Fujitsu and Osaka University accelerate progress toward practical quantum computing by significantly increasing computing scale through error impact reduction in quantum computing architecture

New technologies establish method to run practical quantum algorithms faster than current classical computers with fewer qubits

August 28, 2024
Osaka University
Fujitsu Limited

Introduction to Osaka University's quantum computing research activities

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What is a Quantum computer (QC)?

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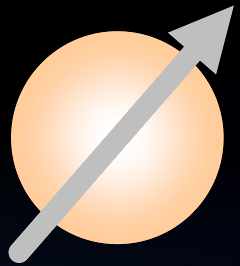
- QCs will dramatically speed up calculations through quantum mechanical phenomena.

Current computer

Either 0 or 1

Quantum computer

Superposition of 0 and 1



2^N serial computations ⟵ N bit ⟶ 2^N parallel computations by quantum entanglement

Exponential speed increase

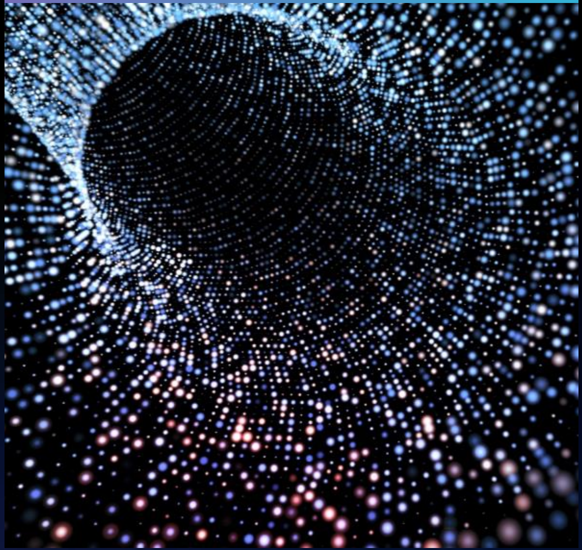
Issues expected to be solved by QCs

- Complicated calculations that cannot be solved quickly and to high degree of precision using current computers

Discovery of new materials and medicines

Predicting financial and economic trends

Discovery of new principles to transform industries



Quantum error correction (QEC)

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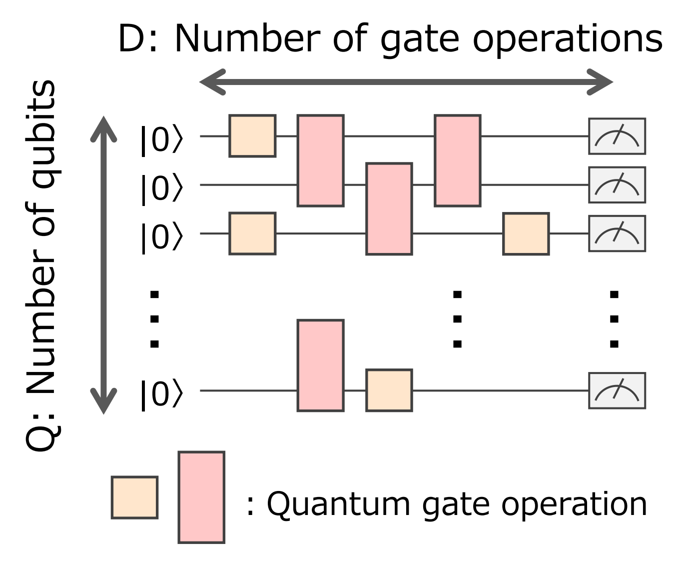
- **Quantum error: noise changes the state of the qubit, leading to incorrect calculations**
  - Noise source: environment (thermal noise, etc.), control signal (fluctuation, etc.)
- **Fidelity of the overall calculation**
  $=(\text{fidelity of qubit})^{(Q \times D)}$
  - e.g. $(0.999)^{(50 \text{ qubits} \times 20 \text{ gate operations})} = 0.368$
- **In QEC, one logical qubit is formed from many physical qubits**
  - Redundancy protects from quantum errors



Physical qubit Logical qubit

Fault-tolerant QC（FTQC）

- **Framework for performing calculations with QEC.**
- **Combination of universal gates (operations on logical qubits) realizes all kinds of quantum calculations.**

Universal gate set（equivalent to AND, XOR, NOT in a current computer）

FTQC Architecture

Logical-CNOT gate	Logical-S gate
Logical-H gate	Logical-T gate

Ex）Phase rotation gate U with angle $\pi/128^*$

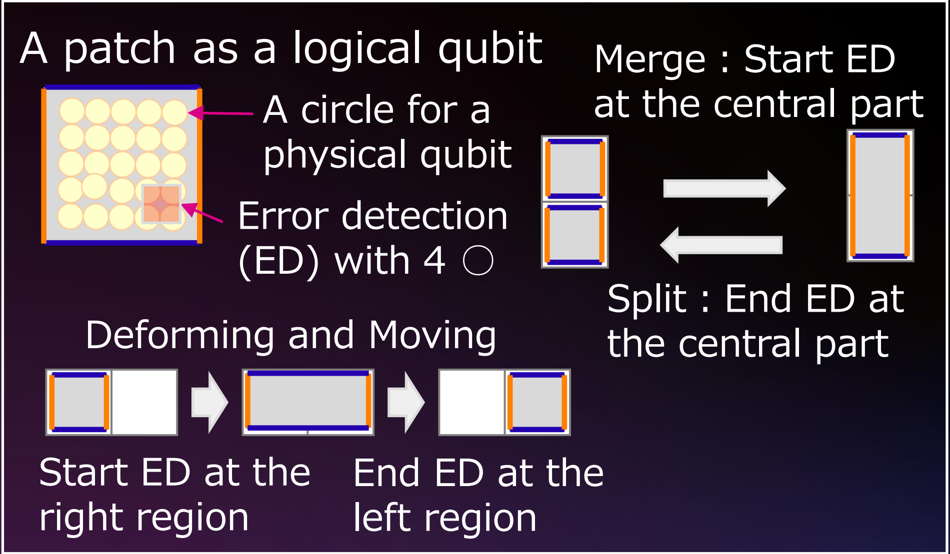
$$\begin{aligned} U = \ &\mathrm{HTSHTSHTSHTHTHTHTSHTHTSHTSHTSHTHTHTSHTSHTHTHTSHTHTSHTHTHTHTHTHTHTSHTSHT} \\ &\mathrm{SHTHTSHTHTSHTHTHTHTSHTHTHTSHTHTSHTHTHTHTSHTSHTSHTHTHTSHTSHTSHTSHTHTSHTS} \\ &\mathrm{HTSHTSHTHTSHTHTSHTSHTHTHTHTHTSHTHTHTHTSHTSHTSHTHTSHTSHTHTHTSHTHTHTHTHTS} \\ &\mathrm{HTSHTHTHTHTHTSHTHTHTHTSHTHTHTHTHTHTH}\omega^7 \end{aligned}$$

