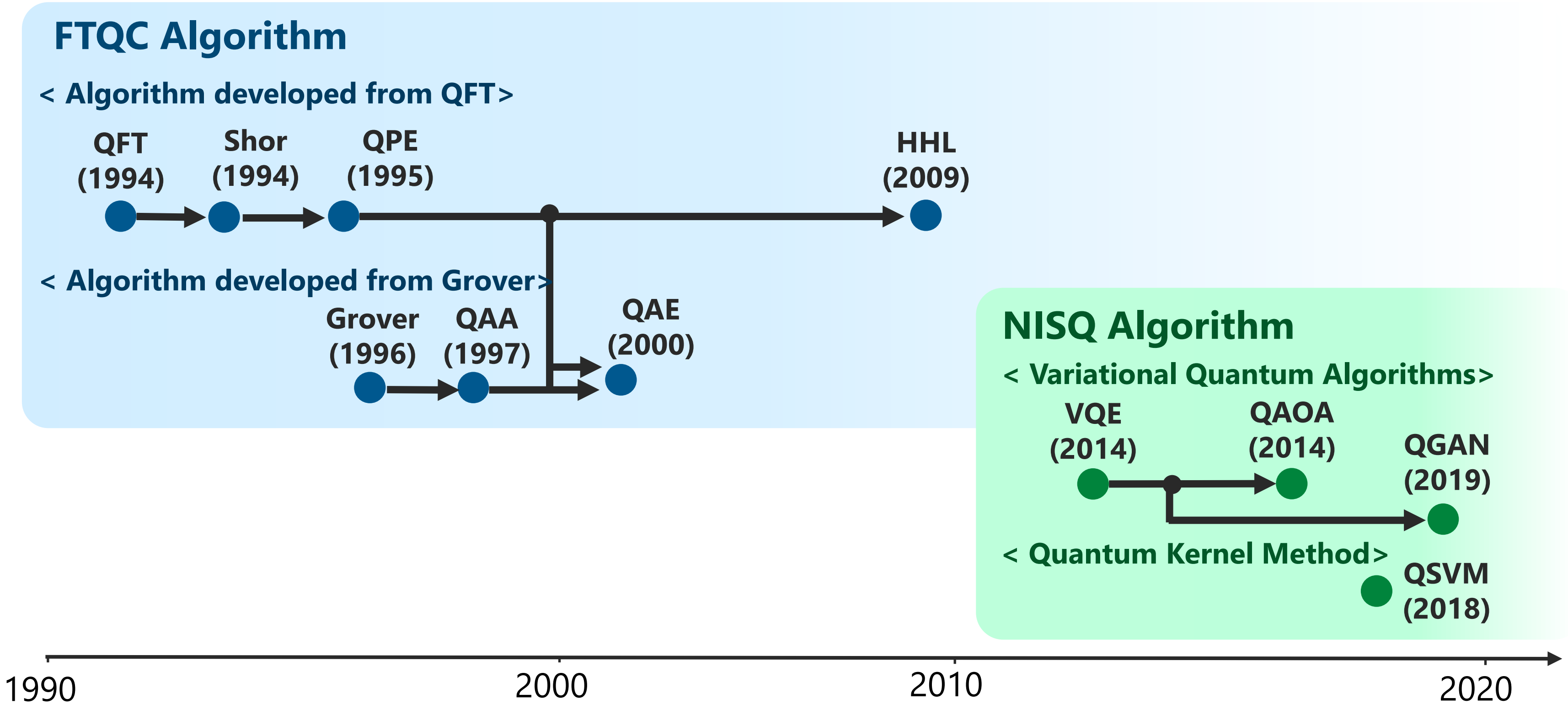
- To enable quantum computers to outperform classical ones, **developing quantum algorithms is essential, which are categorized into FTQC / NISQ algorithm.**
- Although NISQ algorithm development has been active since 2018, **it has yet to demonstrate commercial value.**

Name	Main Applications	Main Issues / Current Situation		Quantum Speed-up
FTQC Algorithm (designed on the premise of error correction)				
QFT (Quantum Fourier Transform)	(Subroutine of Shor, QPE)	Root Cause: High Error Rate	Increasing the number of qubits increases the number of gates	Exponent
Shor	Prime factor decomposition		〃 (for QFT use)	Exponent
QPE (Quantum Phase Estimation)	Exploration of the ground state of molecules, (QAE subroutine)		〃 (for QFT use)	Exponent
Grover	Data Exploration		The circuit becomes deeper as the number of data increases	Quadratic
QAA (Quantum Amplitude Amplification)	(QAE subroutine)		〃	Quadratic
QAE (Quantum Amplitude Estimation)	Monte Carlo method		There is the same issue for the use of QAA and QPE	Quadratic
HHL (Harrow–Hassidim–Lloyd)	Signal processing and machine learning		There is the same issue due to the use of QPE	Exponent
NISQ Algorithm (designed under conditions that cannot be corrected)				
VQE (Variational Quantum Eigensolver)	Exploration of the ground state of molecules	Sufficient circuit depth and low error rate are required		-
QAOA (Quantum Approximate Optimization Algorithm)	Combinatorial Optimization	Unknown advantages in terms of solution quality and speed		-
QSVM (Quantum SVM)	Supervised Machine Learning	Lack of practical superiority		-
QGAN (Quantum Generative Adversarial Network)	Data Generation & Amplification	Inability to generate high-dimensional data		-

Source: Based on The Japan Research Institute, Limited. Hideyuki Mase / Yoshihiro Mino. Fully understanding Quantum Computing. Nikkei Business Publications, 2023, p.62

Ref. Quantum Algorithm Phylogenetic Diagram

- The FTQC algorithm can be broadly divided into two main patterns: the first one uses the high speed of QFT, and the second one uses the high speed of Grover's algorithm.
- Since 2014, research on quantum-classical hybrid algorithms using variational quantum algorithms*1 has progressed. In addition, in recent years, research on quantum machine learning, which integrates quantum algorithms within machine learning, has also progressed*2.

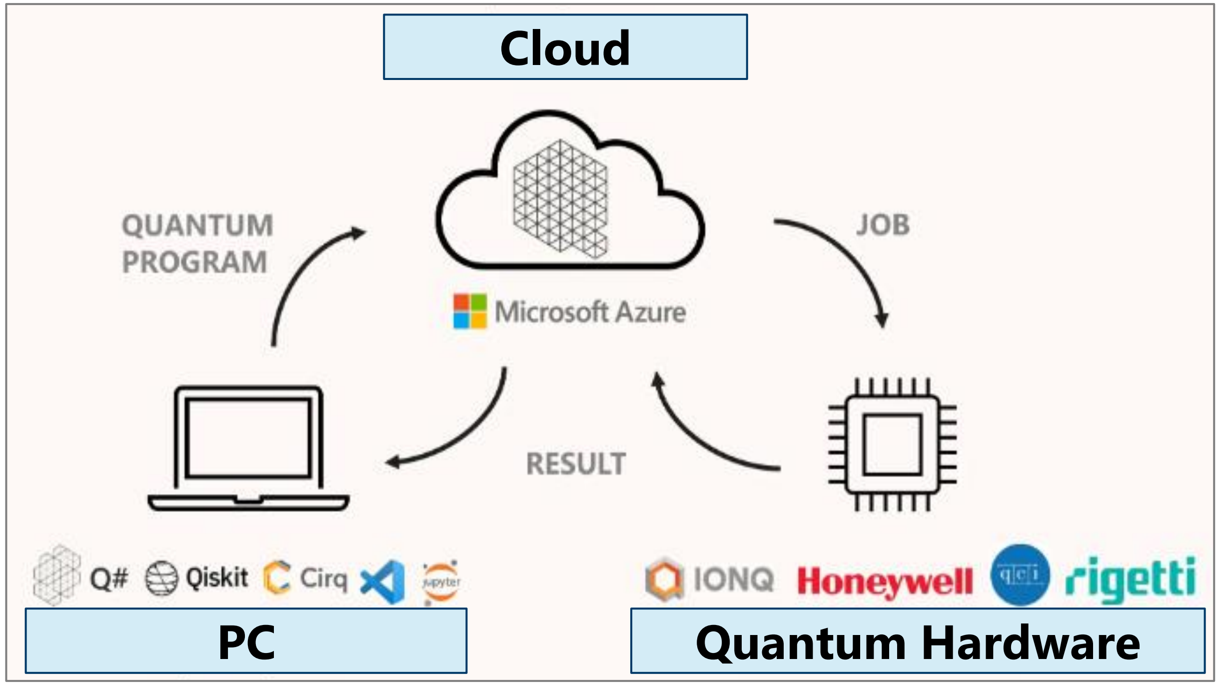


*1 An algorithm that monitors the output of a quantum circuit as appropriate, adjusts its configuration sequentially by a classical computer, and creates a quantum circuit that can perform the desired task.
*2 Even if hardware develops, there is no guarantee that it will achieve theoretical superiority, so there is a possibility that it will become a temporary boom.

QCaaS and SDKs

- When users use quantum computers, **they usually do so via the cloud. Cloud giants have already started offering multiple quantum hardware on their cloud platforms.**
- **For quantum computers to be widely adopted, quantum software needs improvement**, with a focus on developing human-friendly, high-level programming languages closer to machine code.

QCaaS (Quantum Computing as a Service)



Source: Based on https://azure.microsoft.com/en-us/blog/quantum/2021/12/06/azure-quantum-open-flexible-and-future-proofed/

SDKs (Software Development Kits)

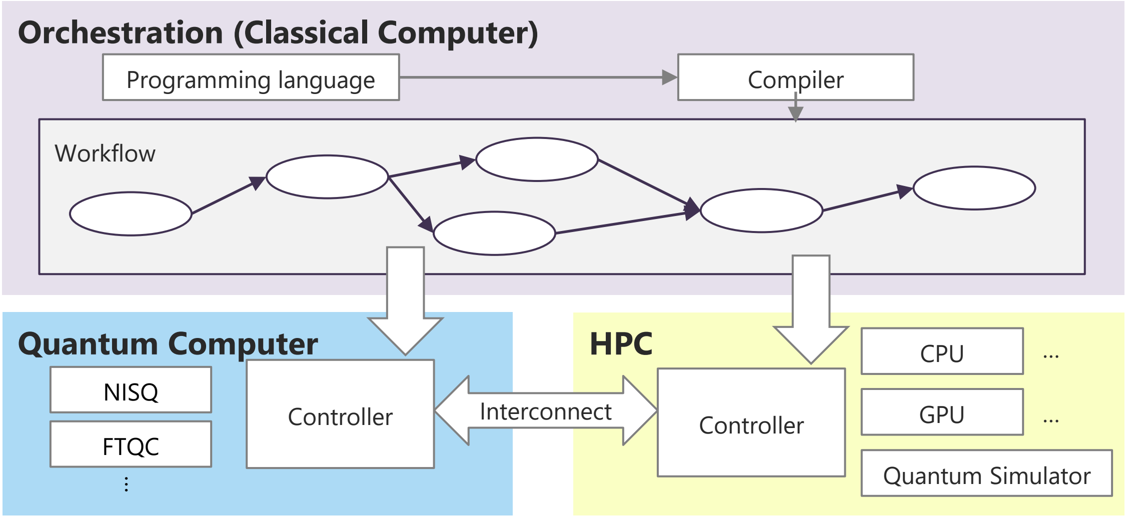
SDK	Developer	Main PG Languages
Bracket	AWS (🇺🇸)	Python
Cirq	Google (🇺🇸)	Python
D-Wave Ocean	D-Wave (🇨🇦)	Python
PennyLane	Xanadu (🇨🇦)	Python
QamuyClient	QunaSys (🇯🇵)	Python
QKD	Microsoft (🇺🇸)	Q#
Qiskit	IBM (🇺🇸)	Python
Qmod	Classiq (🇮🇱)	Python
tket	Quantinuum (🇺🇸)	Python

Quantum Computers and HPC (High performance computing)

- **Quantum computers won't fully replace classical ones** but are expected to be used together.
- Research on **quantum-classical hybrid computing is advancing.**

Quantum-Classical Hybrid Computing

- Programs are split into workflows, assigning tasks to either HPC or quantum processors.
- Integrated quantum-classical research projects are increasing, including efforts by AIST G-QuAT, RIKEN & SoftBank, Riverlane & Rigetti & ORNL, IBM & Rensselaer, and RIKEN & Osaka University.



