Partially Fault-Tolerant Quantum Computing Architecture for Early-FTQC Era

In collaboration with Osaka University
Based on arXiv:2303.13181

December 7, 2023
Fujitsu Limited

Newly Developed Quantum Computing Architecture

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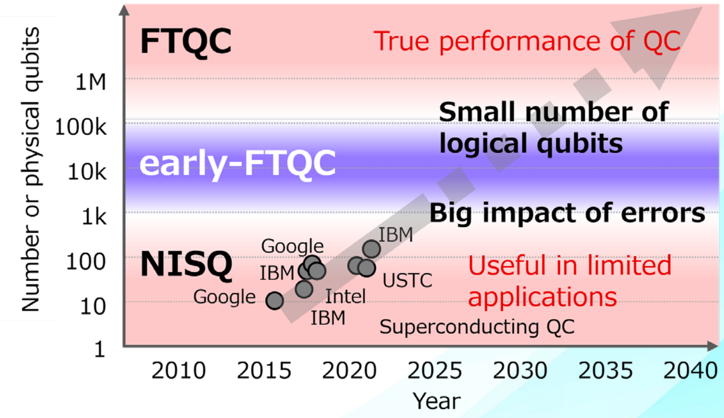
- **We developed an architecture that fills the gap between NISQ and FTQC**

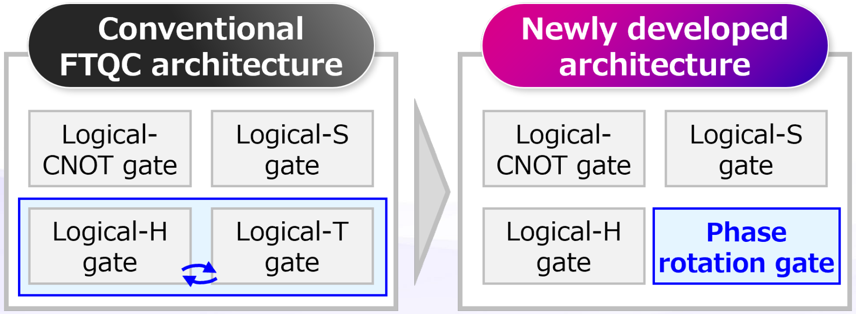
  NISQ: Noisy Intermediate-Scale Quantum computer
  FTQC: Fault-Tolerant Quantum Computer

- **New phase rotation gate is introduced into the universal quantum gate set**
- **64 logical qubits can be constructed with 10,000 physical qubits**

Development of superconducting quantum computer (QC)