* N.Ross and P. Selinger, *Quantum Information and Computation,* **16** (2016).

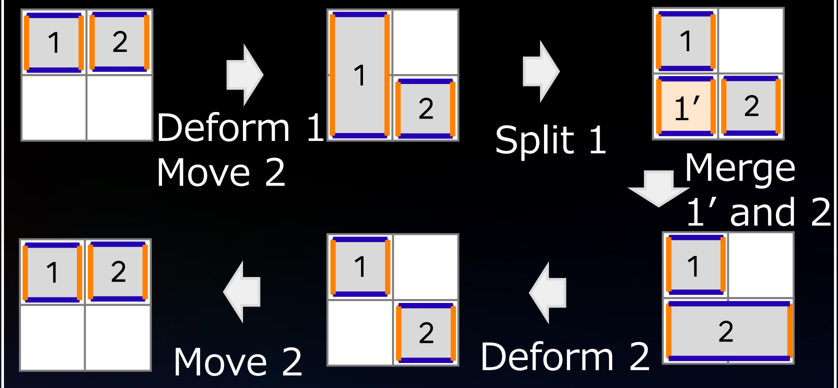
Operations on logical qubits

- **Complicated operations called lattice surgery*1**

Basic operations in Lattice surgery*2



Example of Logical-CNOT gate



5 steps are necessary in this example
Additional working space is needed

*1 C. Horsman, *et al.*, *New Journal of Physics*, **14**, 123011 (2012).
*2 Assuming surface codes（A. Kitaev, *Ann. Phys.*, **303**, 2 (2003).）

Osaka University's QC activities

- **Center for Quantum Information and Quantum Biology (QIQB) established in March 2020**
  - The center consists of six research groups:
    - Quantum Computing, Quantum Information Fusion, Quantum Information Devices, Quantum Communications & Security, Quantum Measurement & Sensing, and Quantum Biology
  - The center promotes research among these and other academic fields
  - Selected as a **Quantum Software Research Hub** in the quantum technology field under the “COI-NEXT*” of JST**

*COI-NEXT: Program on Open Innovation Platforms for Industry-academia Co-creation
**JST: Japan Science and Technology Agency

QIQB center plays an important role in Japan's quantum technology innovation strategy

Fujitsu's QC research activities and new technologies for the quantum computing architecture

Speaker : Shintaro Sato
Fellow
Head of Quantum Laboratory
Fujitsu Research
Fujitsu Limited

Fujitsu's Strategy for QC

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- Cover all the technology layers with the world's leading research institutions
- Put emphasis on software technologies, while working on several types of hardware
- Utilize Fujitsu Hybrid Quantum Computing Platform to develop applications with early input from end users

Quantum Application

Research with end-user input: Materials, Drug discovery, Finance, etc.

- **FUJIFILM, Tokyo Electron, etc.**
- **TU Delft**

Quantum Software

- **QunaSys** Algorithm
- **Keysight Technologies** Error Suppression
- **Osaka Univ.** Error Correction, Cloud Technology

Quantum Platform

Middleware, Compiler

Quantum State Control

Quantum Device & Integration

- **RIKEN** Superconducting Qubit
- **TU Delft** Diamond Spin Qubit
- Exploring other possibilities, Neutral Atom etc.

Organization for joint research

- **Joint press release by Osaka univ. and Fujitsu(Oct. 1, 2021)**

Fujitsu and Osaka University Deepen Collaborative Research and Development for Fault-Tolerant Quantum Computers

Osaka University, Fujitsu Limited

News Facts:

- Osaka University and Fujitsu established the Fujitsu Quantum Computing Joint Research Division as a collaborative research program of the Center for Quantum Information and Quantum Biology (QIQB) of Osaka University
- The joint research division will combine QIQB's advanced quantum error correction and quantum software technologies with Fujitsu's applied knowledge in computing and quantum technologies to strengthen R&D in fault-tolerant quantum computing technology
- Fault-tolerant quantum computing, capable of accurate and large-scale high-speed calculations using quantum error correction codes offers potential to contribute to further progress in fields like drug discovery and finance

R&D of quantum software for FTQC*:

- Quantum error correction
- Performance evaluation
- Human resource development

*FTQC: Fault-tolerant quantum computing

Fujitsu small research lab set up in Osaka university

Recent topic of joint research

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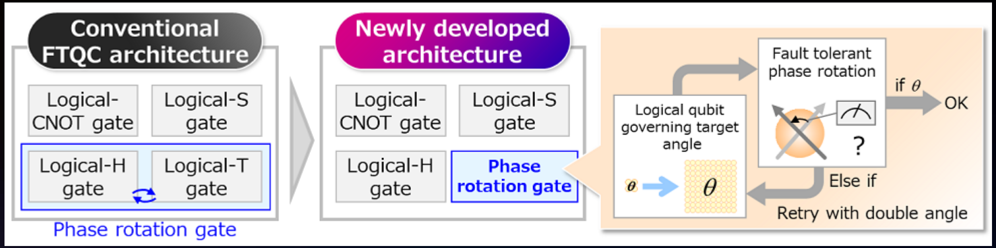
- Original computing architecture (Highly efficient Analog Rotation quantum computing architecture)
- Joint press release and press conference by Osaka univ. and Fujitsu (Mar. 23, 2023)