Source: Based on IEEE Micro, Quantum Computers for High-Performance Computing, Sept.-Oct. 2021, pp. 15-23, vol. 41, DOI Bookmark: 10.1109/MM.2021.3099140、
The Future of Quantum Computing with Superconducting Qubits, arXiv2209.06841

Differences (HPC vs Quantum Computers)

	HPC	Quantum computers
Purpose	Advanced numerical calculations and all about data processing	For a limited purpose demonstrating great power
Bits	0 or 1 (Classic Bit)	0 and 1 (qubit)
Calculation Way	For all inputs, Calculate every time	Simultaneously computation using Quantum Mechanics
Strengths	• Leverage existing technology • Versatility	• Faster processing of specific tasks (fewer calculation steps) • Low power consumption?
Weaknesses	• Power consumption is high • Limitations of microfabrication technology • As the number of inputs increases, the computational cost increases	• Difficult to manufacture and maintain and control quantum states
Prospect	• Performance improvements and new function development will continue in the future, but growth is slowing	• Practical application is progressing for limited problems, and it is expected to speed up

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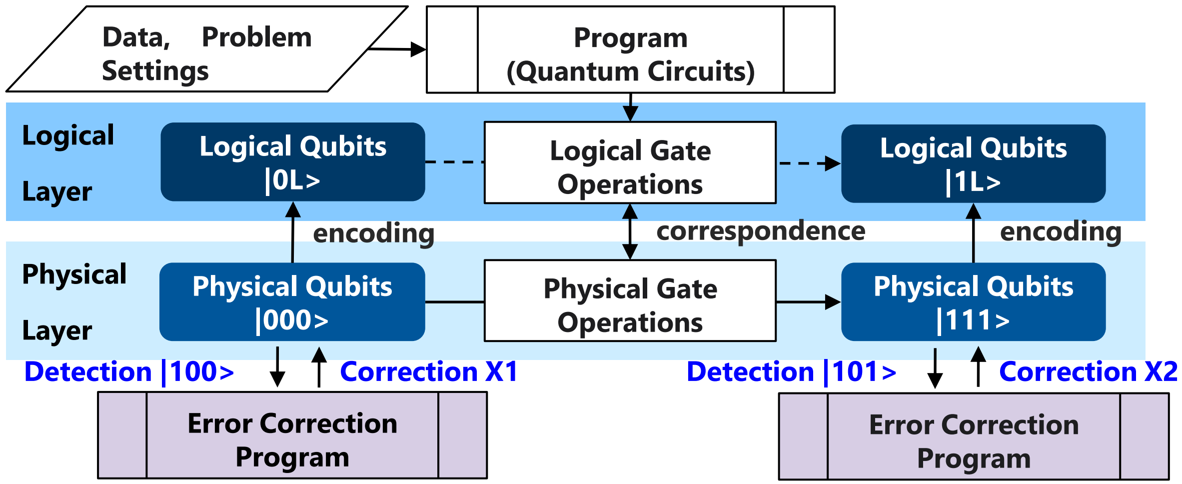
Quantum Error Correction and Mitigation

- Qubits are sensitive to noise and prone to errors. Recently, there has been a rise in quantum error correction experiments, with basic research from companies like Google and QuEra.

Summary

Error Correction

- A technology that detects and corrects errors that occur in qubits.



Source: Based on 嶋田義皓, 量子コンピューティング　基本アルゴリズムから量子機械学習まで, オーム社, 2020, p.176,186-189

- The error correction method known as 'surface code' is regarded as promising, yet there remain numerous challenges to be resolved.
- Surface codes are readily implemented using superconducting hardware, where quantum bits are arranged on a planar surface.

Error Mitigation

- A technology that enhances quantum computer results through statistical post-processing on a classical computer to match expected values.

Recent Research

		Substance
Correction	Google (Dec 2024 / Feb 2023)	Demonstration of scaling quantum error correction with surface codes.
Correction	QuEra (Dec 2023)	Using our proprietary error correction technology, 48 logical qubits are implemented.
Correction	Quantinuum / Microsoft (Apr 2024)	Four logical qubits are generated from 30 physical qubits, with the advantages of quantum error correction outweighing the correction overhead.
Mitigation	IBM (Jun 2023)	Noise amplification technology tailored to the machine's characteristics enables more accurate post-processing.

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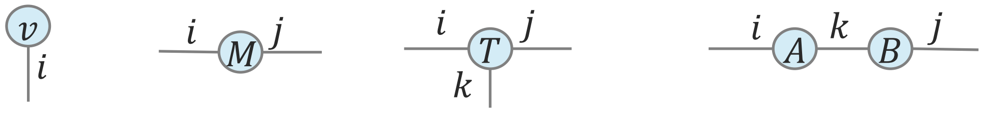
Quantum-Inspired Computing

- Quantum inspiration refers to technologies that have emerged from quantum physics and quantum computer research.
- Typical examples include 'Tensor networks' that can be used to simulate quantum gate methods, and 'Simulated Annealing (SA)' that can be regarded as a simulator of quantum annealing.

Tensor Networks

- A tensor network is a visualization of 'vectors', 'matrices', 'tensors', and their contractions as a network.
- A tensor is an extension of a matrix (two-dimensional array) and generalized to include three or more dimensions, and a contraction is a generalization of the integration of matrices in tensors. The vector is represented by one leg, the matrix is represented by two legs, and the tensor is represented by the n-foot node, and the contraction is expressed by connecting the legs.

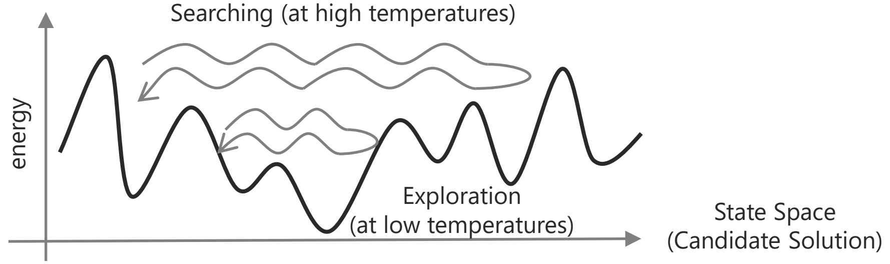


vector v_i matrix $M_{i,j}$ tensor $T_{i,j,k}$ Product of Matrix $A_{i,k}$ and $B_{k,j}$

- It is possible to compress the data expressed by tensors by making full use of computational methods such as decomposing a high-dimensional tensor into a state called a matrix product state and approximating it in a lower dimension, and efficiently reducing it.

Simulated Annealing (SA)

- This is a search method for optimal solutions that mimics the heating and cooling method performed in the process of annealing metals. Although SA is classified as quantum-inspired, SA has long been used as a solution to combinatorial optimization problems than quantum annealing.
- Both SA and quantum annealing assume that the state of the variable follows the Boltzmann distribution and apply it to a statistical mechanics model. By changing the parameters of the model, we narrow down the solution candidates that have the least energy. In SA, the temperature parameter is reduced. In quantum annealing, a solution is searched for while performing an operation that slowly weakens the influence of the transverse magnetic field.
- Most of the quantum annealing applications can be demonstrated using SA.

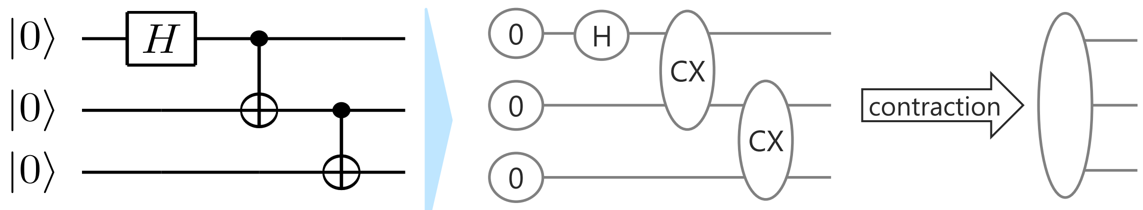


Ref. Tensor Network Utilization

- Tensor networks can be applied to quantum gate simulations, machine learning methods, etc.
- At present, it may be possible to solve problems that cannot be handled by actual quantum computers, and it is expected that useful applications will be discovered.

Simulation of Gate-based Methods

- A quantum circuit can be represented by a tensor network, and the calculation result of the circuit can be simulated by performing a contraction calculation.
- If we can simplify the calculation by making good use of methods such as approximation when performing contraction, there is a possibility that large-scale problems can be solved with realistic accuracy.

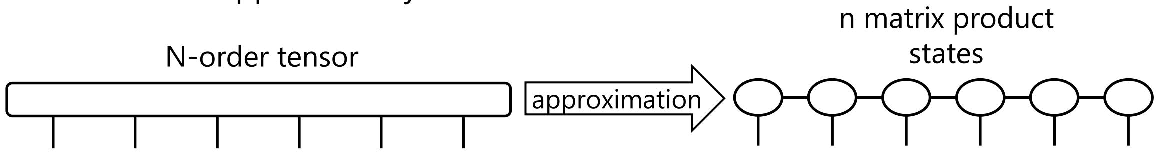


Quantum circuits   Expressed in tensor networks

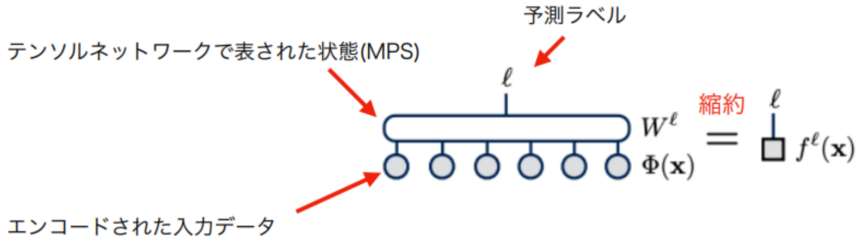
- It is expected to be applied to applications similar to the quantum gate method, but an effective application has not yet been found.
- There are problems that cannot be solved by actual quantum computers at the moment.
- In general, shallow quantum circuits can be solved with a large number of qubits, but they are not suitable for deep quantum circuits.