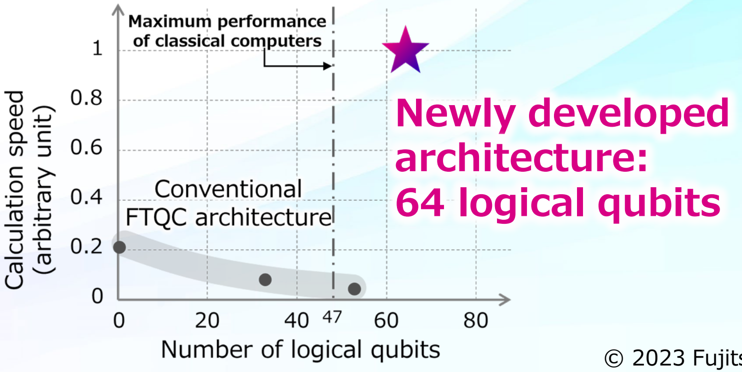


Universal quantum gate set



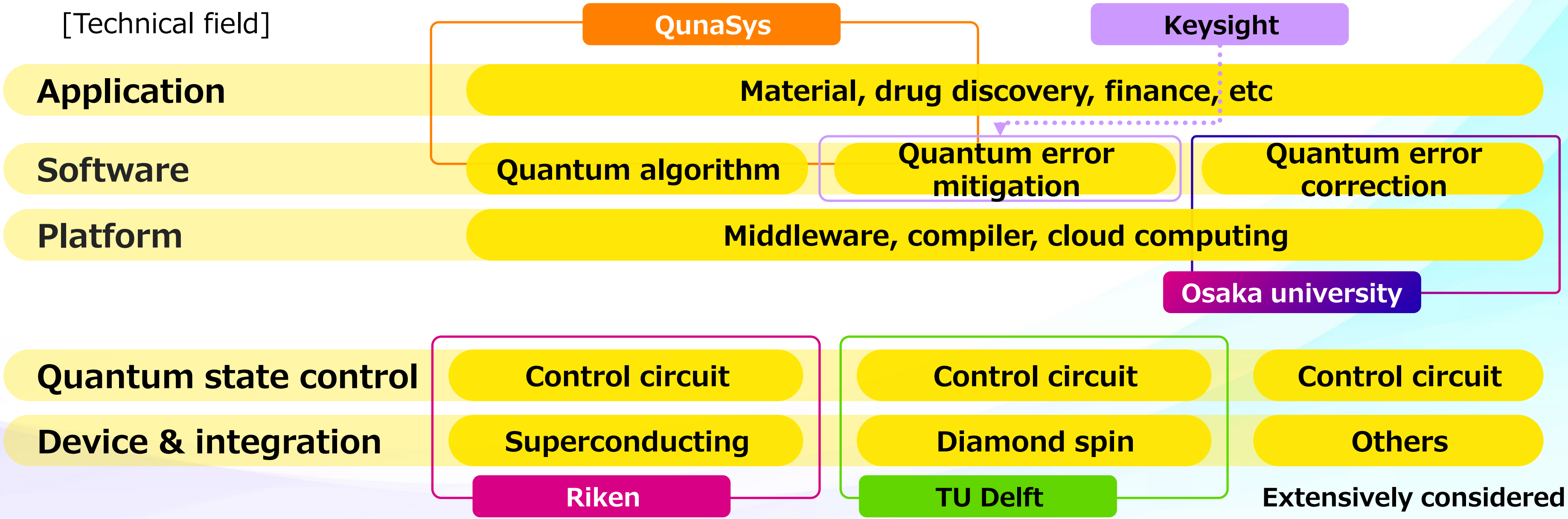
Phase rotation gate

Performance of QC architecture with 10,000 physical qubits



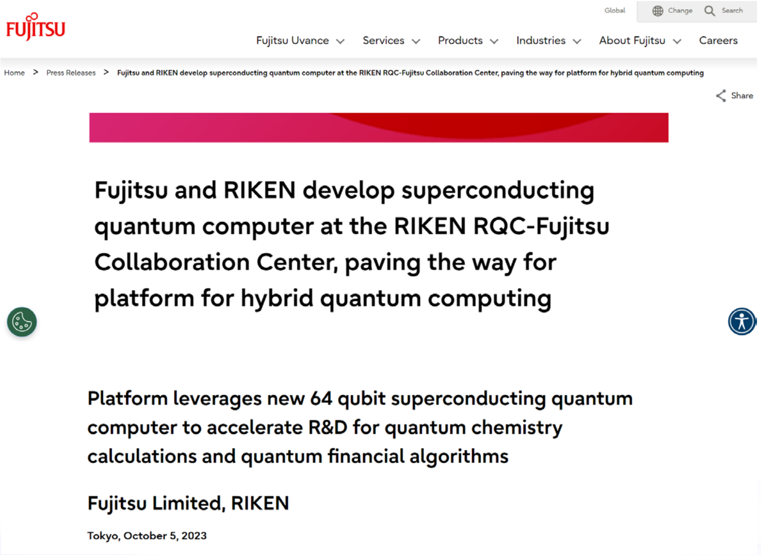
Our QC activities

- Cover every layer of QC stack: device, platform, software and application
- Focus on software technologies while exploring a wide range of hardware
- Promote joint research with the world's leading research institutes