Fujitsu and Osaka University develop new quantum computing architecture, accelerating progress toward practical application of quantum computers

Realizing highly accurate quantum error correction even for quantum computers with about 10,000 physical qubits

Osaka University, Fujitsu Limited

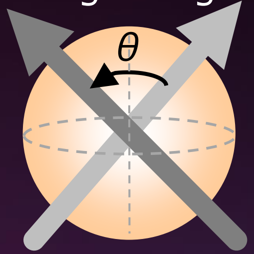


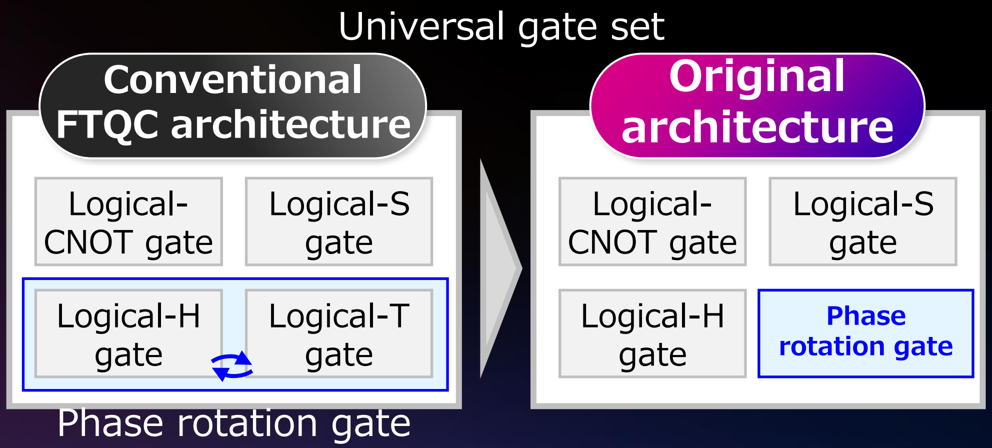
[Fujitsu and Osaka University develop new quantum computing architecture, accelerating progress toward practical application of quantum computers (fujitsu.com)]

Our original architecture

- **Realizing practical quantum computing with fewer qubits**
  - Efficiently perform phase rotation* (essential for quantum computing), reducing the number of qubits and quantum gate operations
  - Accuracy is limited because errors in phase rotation gate cannot be corrected.

Target angle





* Rotating a qubit by an arbitrary phase angle. Conventionally, T or H gate are operated many times.

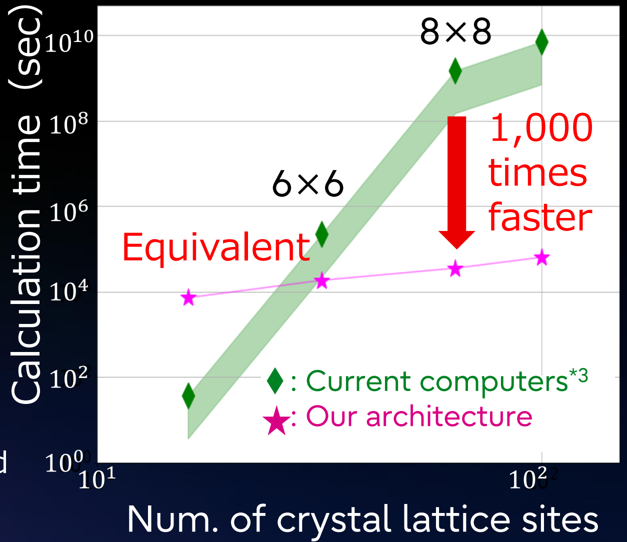
Toward practical application

① Accuracy improvement of phase rotation gate for

② Implementation on quantum computers

Purpose and effect

- **Purpose**
  - **Expanding the computing scale of our original quantum computing architecture and applying it to practical computing**
- **Effect**
  - **Quantum advantage*1 can be achieved in 10,000s of qubits range*2**
  - 40,000 qubits in 6x6 lattice = equivalent to current computers
  - 1,000x calculation speed possible with 60,000 8×8 lattice
    (equivalent of going from 5 years to 10 hours)

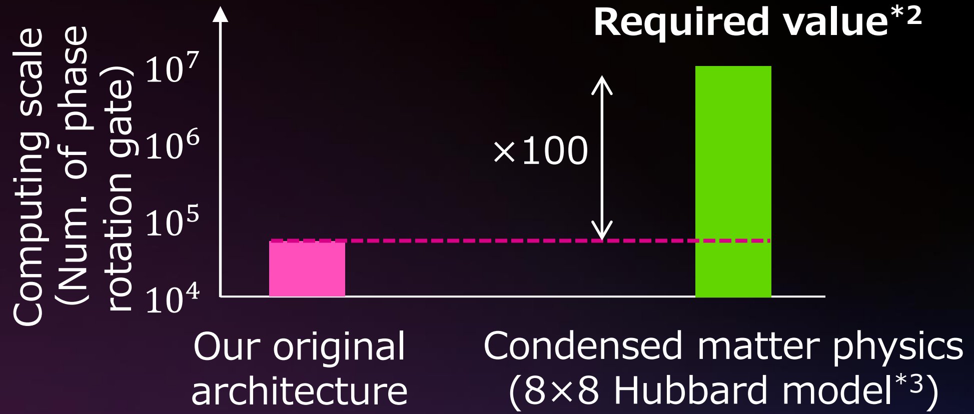


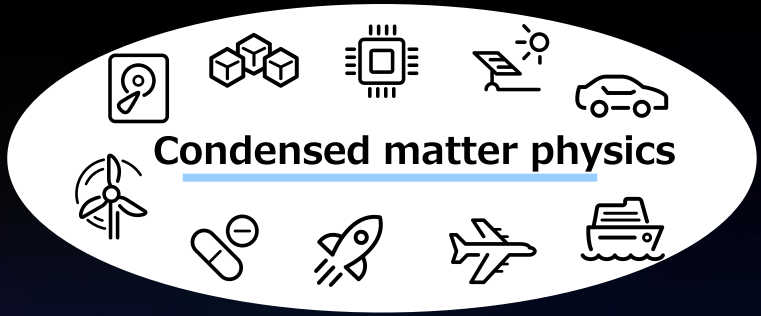
*1 Exceeding the speed of current computers in practical calculations.
*2 Estimation of the num. of qubits and computation time required for the Hubbard model (a model used for the analysis of high-temperature superconductors).
*3 Created with reference to N. Yoshioka, et al., *npj Quantum Inf* **10**, 45 (2024).