Utilization for Machine Learning

- Machine learning models can be generally represented by n-order tensors.
- An n-order tensor can be approximated by n matrix product states (MPS).
- By combining matrix product states, various machine learning models can be constructed approximately.



- By contracting the tensor network to a single vector, it is possible to construct a model that makes predictions and classifications. The classification model using tensor network had an equivalent performance to existing models on MNIST and Fashion-MNIST.



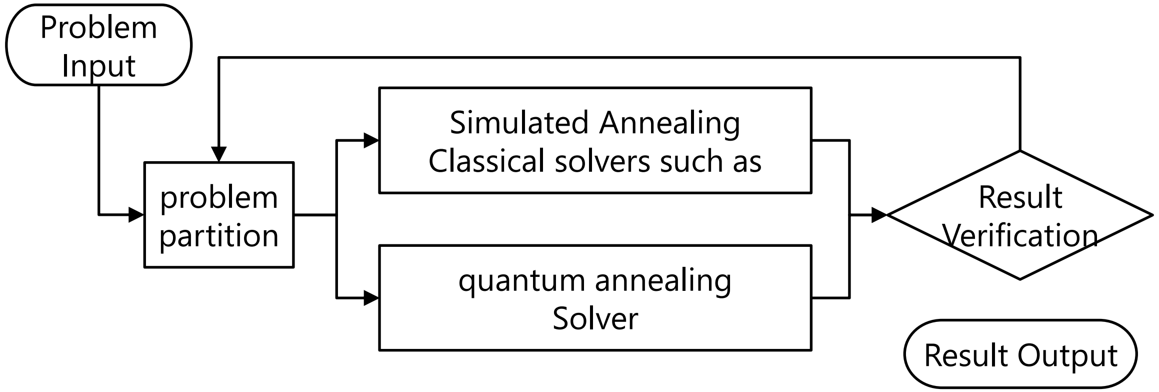
Source：Tensor Network Quantum Virtual Machine for Simulating Quantum Circuits at Exascale | ACM Transactions on Quantum Computing,
日本総研 渡邉一生. 量子回路のテンソルネットワークシミュレーション　～縮約密度行列の計算～ #量子コンピュータ - Qiita

Hybrid Solver and Black-Box Optimization (Quantum Annealing)

- New initiatives in quantum annealing technology include 'hybrid solvers' and 'black box optimization'.
- The hybrid solver aims to solve large-scale combinatorial optimization problems that could not be solved by conventional quantum annealing alone by using classical computers together. Black-Box Optimization is an existing method, but quantum annealing can be applied to some of the learning computations.

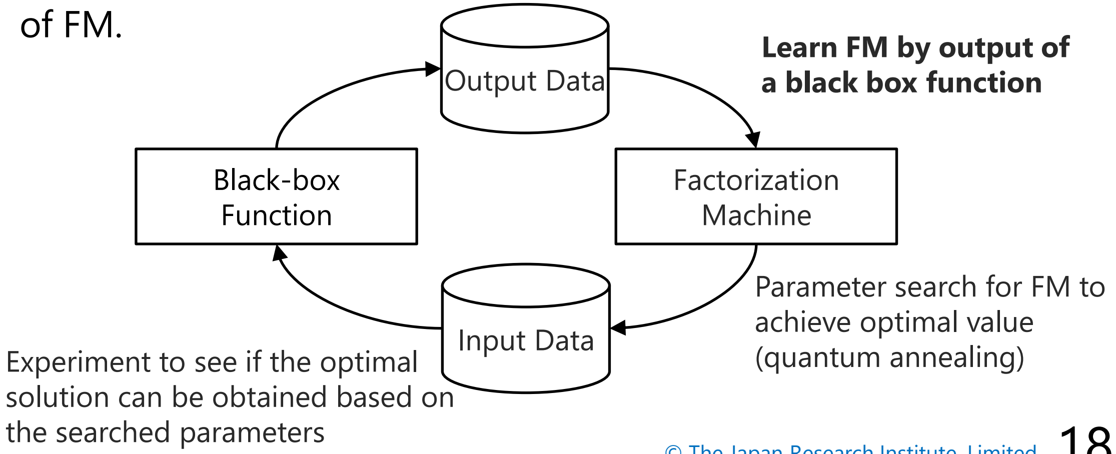
Hybrid Solver

- It uses a combination of classical and quantum computers to solve combinatorial optimization problems. The basic method is to divide a large problem into multiple small subproblems, and then synthesize the results of iterative calculations of the subproblems to obtain the overall optimal result.
- D-Wave provides a hybrid solver called "Leap's Hybrid Solvers" on its cloud service.



Black-Box Optimization (BBO)

- When the details of the objective function are black boxes, it is a method to find an input whose output is the optimal solution. Here, we use the Factorization Machine (FM), which is a type of machine learning model that uses matrix decomposition, to reproduce the behavior of the black box function.
- Since FM can be represented in QUBO format, quantum annealing can be used to determine the parameters that optimize the output of FM.



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Overview of Policy Developments in Nations

- **In 2023, countries and regions around the world will invest** huge amounts of public funds in quantum technology **under the quantum nation strategy.**

Region / Country		Investment ($B)[*1]	Main Initiatives
North America	US	3.8	In 2018, the National Quantum Initiative Act was enacted, and USD 1.2 billion was invested over five years. Currently, the current bill is being considered for reapproval and renewal.
	Canada	1.4	**In 2023, the "Quantum State Strategy" will be announced.** The company will invest CAD 360 million over seven years. **It focuses on three pillars: research, human resources, and commercialization.**
Europe	EU	1.1	In 2018, the "quantum flagship" was announced. EUR 1 billion will be invested over 10 years. More than 5,000 researchers participated.
	UK	4.3	**In 2023, he announced a new national quantum strategy that sets a vision for the next 10 years.** Over 10 years, the government will invest 2.5 billion GBP and the private sector will invest 1 billion GBP.
	Netherlands	1.0	In 2019, the "Agenda for the Quantum Technology Nation" was formulated. **In '23, Quantum Delta NL (National Ecosystem) invested 6,020 EUR.**
	Germany	5.2	**In 2023, we announced a €3 billion quantum computer development project ('23~'26).**
	France	2.2	In 2021, the company announced its quantum strategy. A total of EUR 1.8 billion in public and private funding will be provided over four years (EUR 1 billion will be invested by the government).
	Sweden	0.001	In 2018, he established the Quantum Technology Center (WACQT) as a quantum state research program. Invested SEK 1 billion over 12 years.
	Denmark	0.15	**In 2023, a quantum technology strategy was introduced, divided into two main areas: 1) Research & Innovation and 2) Commercialization & Practical Applications.** The plan involves investing a total of 1 billion Danish Krone from 2023 to 2027.
	Russia	0.8	In 2021, the company announced that it would invest USD 790 million over five years in quantum computer research.
Asia	China	15.3	The company has invested more than USD 15 billion in research and development of quantum technology with a view to security, defense, and AI applications (estimates, no official government announcement).
	Japan	1.8	**4.2 billion yen in funding for quantum cloud computing in 2023. Approximately 120 billion yen has been allocated for FY24.**
	Israel	0.4	**In 2023, the Innovation Agency will establish a consortium to provide 115 million ILS (new shekels) (about 4.8 billion yen).**
	Australia	0.16	**In 2023, the "Quantum State Strategy" will be announced.** We will work on five priority themes until '30. The company invested 1 billion AUD (approximately JPY 103 billion).
	Korea	2.4	**In 2023, the "Quantum Science and Technology Strategy" will be announced.** By '35, at least 3 trillion KRW (about 330 billion yen) will be invested **in private-government cooperation**.
	India	1.7	**In 2023, the company announced a "National Quantum Mission" that will invest 6 billion INR (about 10.8 billion yen) over eight years.**

*1 Cumulative investment amount up to 2023 (including budgeted amount) based on various information. Keep in mind that quantum-related budgets may be included in some of the larger national projects, and not all of them are accurate.

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Ref. What is Quantum Technology?

- Quantum technology is an umbrella term for technologies that use quantum mechanics (the laws of physics) to improve information communication and measurement, and to develop materials.
- A quantum computer is a "computer" that applies quantum technology.

Theory	Examples of the Application of the Theory		Overview	Use Cases (Expectations for the Future)
Quantitative Dynamics	Information Communication	**Quantum Computers**	Even with current supercomputers, problems that require an enormous amount of time to calculate can be solved in a short time.	• Development of chemicals and materials • Optimization of transportation and logistics • Faster Financial Simulation
		Quantum Key Distribution (QKD)	The "key" that solves the code is placed on a photon and delivered by optical fiber.	• Cryptography that even quantum computers can't crack
	Measurement	**Quantum Sensors**	Measure temperature, magnetism, acceleration, etc. with orders of magnitude higher sensitivity and accuracy.	• Ultra-early diagnosis and treatment • Earthquake and volcanic disaster prevention • Safe autonomous vehicles
	Material	**Quantum Materials**	Materials that precisely control quantum states using nanotechnology.	• Low power consumption and large memory capacity • Generate electricity from heat, vibration, light, and more in a single device

Source: Based on The Japan Research Institute, Limited. Hideyuki Mase / Yoshihiro Mino. Fully understanding Quantum Computing. Nikkei Business Publications, 2023, p.26-27

Japan's Approach to Quantum Technology (1/4)

- Japan's 2022 Quantum Technology Strategy targets **10 million users, 50 trillion JPY in production, and quantum unicorns by 2030, emphasizing global collaboration.**

The National Strategy

- Japan’s Quantum Technology Strategy, launched in 2020 and updated in 2022, sets the vision and plans for quantum industrialization. With rapid global progress, swift action is critical.
- Key measures will strengthen efforts toward 2030 goals: 10 million quantum technology users in Japan, Through quantum technology, production to 50 trillion JPY (340 billion USD), fostering quantum unicorn companies to create future markets.
- Adding "Globalization" enhances international collaboration under the "Quantum Future Industry Development" plan.

Research
Quantum Technology Innovation Strategy
(Revised January 2020, April 2022)
R&D Strategies

Vision
Vision of Quantum Future Society
(April 2022)
Strategies for social change (future vision, etc.)