Recent press release

Successful development of 64-qubit superconducting quantum computer (Oct. 5, 2023)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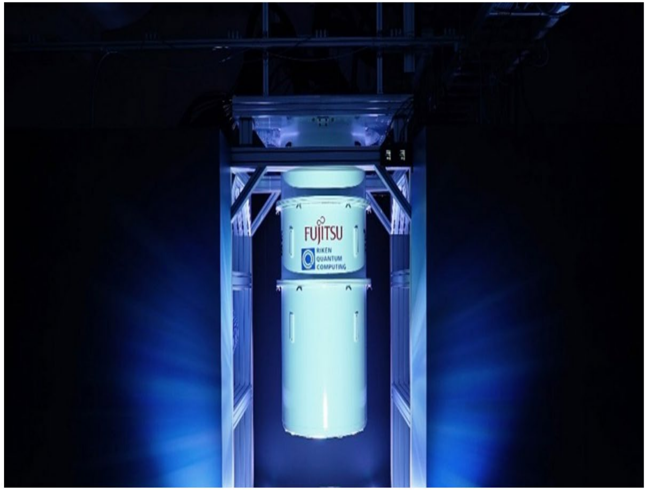
Fujitsu and RIKEN develop superconducting quantum computer at the RIKEN RQC-Fujitsu Collaboration Center, paving the way for platform for hybrid quantum computing

Platform leverages new 64 qubit superconducting quantum computer to accelerate R&D for quantum chemistry calculations and quantum financial algorithms

Fujitsu Limited, RIKEN

Tokyo, October 5, 2023



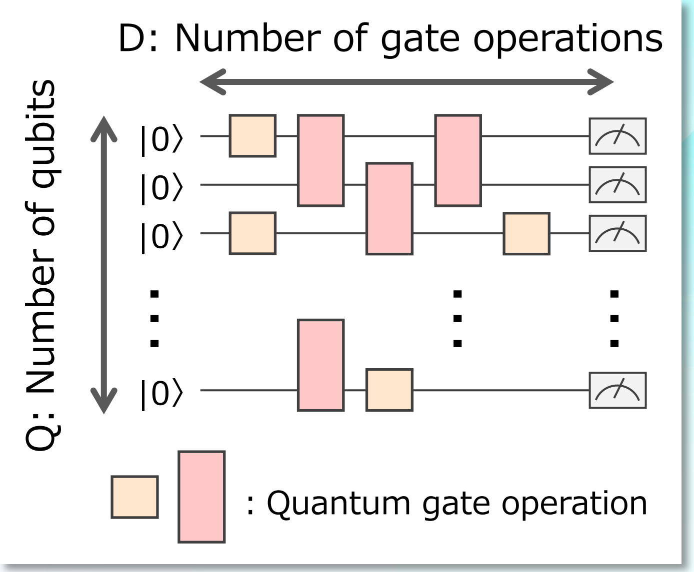
Quantum computer developed at the RIKEN RQC-Fujitsu Collaboration Center

https://www.fujitsu.com/global/about/resources/news/press-releases/2023/1005-01.html

Quantum error correction (1)

Quantum error: noise changes the state of the qubit, leading to incorrect computations

- Noise source: environment (thermal noise, etc), control signal (fluctuation, etc)



Fidelity of the overall computation = (fidelity of qubit)$^{(Q \times D)}$

- e.g. $(0.999)^{(50 \text{ qubits} \times 20 \text{ gate operations})} = 0.368$

Quantum error correction (2)