① Accuracy improvement of phase rotation gate

Issues of our architecture

- **Accuracy improvement of phase rotation gate is essential for expansion of the computing scale.**
  - Two orders of magnitude less than the scale of condensed matter physics*1



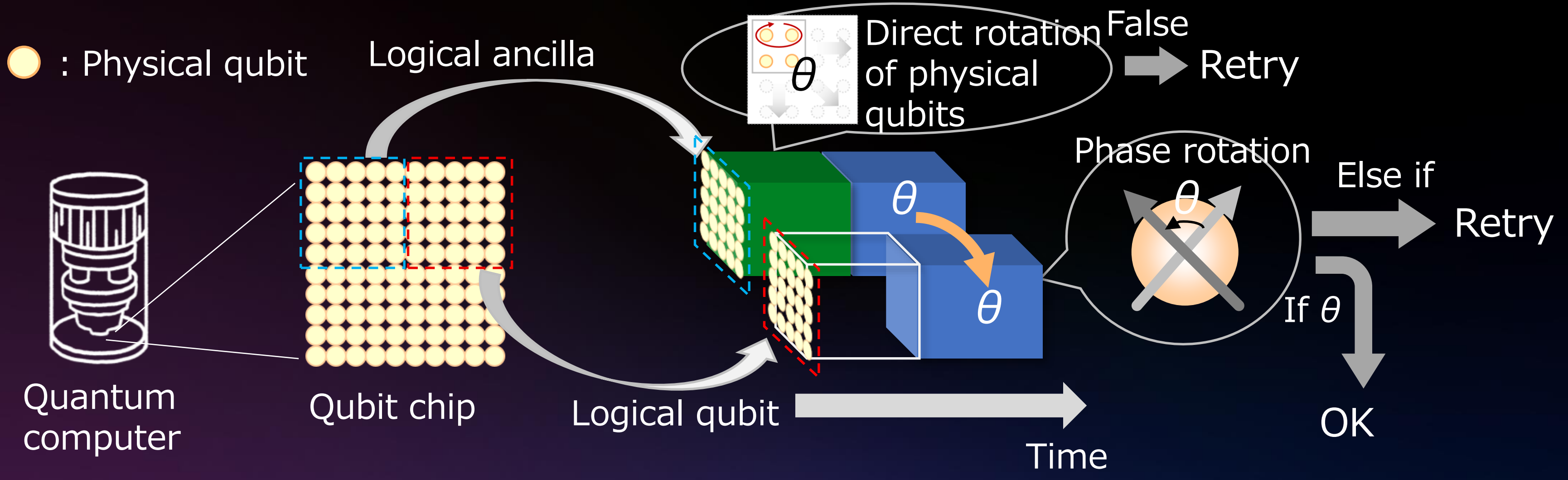


*1 Analyzing the properties of industrial materials such as metals and semiconductors using computational models
*2 Number of phase rotation gates required to estimate electron energy
*3 Used for analysis of high-temperature superconductivity, leading to reduction of transmission loss in electric power infrastructure, etc.

Details of phase rotation gate

- Generate a phase angle and transport it to the qubit*1
- Repeat until success*2

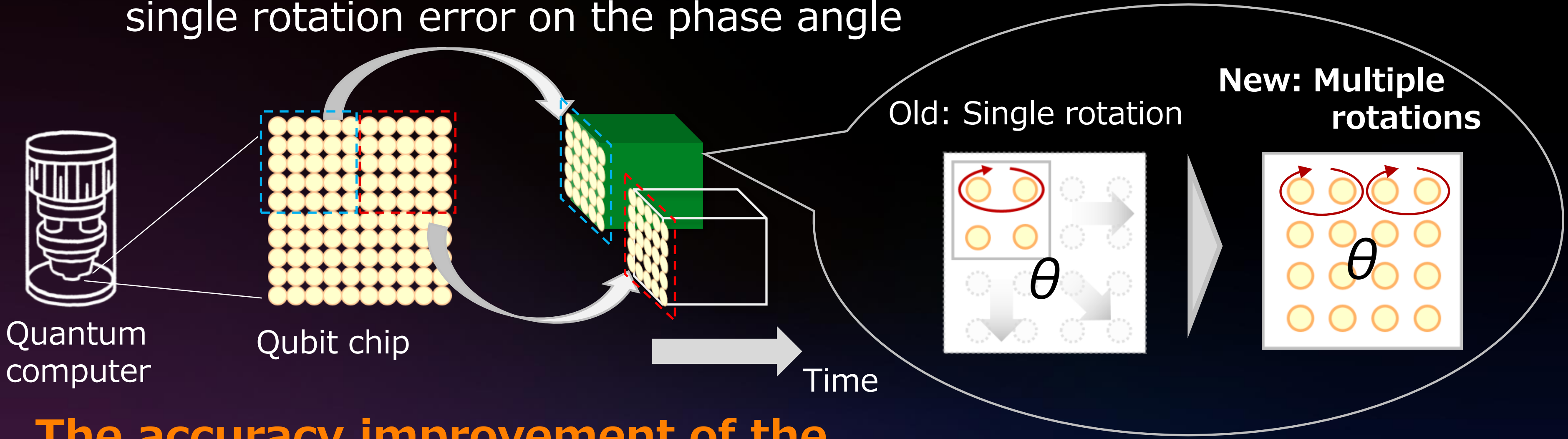
Time lapse of the phase rotation gate
(Green : generating θ、Blue : transfer of θ)



*1 Via an ancilla so as not to destroy the state of the qubit
*2 Both phase angle generation and transportation may fail with a certain probability.