Industry
Strategy of Quantum Future Industry Development
(April 2023)
Practical Application and Industrialization Strategies

Promotion Measures
(April 2024)
3 strategies to strengthen and complement the strategy. Strengthening International Cooperation

Source: Based on https://www8.cao.go.jp/cstp/ryoshigijutsu/240409_q_measures_o.pdf

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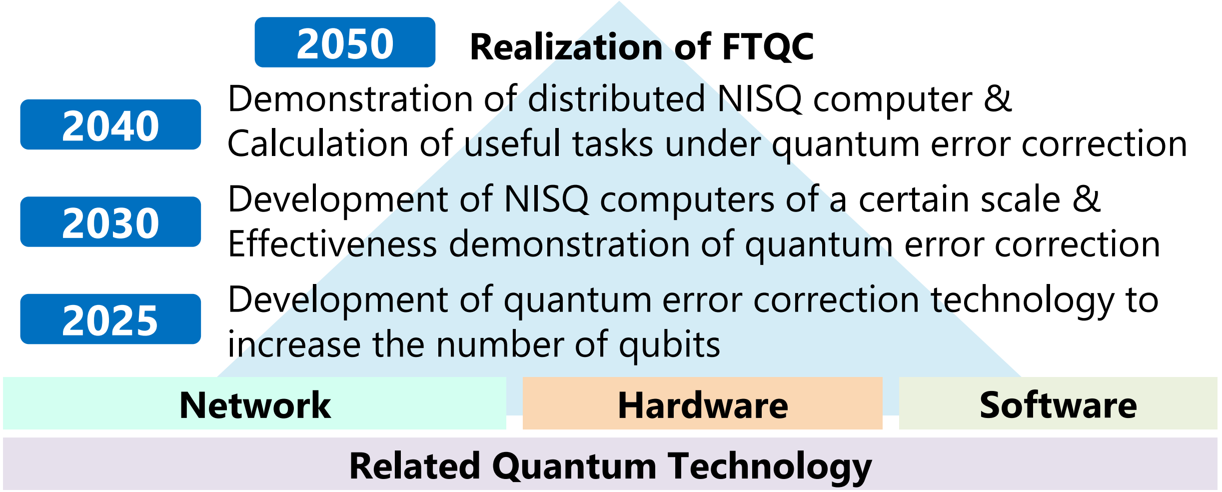
Japan's Approach to Quantum Technology (2/4)

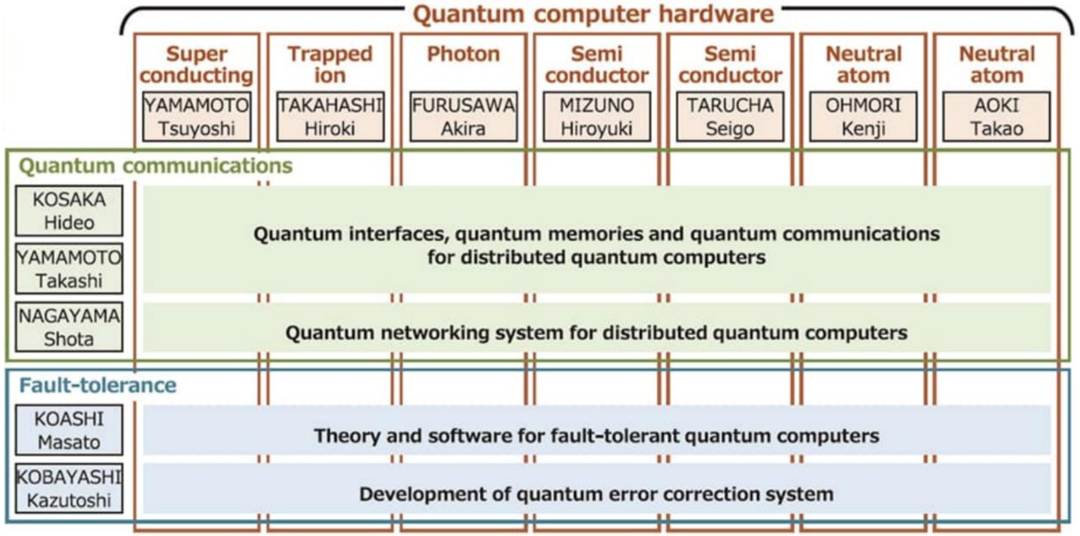
- Japan started **the Moonshot Program**, conducting R&D into the relevant hardware, software, and networks.

The Moonshot Research and Development Program: Goal 6

- The Moonshot Program launched was launched in 2020 by the Cabinet Office to promotes high-risk, high-impact R&D. To realize "Human Well-being", ten Moonshot goals were decided in the area of society, environment, and economics.
- Moonshot Goal 6: Fault-tolerant universal quantum computer
  - Realize a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050.
  - Developing a certain scale of NISQ computer and demonstration of the effectiveness of quantum error correction by 2030.
- With the potential for massively integrated quantum computers via quantum communication, R&D projects will focus on three areas: 1) hardware, 2) communication networks, and 3) theory and software.
- Considering the recent progress in quantum error correction technology and other current developments, they are carefully considering the update of thier milestones and the restructuring of their program portfolio.



Source: Based on https://www8.cao.go.jp/cstp/english/moonshot/sub6_en.html



Source: https://www.jst.go.jp/moonshot/en/program/goal6/index.html

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Japan's Approach to Quantum Technology (3/4)

- **Industry, government, and academia have been collaborating** under the National Strategy.

Industry-Government-Academia Consortium

Name	Government / Academia	Enterprise	Summary
Moonshot Goal 6	RIKEN, Institute for Molecular Research, The University of Tokyo, Osaka University, OIST*5, etc.	NEC, Hitachi, Fujitsu, NTT, NanoQT, Hamamatsu Photonics, QuEL, LQUOM, Ulvac Cryogenics, etc.	• By 2050, they will realize a large-scale error-tolerant general-purpose quantum computer. • Number of PJs: 12
Q-LEAP*1	RIKEN, NICT*6, AIST*7, Osaka University, Keio University, Nagoya University, etc.	Fujitsu, Hitachi, QunaSys, etc.	• R&D of superconducting methods, research and development of quantum software, development of human resource development program.
Q-STAR*2	JST*8, AIST*7, NIMS*8, Kyushu University, Tohoku University, etc.	Toshiba, NEC, Fujitsu, Hitachi, Canon, KYOCERA, Sumitomo Corporation, Sumitomo Mitsui Financial Group, etc.	• Creation of quantum industries, international collaboration, and policy proposals. • Number of Members: 105
SQAI*3	University of Tokyo, RIKEN, Keio University, OIST*5, University of Chicago, Kawasaki-City	Toyota, IBM, Mitsui Chemicals, NVIDIA, Sumitomo Mitsui Financial Group, Mizuho R&T, Deloitte, IQM, Strangeworks, etc.	• Quantum AI technology is created, and quantum HPC is present. • Number of Members: 43
QSRH*4	Osaka University, kyoto University, Kanazawa Institute of Technology, RIKEN	Toyota Tsusho Corporation, AWS, Fujitsu, Hitachi, Sony, IHI, QunaSys, JX Nippon Oil & Gas Exploration Corporation, AGC, etc.	• Build a quantum software platform to solve social issues and promote its implementation and dissemination. • Number of Members: Approximately 36

*1 The Ministry of Education, Culture, Sports, Science and Technology's "Photonics and **Q**uantum **Leap** Flagship Program"
*2 **Q**uantum **ST**rategic industry **A**lliance for **R**evolution
*3 The Japan Science and Technology Agency (JST) COI-NEXT Program "**S**ustainable **Q**uantum **AI** Research Center"
*4 **Q**uantum **S**oftware **R**esearch **H**ub *5 **O**kinawa **I**nstitute of **S**cience and **T**echnology *6 **N**ational **I**nstitute Of **I**nformation And **C**ommunications **T**echnology
*7 National Institute of **A**dvanced **I**ndustrial **S**cience and **T**echnology *8 **J**apan **S**cience and **T**echnology Agency *9 **N**ational **I**nstitute for **M**aterials **S**cience

Japan's Approach to Quantum Technology (4/4)

- In 2023, Japan launched its first domestically produced quantum computer. Most of the parts of Unit 3, except for the refrigerator, were domestically produced.
- The need to build a supply chain for quantum computers is increasing, and this is one of the activities of AIST*1 G-QuAT*2.

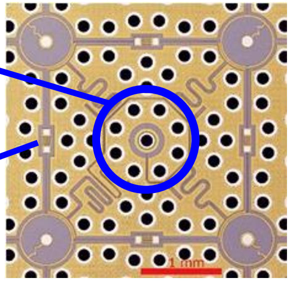
*1 National Institute of Advanced Industrial Science and Technology
*2 Global Research and Development Center for Business by Quantum-AI technology

Development of a Domestically Produced Quantum Computer

- In March 2023, RIKEN, Fujitsu, NTT, and others released Japan's first 64-qubit superconducting quantum computer via the cloud for research. Its advantage is easy qubit expansion using a 'two-dimensional integrated circuit' and 'vertical wiring package'.
- By October, Fujitsu and RIKEN unveiled a second unit for corporate use, and in December, Osaka University and others introduced a third unit as a testbed for domestic parts.

Two-Dimensional Integrated Circuits

Readout Circuit

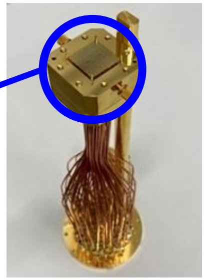


Qubit-to-Qubit Coupling

Increase the number of qubits by arranging a basic unit consisting of four qubits arranged in a square in two dimensions.

Vertical Wiring Package

Qubit Circuits



When enlarging the qubit circuit, connect the read wiring perpendicular to the qubit circuit.

Photo source: https://www.riken.jp/pr/news/2023/20230324_1/index.html

Supply Chain Resilience at AIST G-QuAT

- National strategies highlight quantum computing supply chains, with risks of supplier dependence from different methods to make qubits. This global supply chain, like in automotive and aerospace, may form.
- Japan's tech skills are widely recognized. G-QuAT, established by AIST in 2023, aims to build a global ecosystem by promoting commercialization, market development, collaboration, and enhancement supply chain resilience.