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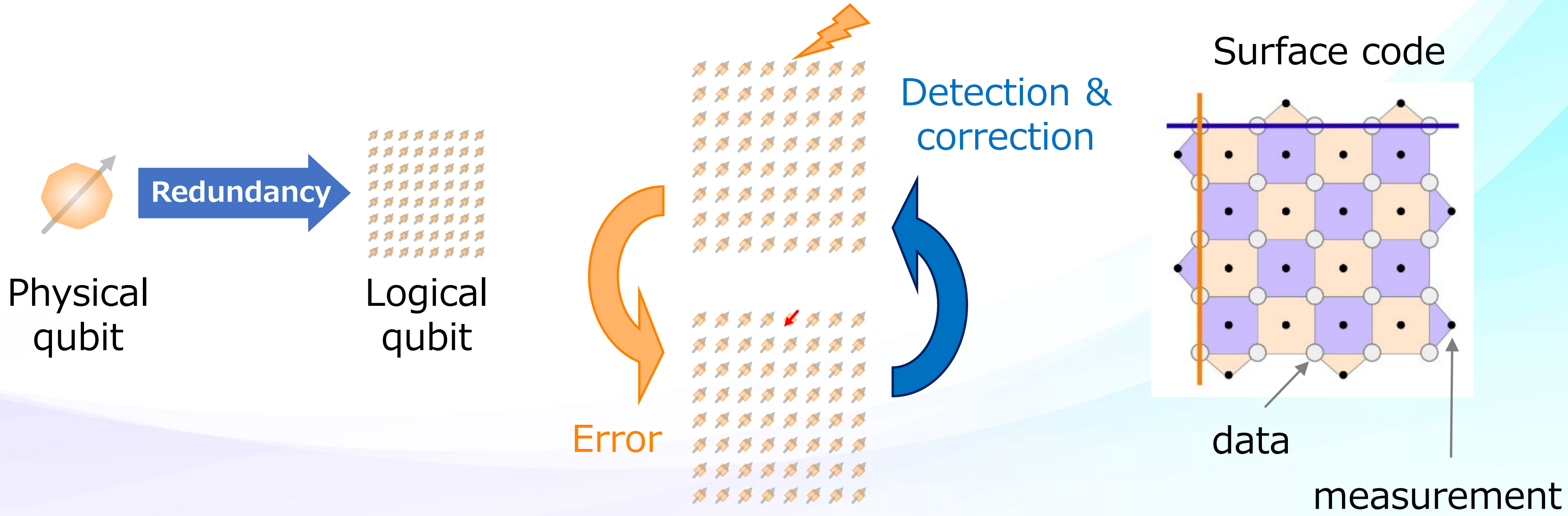
In quantum error correction, a single logical qubit is constructed from several physical qubits

- Redundancy protects quantum information from errors



Need for a new QC architecture

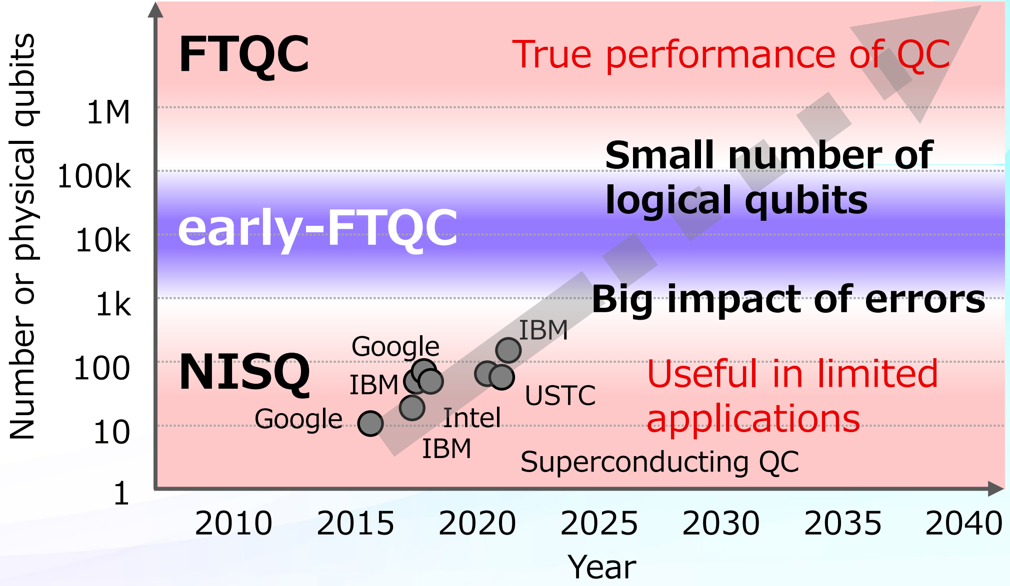
QEC is an essential requirement to realize practical QC

- QEC needs enormous physical qubits and gate operations

Early-FTQC era regime

- Promise of small number of logical qubits
- How to make QEC practical?