Accuracy improvement

- **Development of new phase angle generation**
  - Making rotation of physical qubits redundant, reducing the effect of a single rotation error on the phase angle



The accuracy improvement of the phase rotation gate leads to 1,000 times greater computing scale

Effect of increasing computing scale

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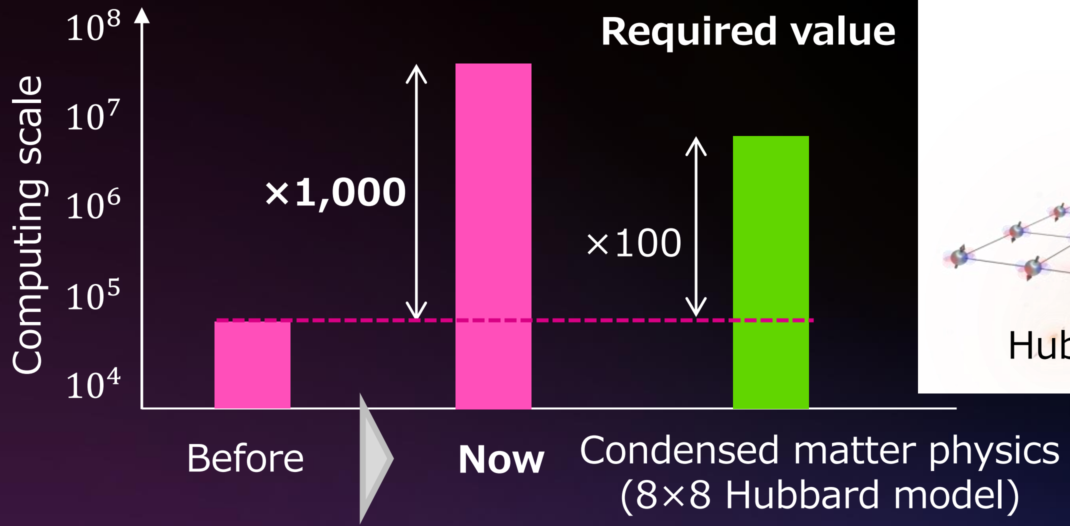
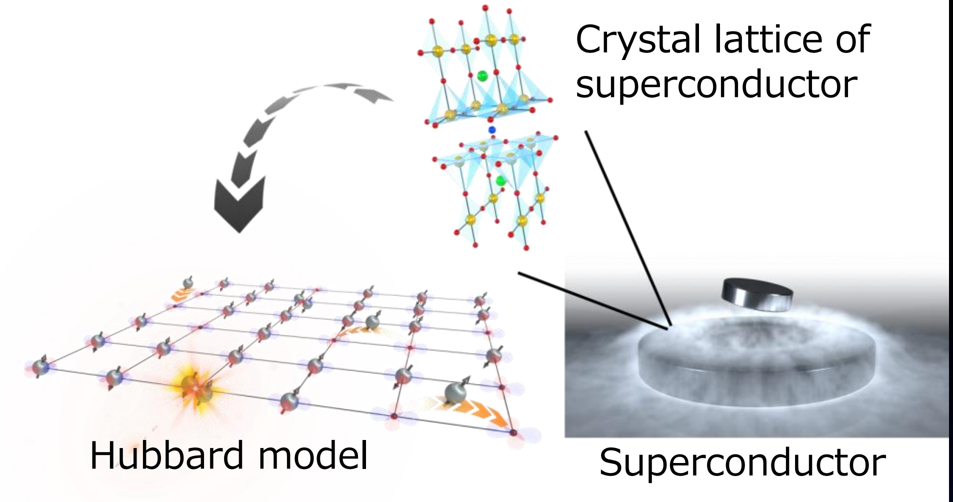
- Analysis of the Hubbard model became possible with this architecture



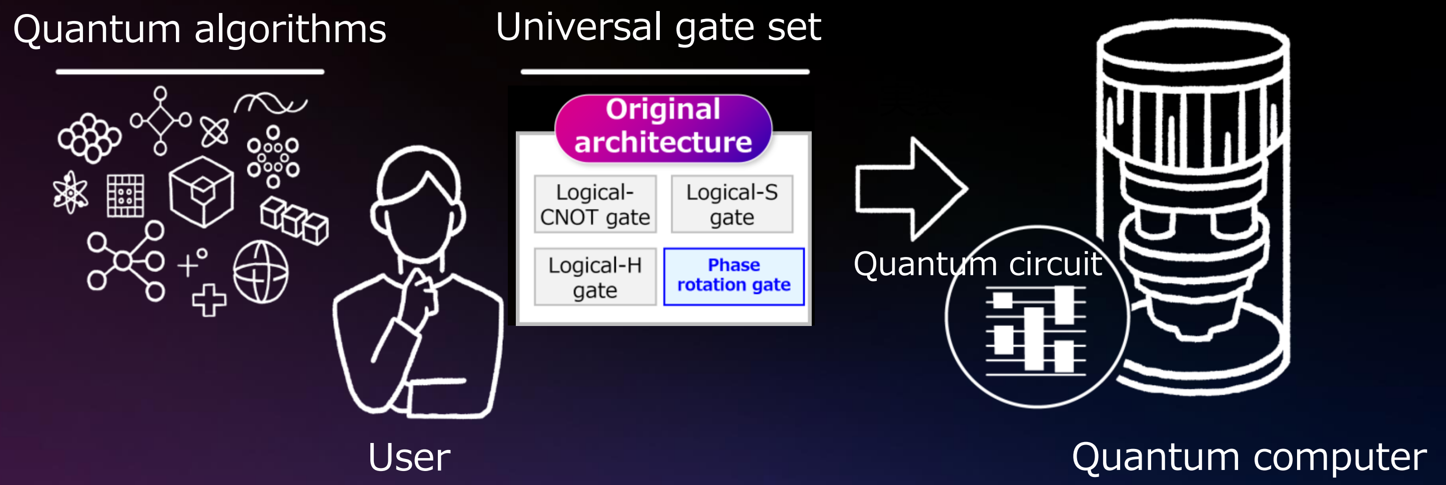


Hubbard model analysis will lead to the discovery of new materials and the reduction of electricity transmission costs