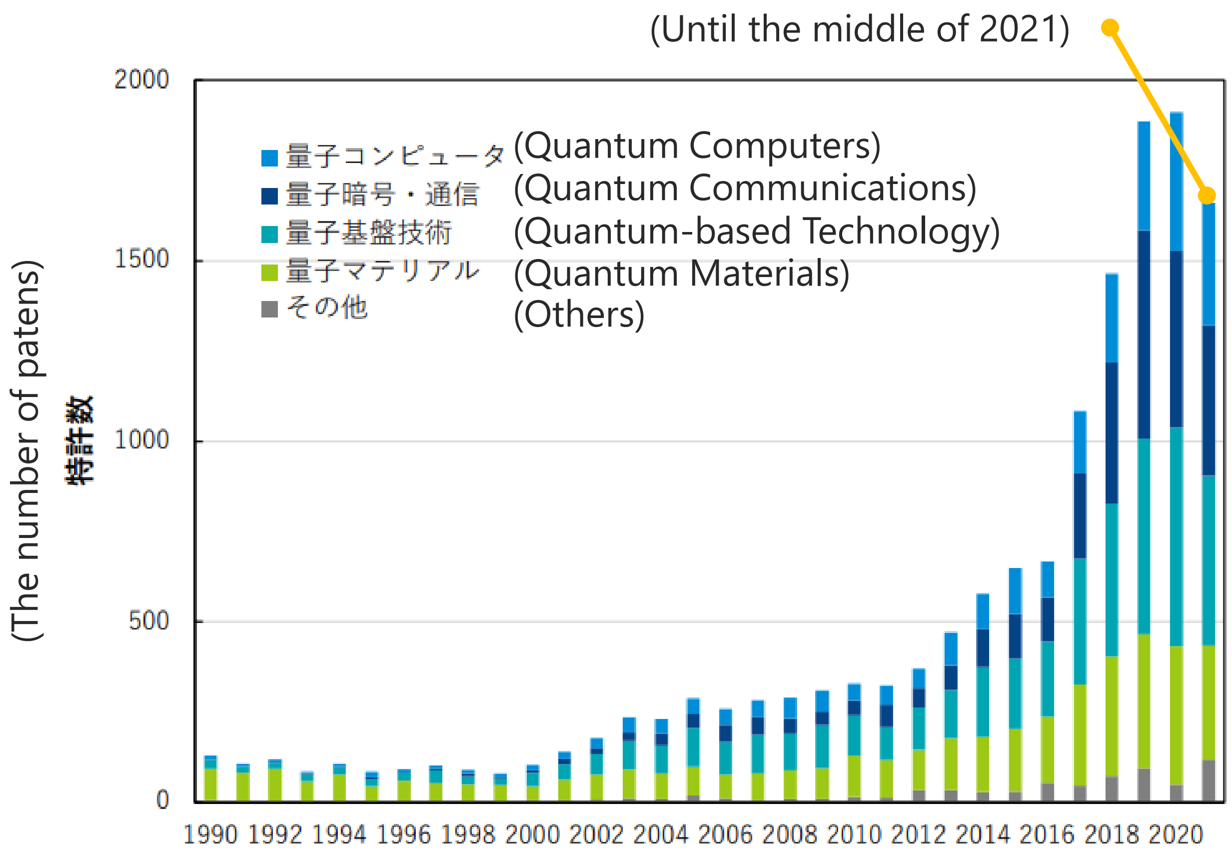
Action Items	Implementation Details
(1) Creation of Use Cases	Supporting early market formation and business use
(2) Quantum Computer System Development	**Supply Chain Resilience**
(3) Device/Control Path Design/Manufacturing	Support for large-scale quantum computers, etc.
(4) Fostering Human Resources for the Global Quantum Industry	Training of managers, improvement of user literacy, etc.

Source: Based on Document 2-3 of the 16th Quantum Technology Innovation Conference (Advisory Panel for Strengthening Innovation Policy "Quantum Technology Innovation")

Patent Trends

- Quantum technology patents are rising annually, especially in the U.S. and China.
- Key application areas include medicine, pharmaceuticals, chemicals, and finance.

The Number of Patents for Quantum Technology



Source: Center for Research and Development Strategy, Japan Science and Technology Agency, 論文・特許マップで見る量子技術の国際動向, p.26, 2022

Nationality and Region in Application Fields

Application Areas	Japan	U.S.	Europe	China	Korea	other	sum
Medical & Pharmaceutical	**14**	**104**	**25**	**20**	**2**	**21**	**186**
Finance	**14**	**60**	**6**	**25**	**0**	**8**	**113**
Autonomous driving	1	20	7	5	1	4	38
Logistics & Delivery	28	40	6	12	0	6	92
Space & Military	1	3	4	9	0	2	19
Cryptanalysis	6	19	9	11	4	7	56
Project management	12	11	4	10	0	2	39
Chemistry	**31**	**67**	**15**	**16**	**3**	**11**	**143**
Climate	0	3	2	7	0	2	14
Transportation facilities	8	9	11	14	1	3	46
Energy	6	19	1	35	1	1	63
Other	17	66	22	42	9	7	163

Source: Based on Japan Patent Office, 令和５年度　特許出願技術動向調査報告書(要約)　ー量子計算機関連技術ー, p.61, 2024
Ref. : Current patent trends in the domain of financial software 日経Fintech Camp FinTech Camp 量子コンピューターの最新動向（前編） - レッスン3 各国の政策、特許の動向, 2024

Use Cases in Universal Gate-Based Quantum Computers

- Gate-based Quantum Computers are advancing across various fields, notably finance, chemicals, IT, and manufacturing. However, **it remains at the theoretical verification stage, with no practical use yet.**

	Desk/Theoretical Verification	(Solve Small Problems)	Demonstration Experiment	Business Utilization
Finance	**(1) Determining Option Pricing (JPMorgan, IBM)** **(2) Numerical Computation by Improved QAE (Keio University, IBM, MUFG, Mizuho R&T)**	• Application of Amplitude Encoding Algorithms (Keio University, IBM, Mizuho R&T, MUFG, SONY, SMTB) • Portfolio Optimization with HHL (JP Morgan) • Application to Index Tracking (BBVA)	N/A	
Chemistry	**(3) Modeling Chemical Reactions on Material Surfaces (IBM)** • Energy Calculation using a Variational Quantum Eigenvalue Solver (ExxonMobil, IBM) • Calculation of Chemical Reaction Energy of Lithium-Air Batteries (Mitsubishi Chemical)	• Calculation of Thermodynamic Properties using the VQE Algorithm (ExxonMobil, IBM) • Excited State Energy Calculation for OLED Light-Emitting Materials (Mitsubishi Chemical, IBM, Keio University, JSR) • Photochemical Reaction Analysis by State-Mean Orbital Optimization VQE (QunaSys, Osaka University)	N/A	
IT	• Extractive Document Summarization (JP Morgan) • Representation of Binary Decision Trees using Quantum Circuits (Fraunhofer Society, BASF) • Image Classification by Self-Supervised Quantum Machine Learning (University of Oxford)	**(4) Time Series Forecasting with QML(Quantum Machine Learning) (Barclays Securities)** • Performance Evaluation of Quantum Bayesian Networks (Wichita State University, Boeing)	N/A	
Manufacture	**(5) Optimization of the Vehicle Paint Process (University of Virginia, GM)** • Examination of Automotive Materials using VQE Algorithm (Toyota, QunaSys)	**(6) Classification of Automotive Images by QML (Quantum Machine Learning) (Leiden University, Volkswagen)**	N/A	

Source: Based on The Japan Research Institute, Limited. Hideyuki Mase / Yoshihiro Mino. Fully understanding Quantum Computing. Nikkei Business Publications, 2023, p.184-185

Examples of Initiatives (Finance)

- Quantum Algorithm for accelerating Monte Carlo (QAE) can help make financial tasks, like option pricing, faster.
- QAE needs FTQC (Fault-Tolerant Quantum Computer), so **researchers are working on ways to use it with current quantum computers (NISQ)**. But, **it hasn't been used for practical calculations yet.**

(1) Determining Option Pricing

Abstract

Desk/Theoretical Verification

- Demonstration of speeding up the calculation of option pricing by QAE (Quantum Amplitude Estimation).

Introduction

- Monte Carlo simulations are used to determine option pricing, but the problem is that the amount of computation is large.

Methods and Results

- A quantum computer from IBM with 11 qubits was used.
- In the calculation of the European option, it was demonstrated that there is a possibility of squaring acceleration compared to the classical Monte Carlo simulation.
- In theory, QAE can cut down the number of steps for Monte Carlo simulations. For example, instead of taking 1 million steps like in a classic method, QAE might only need 1,000 steps.

Source: Option Pricing using Quantum Computers (https://arxiv.org/abs/1905.02666)
Ref. : 日経Fintech Camp FinTech Camp 量子コンピューターの最新動向（後編） - レッスン4 量子コンピューターの活用動向（量子ゲート方式）, 2024

(2) Numerical Calculations based on Improved QAE

Abstract

Desk/Theoretical Verification

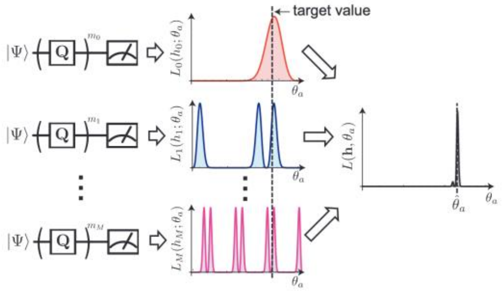
- Demonstration by replacing QPE (quantum phase estimation) with maximum likelihood estimation using a classical computer.

Introduction

- They want the QAE to work on NISQ devices instead of FTQC.
- QPE is a subroutine of QAE, which is one of the reasons that it is difficult to work on NISQ.

Methods and Results

- Repeatedly measure the results after amplitude amplification by QAE.
- Using the obtained values, the amplitude value is estimated using classical maximum likelihood estimation: no QPE is used.



Compute with quantum computer

Calculated in the classical computer

Source: Amplitude estimation without phase estimation (https://arxiv.org/abs/1904.10246v2)

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Examples of Initiatives (Chemistry, Information)

- **Chemistry: While promising**, current quantum computers struggle with large, complex systems.
- **IT:** Efforts are underway **to enhance AI models** (e.g., classification, prediction accuracy).

(3) Modeling of Chemical Reactions on Material Surfaces

Abstract

Desk/Theoretical Verification

- Introducing the workflow for quantum computation of chemical reaction modeling on the surface of materials. As an example, calculations on the dissociation of water on the magnesium surface were carried out.

Introduction

- In today's quantum computers, calculating chemical reactions for large and complex systems is very difficult. The bigger and more complicated the system, the harder it is for quantum computers to handle them.
- It is important to develop a method to divide a large system into problems of a smaller system.

Methods and Results

- Experiments using various IBM quantum computers (5~27 qubits).
- Using VQE, they were able to calculate the energy of the dissociation reaction of water on the surface of magnesium materials with high accuracy.

Source: Quantum Computation of Reactions on Surfaces Using Local Embedding (https://arxiv.org/abs/2203.07536)

(4) Time Series Forecasting by QML

Abstract

Desk/Theoretical Verification

- Predict short-term fluctuations in Apple's stock price and the price of Bitcoin using Quantum machine learning (using QNNs*1) and classical machine learning (using BiLSTM*2).

*1 **Q**uantum **N**eural **N**etwork**s**: quantum algorithms based on parametrized quantum circuits. The weight of classical neural networks (NNs) corresponds to the parameter of the quantum circuit.
*2 **LSTM**(**L**ong **S**hort **T**erm **M**emory): hold some of the input information and perform calculations.

Introduction

- Since QNNs have a small number of parameters to be trained, it is possible to predict time series quickly and efficiently.
- Classical BiLSTM is with thousands of parameters, but QNNs are with only a few parameters.