An architecture tailor-made for this era is required



The conventional FTQC architecture

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Universal quantum gate set for QC

- Four gates: CNOT, H, S, T
- Circuits formed by the first three gates can be efficiently simulated classically
- The power of QC is realized only when T gate is involved

Conventional FTQC architecture

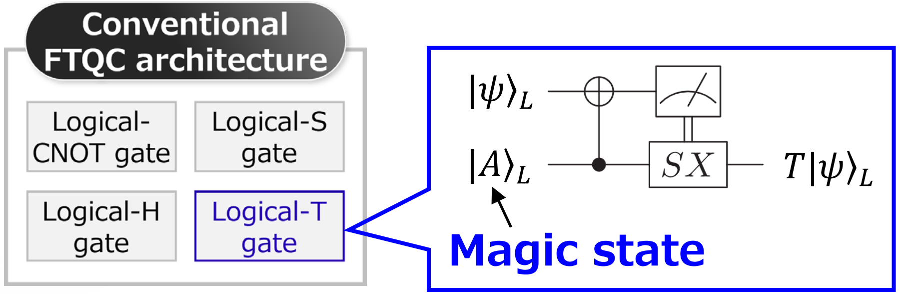
Logical-CNOT gate	Logical-S gate
Logical-H gate	Logical-T gate

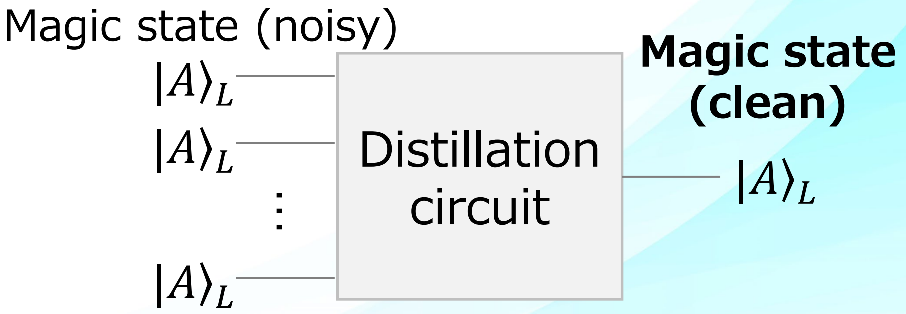
Each gate in the universal gate set can be reliably implemented in conventional FTQC architecture

QEC for T gate needs enormous number of physical qubits and gate operations

Reliable T gate implementation

- **Logical-T gate is implemented by the gate teleportation with the magic state**
- **Magic state creation via a distillation process**