② QC Implementation

Necessity of implementation

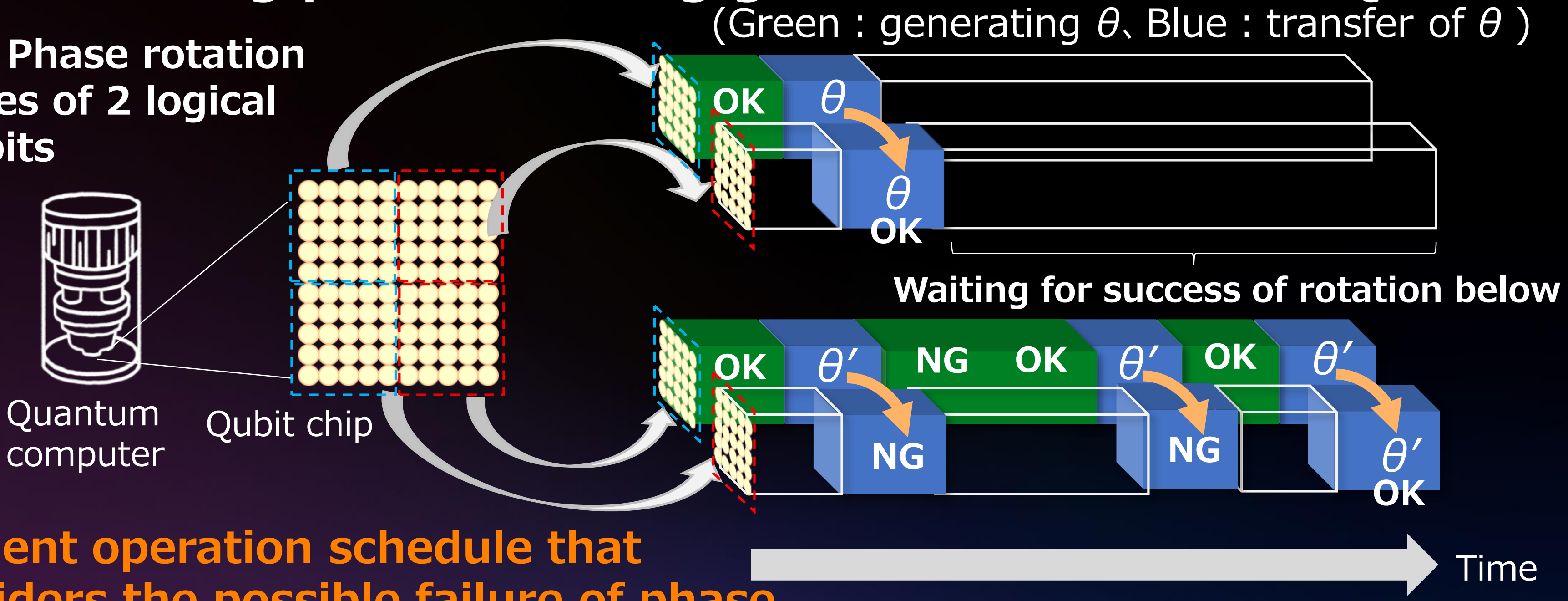
- **QC architecture only proposes basic computational rules**
  - To solve concrete problems, we need to clarify how to operate the qubits according to the rules of the architecture.



Implementation challenges

- **Just adding phase rotating gates can slow down QC**

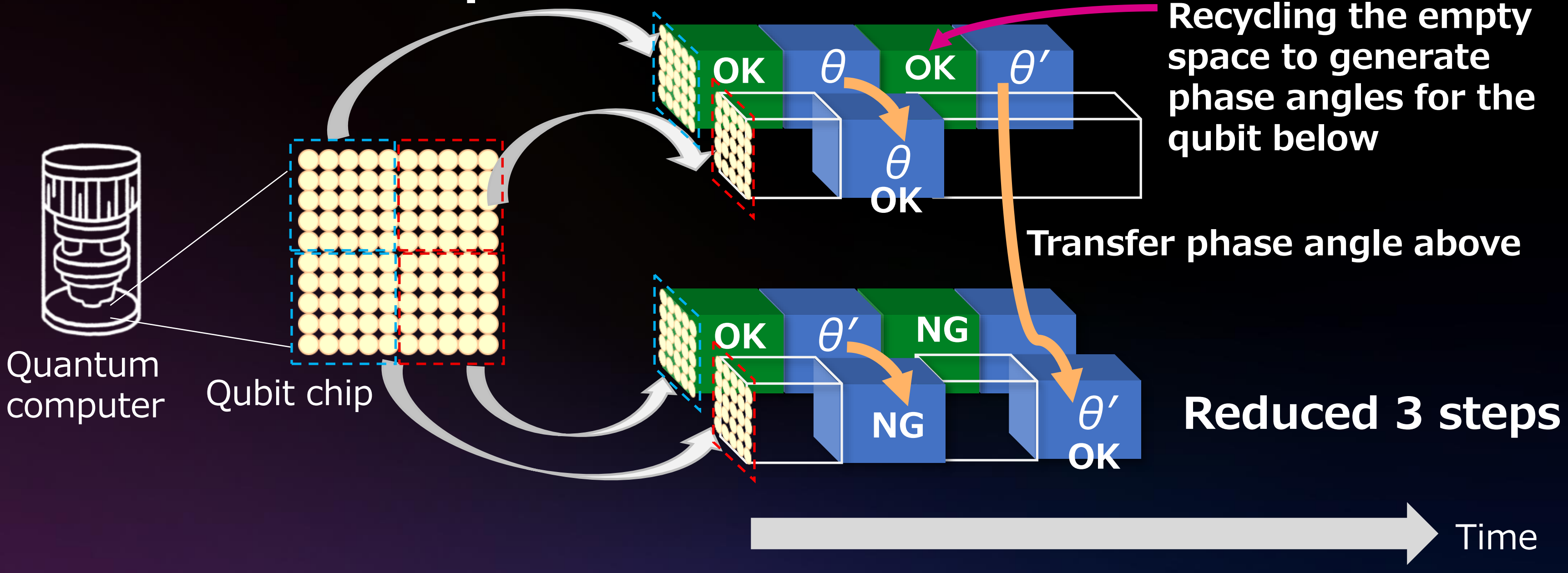
Ex: Phase rotation gates of 2 logical qubits