Methods and Results

- In an experiment to predict future prices using past price data, they showed that both BiLSTM and QNN could predict Apple's stock price and Bitcoin's price with similar accuracy.

Source: Quantum Machine Learning in Finance: Time Series Forecasting (https://arxiv.org/abs/2202.00599)

Examples of Initiatives (Manufacture)

- The automotive industry is at the forefront, using quantum annealing **to solve optimization problems like parts selection and factory work shifts, reducing production costs.**

(5) Optimization of the Vehicle Painting Process

Abstract

Desk/Theoretical Verification

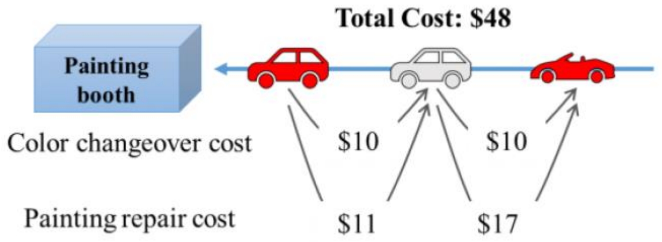
- In the vehicle painting process, reducing costs and paint defects by optimizing the order of the vehicles to be worked.

Introduction

- In a vehicle paint line, changing the paint color between different models costs money. Also, the chance of paint defects can change depending on the order in which the vehicles are painted.

Methods and Results

- Defined the cost of changing the paint and the probability of paint defects as evaluation functions, and the optimal solution is calculated by QAOA (Quantum Approximate Optimization Algorithm).
- In a demonstration, an IBM quantum computer with 9 qubits was used to optimize the order of painting three vehicles (Right Figure).



Source: Paint shop vehicle sequencing based on quantum computing considering color changeover and painting quality (https://arxiv.org/abs/2206.11204)

(6) Classification of Automotive Images by QML

Abstract

Desk/Theoretical Verification

- Propose a method to optimize the hyperparameters of QML (Quantum Machine Learning), which determines a car model by looking at images of the vehicles.

Introduction

- Image recognition algorithms can require a lot of computational resources and effort to adjust hyperparameters.

Methods and Results

- By applying tensor networks, the search space for hyperparameters is compressed.
- The quantum-classical hybrid machine learning model (the neural network) is used to identify a car model from car images.
- By combining these, they can achieve the same level of accuracy and speed compared to conventional search methods.

Source: Hyperparameter optimization of hybrid quantum neural networks for car classification (https://arxiv.org/abs/2205.04878)

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Use Cases in Quantum Annealing

- Unlike the quantum gate method, **quantum annealing has real-world applications.** However, **its advantages over classical computers are small, which limits its use in business cases.**

	Desk/Theoretical Verification	Demonstration Experiment	Business Utilization
Finance		• Reverse Stress test (HSBC) • Portfolio Optimization (1QBit, NatWest, etc.) • Stock Position Forecast (Nomura Asset Management, Tohoku University) • Prediction of Fluctuations in Asset Value (Shanghai University, etc.) • Fraudulent Transaction Detection (SMBC Group, Japan Research Institute, NEC) **(1) Finding Optimal Arbitrage Opportunities (1QBit)**	N/A
Chemistry	**(2) Adjusting Parameters in Material Design (University of Tokyo, Waseda University, NIMS)** • Calculation of Structural Similarity of Molecules(Fujitsu)	**(2) Adjusting Parameters in Material Design (University of Tokyo, Waseda University, NIMS)** • Search for Stable Structures of Composite Polymers (Keio University, Fixstars, Waseda University)	N/A
IT	• Clustering of Time Series Data (Volkswagen, Leiden University) • Search Algorithm (Lockheed Martin)	• Clustering of Time Series Data (Volkswagen, Leiden University) • Non-Negative Binary Matrix Decomposition (Los Ramos National Laboratory, NTT DATA, Ochanomizu University, etc.)	**(3) Optimize Television ad Allocation (Recruit)**
Manufacture /Distribution	• Automatic Car Painting Process Sequence Optimization (Volkswagen, Leiden University) • Structural Optimization of Photonic Crystal Lasers (Kyoto University, Keio University, Waseda University)	• Automatic Car Painting Process Sequence Optimization (Volkswagen, Leiden University) • Traffic Optimization (Volkswagen, D-Wave) • Structural Optimization of Photonic Crystal Lasers (Kyoto University, Keio University, Waseda University) **(4) Aircraft Loading Optimization (Airbus)**	• Staffing Optimization (Sumitomo Corporation, Hitachi, Groupnotes , etc.)

Source: Based on The Japan Research Institute, Limited. Hideyuki Mase / Yoshihiro Mino. Fully understanding Quantum Computing. Nikkei Business Publications, 2023, p.219

Examples of Initiatives (Finance, Chemistry)

- **Finance:** Initiatives like **portfolio optimization and asset price forecasting** are underway.
- **Chemistry:** Efforts focus on **reducing experimental costs in material design and new material discovery.**

(1) Finding Optimal Arbitrage Opportunities

Abstract
Demonstration experiment

- When the exchange rates of different currencies are fixed, institutional investors and others look for arbitrage opportunities to make a profit by spotting temporary price differences between cross-currencies.

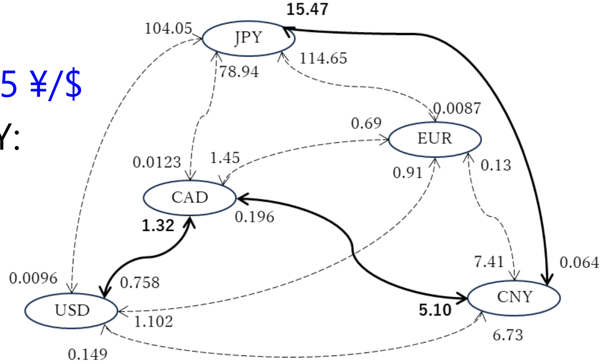
Introduction

- In order to make a profit from arbitrage, it is necessary to quickly find the most profitable price difference between currencies.

Methods and Results

- The conditions of the possible path were formulated, and the optimal exchange route was calculated using quantum annealing (Ignore fees, etc.).
- Direct conversion of USD→JPY: 104.05 ¥/$
- Conversion via USD→CAD→CNY→JPY: 1.32 x 5.10 x 15.47 = 104.14 ¥/$

* If you replace the currencies with transit points and the exchange rates with distances, the problem turns into a shortest path calculation.



Source: https://1qbit.com/whitepaper/arbitrage/

(2) Adjusting Parameters in Material Design

Abstract
Desk/Theoretical Verification

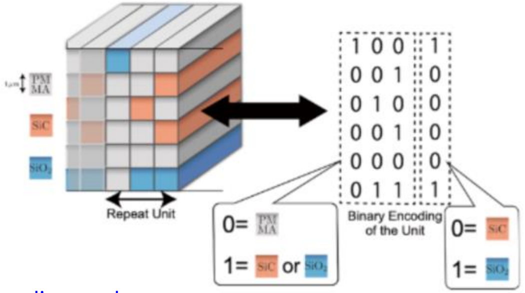
- Search for the optimal material structure of thermal radiation properties calculated by an electromagnetic field analysis method called RCWA (Rigorous Coupled-wave Analysis) using BBO (black-box optimization).

Introduction

- In recent years, the number of parameters to be considered in material design has increased.
- In general, the work of verifying the properties of materials by experiments is enormous in terms of both time and cost, so researchers want to improve efficiency by computer simulation.

Methods and Results

- The material structure is expressed as a binary variable (0/1) (Right Figure).
- Good evaluation results were obtained with a smaller number of samples (≈ number of experiments) than the conventional method.



Source: Koki Kitai, Designing metamaterials with quantum annealing and factorization machines, Phys. Rev. Research, 2020

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Examples of Initiatives (IT, Manufacture/Distribution)

- **IT:** The shift schedule as combinatorial optimization problems are nearing practical application.
- **Manufacturing/Distribution:** Efforts are focused on addressing traffic issues, like selecting optimal routes.

(3) Optimize Television ad Allocation

Abstract

Business Utilization

- Find out which station and at what time a TV commercial should be broadcast.
- Formulated to maximize N-all-reach, which is the number of viewers who watch all kinds of TVCMs more than once.

Introduction

- For each broadcast slot of a TV commercial, the probability that a sample viewer will see the commercial is known.

station	Time Frame					
Station A				・・・		
Station B				・・・		
Station C				・・・		

The probability of seeing a dark blue broadcast slot is high, and the light blue is low.

Methods and Results

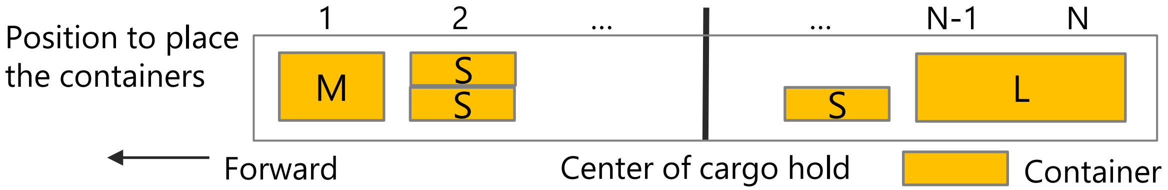
- Using D-Wave's quantum-classical hybrid solver, they solved the optimization problems for up to 500 viewers and obtained a higher N-all-reach than classical solvers.

(4) Aircraft Loading Optimization

Abstract

Demonstration experiment

- Search for the optimal arrangement to load the most cargo containers on an aircraft, and is a competition from Airbus.
- This is a practical problem of arranging three types of containers (L/M/S) while satisfying constraints such as the position of the center of gravity (≈ no extreme bias).



Introduction

- It's difficult to solve optimizations with many constraints, and they want to evaluate the potential of quantum computers in the aircraft industry.

Methods and Results

- A good solution was obtained for the conditions of 35 containers and 20 locations, but the number of qubits was insufficient, and D-Wave's quantum machine was only able to solve small-scale problems.

Source: TV Commercials Allocation for Frequency Optimization: Recruit (Qubits 2023)
Source: Aircraft Loading Optimization -- QUBO models under multiple constraints (https://arxiv.org/abs/2102.09621)

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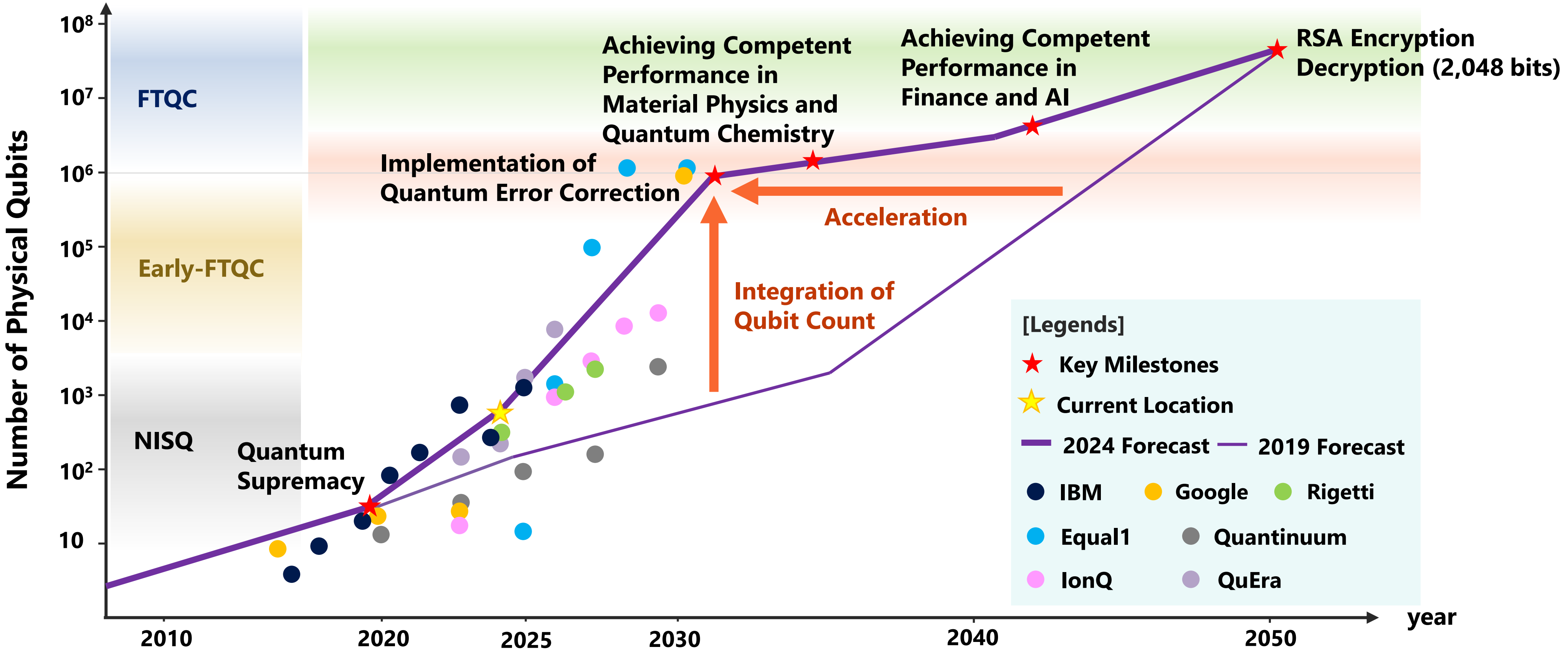
Quantum Computing Roadmap

- Currently, small-scale NISQ with around 1,000 physical qubits exist, but **at least 1 million qubits are needed for FTQC by 2030.**
- While there are promising applications in materials physics and quantum chemistry, **significant improvements** in the number of qubits, error correction, computational speed, and error rates are crucial to achieving this goal.



Source: The Japan Research Institute, Limited. Hideyuki Mase / Yoshihiro Mino. Fully understanding Quantum Computing. Nikkei Business Publications, 2023 , p.248, The Japan Research Institute, Limited, Overview and Trends of Quantum Computing (https://www.jri.co.jp/MediaLibrary/file/column/opinion/pdf/11942.pdf), Fujitsu press release, Fujitsu and Osaka University accelerate progress toward practical quantum computing by significantly increasing computing scale through error impact reduction in quantum computing architecture, Various companies' roadmaps.

Ref. Views on Shor's Algorithms

- In security, Shor's algorithm, which can break RSA encryption, raises concerns about when current ciphers might be compromised.
- Research papers assume that cryptography will not be compromised even with FTQC, which is expected to be realized around 2030, and that further scale-up will be necessary.

Estimating the resources needed to break RSA cryptography (Google, etc.)

- It is estimated that the hardware resources required to run Shor's algorithm on a scale that can crack 2,048 bits of RSA encryption (see figure below).

Number of logical qubits	**14,000**
Number of physical qubits	**23 million**
Number of Toffoli + T gate	**2.7 billion**

Source: Craig Gidney and Martin Eker, How to factor 2048 bit RSA integers in 8 hours using 20 million noisy qubits (https://quantum-journal.org/papers/q-2021-04-15-433/)

Evaluation of the security of RSA cryptography using a quantum simulator (Fujitsu)

- Fujitsu conducted trials using a 39-qubit quantum simulator to evaluate the difficulty of breaking RSA cryptography with quantum computers, applying Shor's algorithm. The study found that cracking RSA encryption would require **FTQC with around 10,000 logical qubits and 2.23 trillion quantum gates.**
- Additionally, it would take approximately 104 days of fault-tolerant quantum computation to accomplish this task—far beyond the current capabilities of quantum computers.
- The research reveals that **the limitations of present quantum computing technology preclude the possibility of this threat in the short term.**

Source: Fujitsu press release, Fujitsu quantum simulator assesses vulnerability of RSA cryptosystem to potential quantum computer cryptography threat (https://www.fujitsu.com/global/about/resources/news/press-releases/2023/0123-01.html)

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Directions of Technological Evolution and Action Plans

- In 2020, practical quantum computing was expected by 2025 but is now delayed to 2030 or later. Investments in future technologies should be made without immediate monetization expectations.

Technology Trends	Directions of Technological Evolution	Example of Action Plans for a Company does Business
Hardware	✓ Superconducting and trapped ion methods are progressing, leading to larger superconducting quantum computers with thousands of physical qubits. ✓ Meanwhile, semiconductors, photonics, and neutral atom methods are also advancing, focusing on demonstrating basic technologies and scalability.	✓ At this point, it is difficult to judge which is the best. ✓ Monitor and comprehend the trends not only in the superconducting method but also in other approaches such as the ion method with great qubit quality and the photonics method that works at room temperature.
Error Correction / Mitigation	✓ Companies, universities, and research institutes are investing in quantum error correction and reduction technologies, advancing basic R&D. ✓ Demonstration experiments with a surface coding system, which is easier to implement on actual machines, are underway.	✓ Considering the ongoing advancements in classical computing, including generative AI, it would be reasonable to remain focused on the use of classical computers while monitoring the latest trends in quantum error correction technology, unless there are substantial breakthroughs.
Cloud Platform / SDK	✓ With improvements in AI-driven coding tools, a wide range of users and researchers can access and use quantum computers via cloud services. ✓ Development of domain-specific, hardware-independent, and highly compatible SDKs is progressing. Many SDKs exist, but those from major cloud companies may dominate.	✓ For the time being, the cloud usage fee is expensive, but experience various hardware and SDKs.
Quantum Algorithms	✓ In the fields of material properties and quantum chemistry, there is a growing number of research papers and initiatives focusing not only on NISQ but also on future-oriented FTQC algorithms.	✓ Learn typical quantum algorithms in a hands-on format. ✓ Investigate the latest quantum algorithms and discuss the possibility of using them based on correct knowledge.
Quantum Annealing	✓ By using classical computers together, it will be possible to solve large-scale problems that could not be solved with current quantum annealing machines. ✓ Mainly in the fields of materials and chemistry, some of the existing machine learning methods are using Black-Box Optimization using quantum annealing.	✓ Since no suitable application has been found for quantum annealing, consider whether to tackle it based on your company's business strategic priorities.
Quantum-Inspired	✓ Mainly for machine learning, there is a growing movement to explore applications for the use of tensor networks. ✓ Pseudo-annealing using dedicated hardware is likely to see only slow growth.	✓ Tensor networks should be considered as a new algorithm in classical computers, and it is necessary to evaluate whether to pursue efforts in this area.

What do Companies need to do now

- We suggest identifying a consortium or community that aligns with your company's needs and training enough specialized professionals to implement quantum algorithms.

		View	Example of Action Plans for a User Company
Market Trends	**Policy Trends**	✓ Countries worldwide will invest heavily to accelerate technological advancements. ✓ Funding will support R&D, industry-government-academia collaboration, start-ups, quantum education content, and a robust supply chain.	✓ Utilizing industry-government-academia consortiums, etc., conduct joint research with universities, research institutes, startups, etc. ✓ Utilize quantum education content to acquire quantum software technology in the medium to long term.
Market Trends	**Market Trends**	✓ Without significant advancements, investment in quantum computers is limited, making it challenging for some companies to secure funding. ✓ Some companies are focusing on demonstration experiments, while others are choosing to stay quiet.	✓ Identify leading players such as start-ups and explore the possibility of future collaboration. ✓ Bring in a use case that is suitable for your company and participate in an academic project.
Market Trends	**Patent Trends**	✓ Companies, universities, and research institutions in the United States and China are likely to increase their patent applications for various hardware implementation methods and quantum algorithms, particularly for defense purposes.	✓ Investigate patent trends in quantum algorithms, software, and more. At the same time, they pay close attention to industry trends related to their own business.
Usage Trends	**Quantum Gates**	✓ Focusing on finance, chemistry, information, and manufacturing, quantum computer-related companies and major user companies will collaborate to identify use cases and develop new and improved quantum algorithms. ✓ For limited use cases, a realistic roadmap for achieving quantum superiority is presented.	✓ Identify algorithms that can be used in your business and understand their research trends. ✓ In order not to fall behind in the future, we will continuously invest in human resource development and research activities. Build a small-scale quantum computing organization and work strategically.
Usage Trends	**Quantum Annealing**	✓ With a focus on optimization, the number of cases of practical application in areas such as finance and chemistry will increase. (However, quantum superiority is unclear.) ✓ It can be used in conjunction with classical computers to solve large-scale problems.	✓ It is valuable to approach optimization problems such as financial engineering with a combinatorial optimization problem approach. ✓ However, since quantum superiority has not been demonstrated, we choose a method that is easier to tackle than classical approaches.