Efficient operation schedule that considers the possible failure of phase angle generation/transfer is required

Acceleration of phase rotation (1/2)

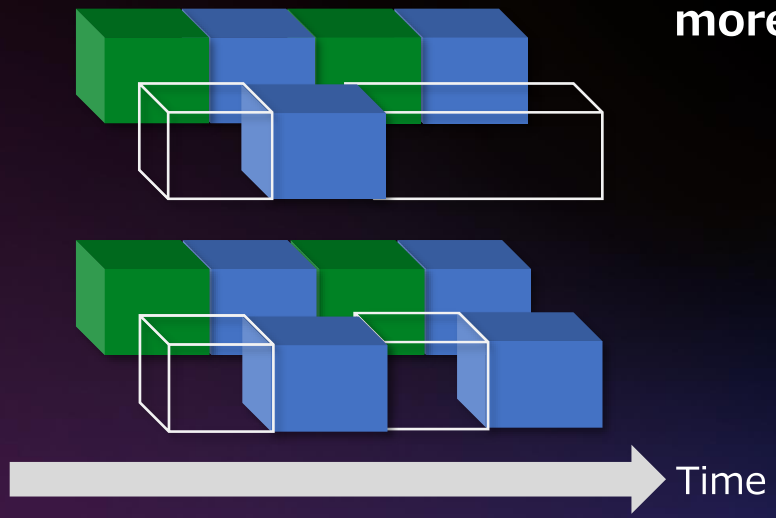
- **Dynamically change the operation schedule of qubits and reduce the impact of failure**



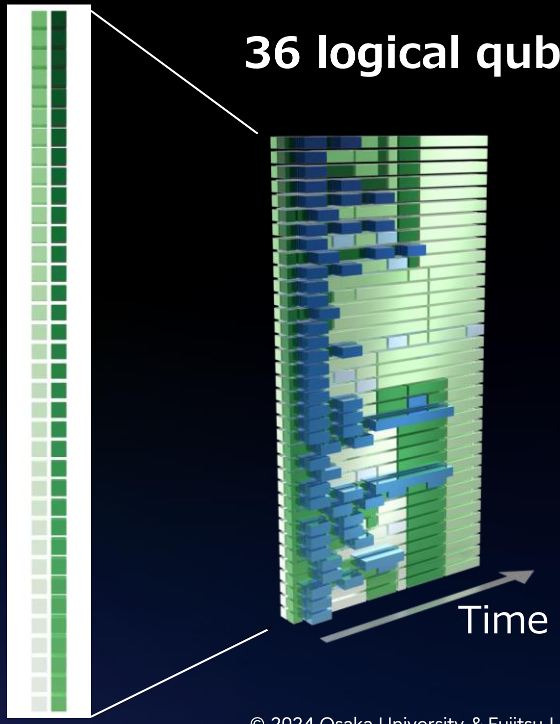
Acceleration of phase rotation (2/2)

- **Optimal parallel execution of phase rotation gates**

Ex: Phase rotation gates of 2 logical qubits

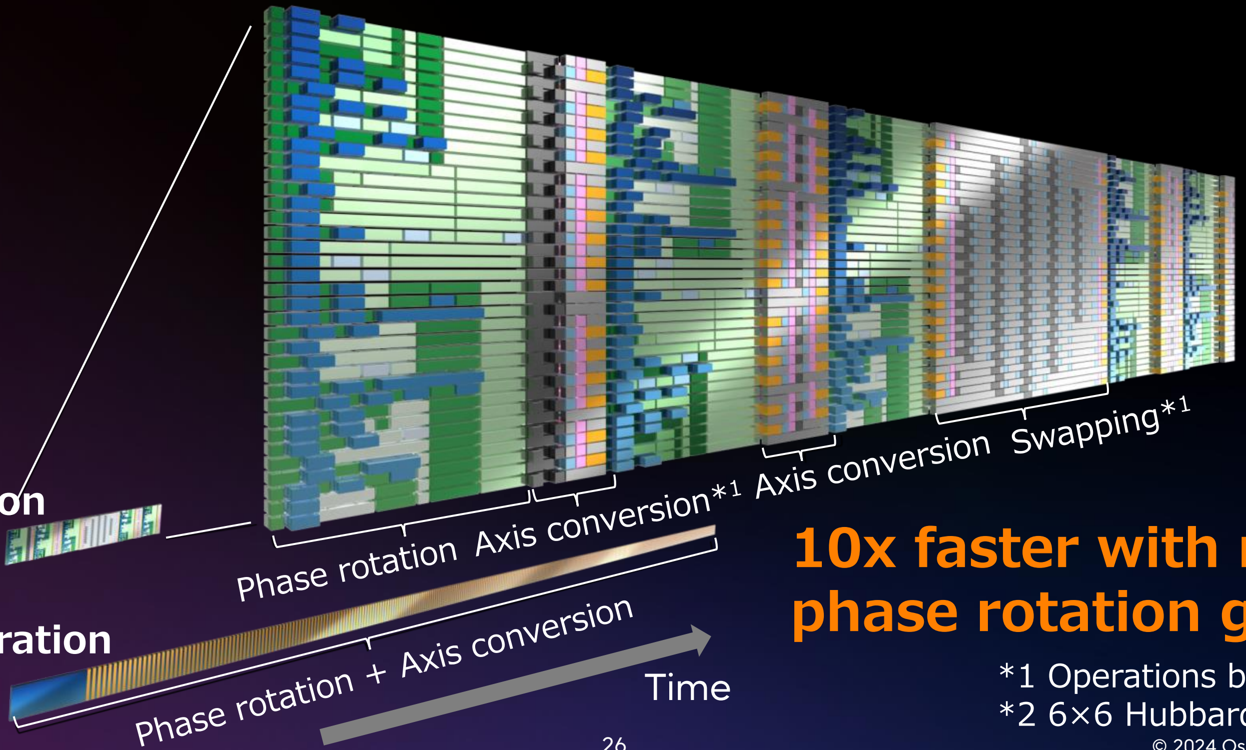


Expand to more qubits



Effect of acceleration

- Operating phase rotation gates in parallel and accelerating operation will reduce overall quantum computation execution time