Ref. Use Cases in Universal Gate-Based Quantum Computers (1/2)

＜Finance＞

- **Determining Option Pricing (JPMorgan, IBM)**
  Nikitas Stamatopoulos and Daniel J. Egger and Yue Sun and Christa Zoufal and Raban Iten and Ning Shen and Stefan Woerner, Option Pricing using Quantum Computers, Quantum 4, 291 (2020)
- **Numerical Computation by Improved QAE (Keio University, IBM, MUFG, Mizuho R&T)**
  Yohichi Suzuki and Shumpei Uno and Rudy Raymond and Tomoki Tanaka and Tamiya Onodera and Naoki Yamamoto, Amplitude estimation without phase estimation, Quantum Information Processing (2020)
- **Application of Amplitude Encoding Algorithms (Keio University, IBM, Mizuho R&T, MUFG, SONY, SMTB)**
  Kouhei Nakaji and Shumpei Uno and Yohichi Suzuki and Rudy Raymond and Tamiya Onodera and Tomoki Tanaka and Hiroyuki Tezuka and Naoki Mitsuda and Naoki Yamamoto, Approximate amplitude encoding in shallow parameterized quantum circuits and its application to financial market indicators, Physical Review Research (2022)
- **Portfolio Optimization with HHL (JP Morgan)**
  Romina Yalovetzky and Pierre Minssen and Dylan Herman and Marco Pistoia, NISQ-HHL: Portfolio Optimization for Near-Term Quantum Hardware, arXiv2110.15958 (2021)
- **Application to Index Tracking (BBVA)**
  Samuel Fernandez-Lorenzo and Diego Porras and Juan Jose Garcia-Ripoll, Hybrid quantum-classical optimization with cardinality constraints and applications to finance, Quantum Science and Technology 6-3-034010 (2021)

＜Chemistry＞

- **Modeling Chemical Reactions on Material Surfaces (IBM)**
  Tanvi P. Gujarati, et al, Quantum Computation of Reactions on Surfaces Using Local Embedding, arXiv:2203.07536 (2022)
- **Energy Calculation using a Variational Quantum Eigenvalue Solver (ExxonMobil, IBM)**
  Spencer T. Stober, Stuart M. Harwood, Dimitar Trenev, Panagiotis Kl. Barkoutsos, Tanvi P. Gujarati, and Sarah Mostame, Considerations for evaluating thermodynamic properties with hybrid quantum-classical computing work flows, Phys. Rev. A 105, 012425 (2022)
- **Calculation of Chemical Reaction Energy of Lithium-Air Batteries (Mitsubishi Chemical)**
  https://www.nikkei.com/article/DGKKZO66383170Z21C22A1XY0000/
- **Calculation of Thermodynamic Properties using the VQE Algorithm (ExxonMobil, IBM)**
  Spencer T. Stober, Stuart M. Harwood, Dimitar Trenev, Panagiotis Kl. Barkoutsos, Tanvi P. Gujarati, and Sarah Mostame, Considerations for evaluating thermodynamic properties with hybrid quantum-classical computing work flows, Phys. Rev. A 105, 012425 (2022)
- **Excited State Energy Calculation for OLED Light-Emitting Materials (Mitsubishi Chemical, IBM, Keio University, JSR)**
  有機EL発光材料性能予測に関する研究成果がNature専門誌に掲載ー量子コンピューター実機を用いた有機EL発光材料の励起状態計算に世界で初めて成功ー, https://www.keio.ac.jp/ja/press-releases/2021/5/26/28-80161/

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Ref. Use Cases in Universal Gate-Based Quantum Computers (2/2)

＜Chemistry＞

- **Photochemical Reaction Analysis by State-Mean Orbital Optimization VQE (QunaSys, Osaka University)**
  Keita Omiya, Yuya O. Nakagawa, Sho Koh, Wataru Mizukami, Qi Gao, and Takao Kobayashi, Analytical Energy Gradient for State-Averaged Orbital-Optimized Variational Quantum Eigensolvers and Its Application to a Photochemical Reaction, Journal of Chemical Theory and Computation Vol 18 (2022)

＜Information＞

- **Extractive Document Summarization (JP Morgan)**
  Pradeep Niroula, Ruslan Shaydulin, Romina Yalovetzky, Pierre Minssen, Dylan Herman, Shaohan Hu, Marco Pistoia, Constrained Quantum Optimization for Extractive Summarization on a Trapped-ion Quantum Computer, Scientific Reports Vol.12-1 (2022)
- **Representation of Binary Decision Trees using Quantum Circuits (Fraunhofer Society, BASF)**
  Songfeng Lu, Samuel L. Braunstein, Quantum decision tree classifier, Quantum Information Processing 13(3) (2014)
- **Image Classification by Self-Supervised Quantum Machine Learning (University of Oxford)**
  Ben Jaderberg, Lewis W. Anderson, Weidi Xie, Samuel Albanie, Martin Kiffner, Dieter Jaksch, Quantum Self-Supervised Learning, arXiv:2103.14653 (2021)
- **Time Series Forecasting with QML(Quantum Machine Learning) (Barclays Securities)**
  Dimitrios Emmanoulopoulos and Sofija Dimoska, Quantum Machine Learning in Finance: Time Series Forecasting, arXiv2202.00599 (2022)
  日本総研 身野 良寛. 量子ニューラルネットワークで時系列データ予測 #量子コンピュータ - Qiita
- **Performance Evaluation of Quantum Bayesian Networks (Wichita State University, Boeing)**
  Sima E. Borujeni and Nam H. Nguyen and Saideep Nannapaneni and Elizabeth C. Behrman and James E. Steck, Experimental evaluation of quantum Bayesian networks on IBM QX hardware, arXiv2005.12474 (2020)

＜Manufacture＞

- **Optimization of the Vehicle Paint Process (University of Virginia, GM)**
  Jing Huang, Hua-Tzu Fan, Guoxian Xiao, Qing Chang, Paint shop vehicle sequencing based on quantum computing considering color changeover and painting quality, arXiv 2206.11204 (2022)
- **Examination of Automotive Materials using VQE Algorithm (Toyota, QunaSys)**
  菅 義訓、高 翔、芝宮 徹、楊 天任, 量子コンピューティングの自動車材料デザインへの適用可能性, 自動車技術会論文集 54 (1), 200-205 (2023)
- **Classification of Automotive Images by QML(Quantum Machine Learning) (Leiden University, Volkswagen)**
  Asel Sagingalieva, Mo Kordzanganeh, Andrii Kurkin, Artem Melnikov, Daniil Kuhmistrov, Michael Perelshtein, Alexey Melnikov, Andrea Skolik, David Von Dollen, Hyperparameter optimization of hybrid quantum neural networks for car classification, arXiv 2205.04878 (2022)

Ref. Use Cases in Quantum Annealing (1/2)

＜**Finance**＞

- **Reverse Stress Test (HSBC)**
  Quantitative Reverse Stress Testing using Simulated and Quantum Annealing Applied to XVA, https://www.dwavesys.com/resources/application/quantitative-reverse-stress-testing-using-simulated-and-quantum-annealing-applied-to-xva/
- **Stock Position Forecast (Nomura Asset Management, Tohoku University)**
  Masayuki Ohzeki, Challenging Collaborations with T-QARD, Qubits Europe 2019, https://www.dwavesys.com/media/20jlrutg/24_qubits2019327-2.pdf
- **Prediction of Fluctuations in Asset Value (Shanghai University, etc.)**
  Yongcheng Ding, Javier Gonzalez-Conde, Lucas Lamata, José D. Martín-Guerrero, Enrique Lizaso, Samuel Mugel, Xi Chen, Román Orús, Enrique Solano, Mikel Sanz, Towards Prediction of Financial Crashes with a D-Wave Quantum Computer, arXiv:1904.05808 (2019)
- **Fraudulent Transaction Detection (SMBC Group, Japan Research Institute, NEC)**
  量子アニーリングの業務活用に向けた共同研究, https://www.jri.co.jp/page.jsp?id=38496
- **Portfolio Optimization (1QBit, NatWest, etc.)**
  Quantum-Inspired Hierarchical Risk Parity, https://1qbit.com/whitepaper/quantum-inspired-hierarchical-risk-parity
- **Finding Optimal Arbitrage Opportunities (1QBit)**
  Finding Optimal Arbitrage Opportunities Using a Quantum Annealer, https://1qbit.com/whitepaper/arbitrage/

＜**Chemistry**＞

- **Adjusting Parameters in Material Design (University of Tokyo, Waseda University, NIMS)**
  Koki Kitai, Jiang Guo, Shenghong Ju, Shu Tanaka, Koji Tsuda, Junichiro Shiomi, and Ryo Tamura, Designing metamaterials with quantum annealing and factorization machines, Phys. Rev. Research 2, 013319 (2020)
- **Search for Stable Structures of Composite Polymers (Keio University, Fixstars, Waseda University)**
  Katsuhiro Endo, A phase-field model by an Ising machine and its application to the phase-separation structure of a diblock polymer, Sci Rep 12, 10794 (2022)
- **Calculation of Structural Similarity of Molecules(Fujitsu)**
  デジタルアニーラの原理と材料開発への応用, https://www.jstage.jst.go.jp/article/vss/63/3/63_20180509/_pdf/-char/ja

Ref. Use Cases in Quantum Annealing (2/2)

＜IT＞

- **Clustering of Time Series Data (Volkswagen, Leiden University)**
  Sheir Yarkoni, Andrii Kleshchonok, Yury Dzerin, Florian Neukart, Marc Hilbert, Semi-supervised time series classification method for quantum computing, arXiv:2006.11031 (2020)
- **Search Algorithm (Lockheed Martin)**
  Robert A. Dunn, Searching and Sorting Algorithms for Quantum Annealing Computers, arXiv:2204.13233 (2022)
- **Non-Negative Binary Matrix Decomposition (Los Ramos National Laboratory, NTT DATA, Ochanomizu University, etc.)**
  Daniel O'Malley, Velimir V. Vesselinov, Boian S. Alexandrov, Ludmil B. Alexandrov, Nonnegative/binary matrix factorization with a D-Wave quantum annealer, arXiv:1704.01605 (2017)
- **Optimize Television ad Allocation (Recruit)**
  TV Commercials Allocation for Frequency Optimization: Recruit, Qubits 2023, https://www.youtube.com/watch?v=GRpl2QQumLU

＜Manufacture/Distribution＞

- **Automatic Car Painting Process Sequence Optimization (Volkswagen, Leiden University)**
  Sheir Yarkoni, Alex Alekseyenko, Michael Streif, David Von Dollen, Florian Neukart, Thomas Bäck , Multi-car paint shop optimization with quantum annealing, arXiv:2109.07876 (2021)
- **Structural Optimization of Photonic Crystal Lasers (Kyoto University, Keio University, Waseda University)**
  量子アニーリングを活用したフォトニック結晶レーザーの構造最適化に成功 ―量子計算技術を活用したスマート製造分野の発展に向けて―, https://www.keio.ac.jp/ja/press-releases/files/2022/9/9/220909-2.pdf
- **Traffic Optimization (Volkswagen, D-Wave)**
  Florian Neukart, Gabriele Compostella, Christian Seidel, David von Dollen, Sheir Yarkoni, Bob Parney, Traffic flow optimization using a quantum annealer, arXiv:1708.01625 (2017)
- **Aircraft Loading Optimization (Airbus)**
  2020 Airbus Quantum Computing Challenge, https://www.airbus.com/en/innovation/disruptive-concepts/quantum-technologies/airbus-quantum-computing-challenge
- **Staffing Optimization (Sumitomo Corporation, Hitachi, Groupnotes, etc.)**
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  勤務シフト最適化ソリューション, https://www.hitachi.co.jp/products/it/finance/solutions/application/common/CMOS-PersonnelShift/index.html
  グルーヴノーツ、量子コンピュータ技術を活用した「スケジューリング最適化」パッケージを正式リリース, https://www.groovenauts.jp/wp-content/uploads/2019/12/20191220.pdf

Update History

Ver.	Publication Date	Main Updates
1.0	January 15, 2025	Initial Edition