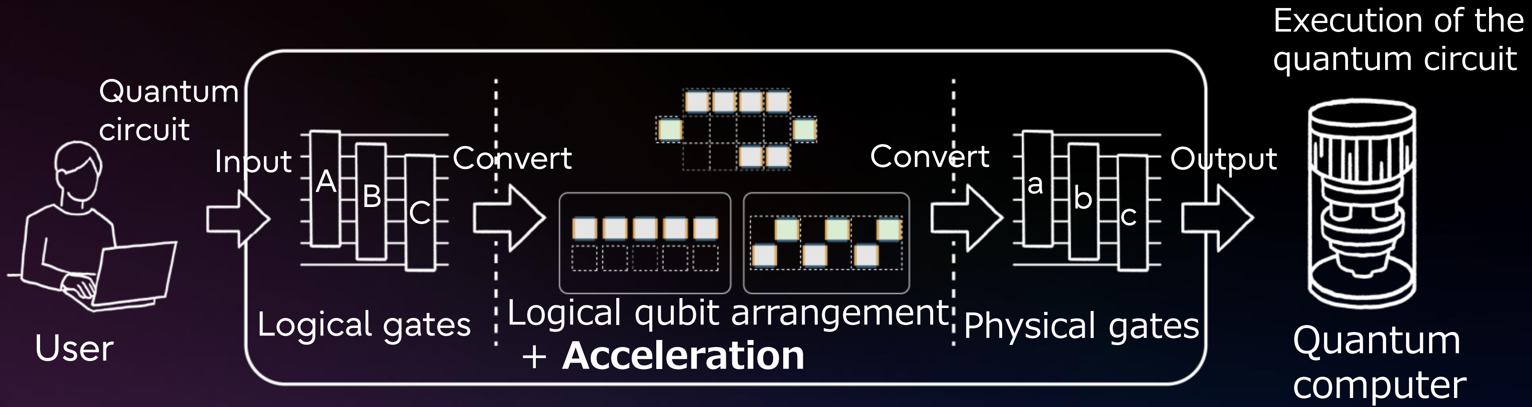


10x faster with many phase rotation gates*2

*1 Operations by lattice surgery
*2 6×6 Hubbard model

Implementation method

- **Construction of a quantum circuit generator*1 that automatically generates specific and efficient operation procedures for qubits based on our architecture**
  - Converting logical to physical gates in a single pass



Establishment of implementation method for Early-FTQC era*2

*1 Highly parallelizable quantum circuit generator for original quantum computing architecture
*2 An era in which quantum computers work with only a maximum of 100,000 physical qubits and FTQC is considered to be impossible to achieve.

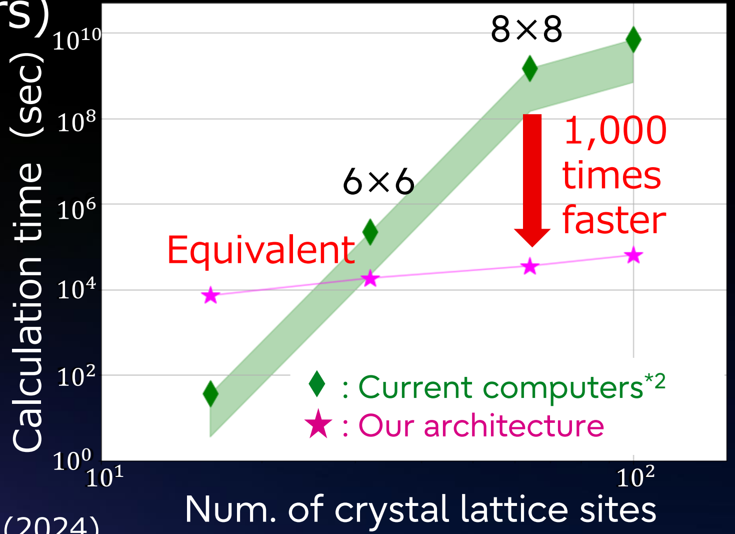
Impact if ① Accuracy improvement of phase rotation gate / ② QC Implementation are achieved

Resource estimation for Hubbard model

- **Quantum advantage can be achieved in the 10,000s of qubits range*1**
  - 40,000 qubits (6×6 lattice) = equivalent to current computers
  - 1,000x speed increase is possible with 60,000 qubits (8×8 lattice) (calculation speed of 10 hours vs. 5 years)

60,000 qubits is significantly less than the 1 million thought to be required for FTQC

We have shown the way to achieving the quantum advantage in the Early-FTQC era



*1 Our architecture is applicable to more general models.
*2 Created with reference to N. Yoshioka, et al., *npj Quantum Inf* **10**, 45 (2024).

Future development

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- We will continue developing this architecture and realize practical quantum computing on a real device for the first time in the world.

Condensed matter physics and quantum chemistry

- Development of next-generation battery
- Materials design (Automobiles, aircraft, and space shuttle)
- High performance solar battery opener
- Earth-friendly ammonia production
- High-efficiency hydrogen energy generation (artificial photosynthesis)

Quantum machine learning

- Solving advanced optimization problems (drug discovery, finance, logistics)
- Acceleration and energy saving of AI

Thank you!