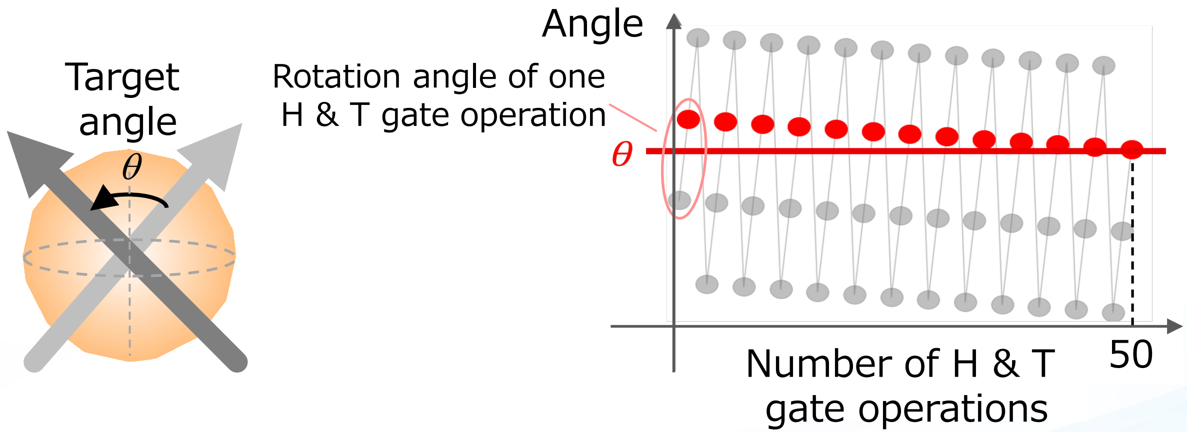


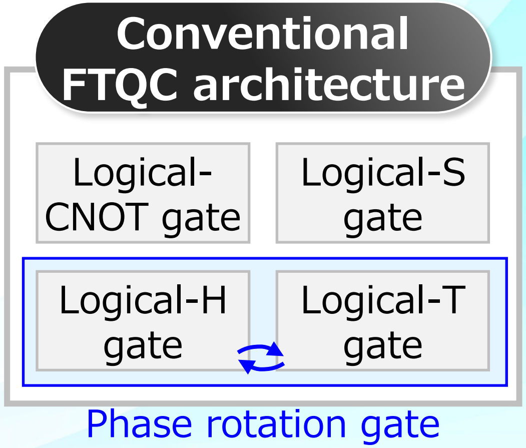


Dozens or hundreds of logical qubits are necessary to clean the magic state

Implementing phase rotation

Arbitrary rotation requires huge number of H and T gate operations – 50 times on average

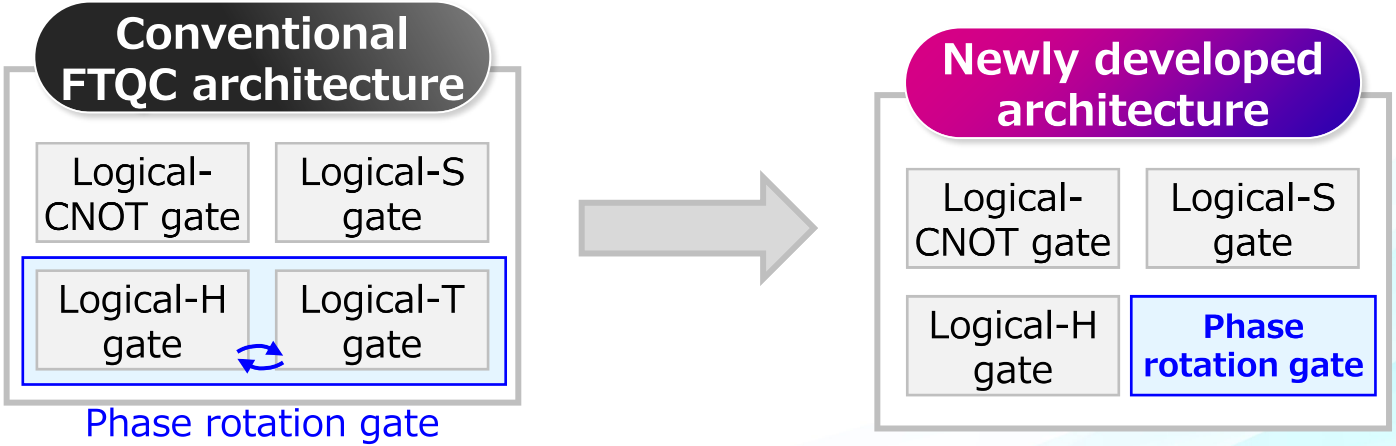




QEC overhead for phase rotation is enormous

Newly developed architecture

Introducing new phase rotation gate into the universal gate set



About 1/10 in number of physical qubit
About 1/20 in number of gate operation

New method for phase rotation

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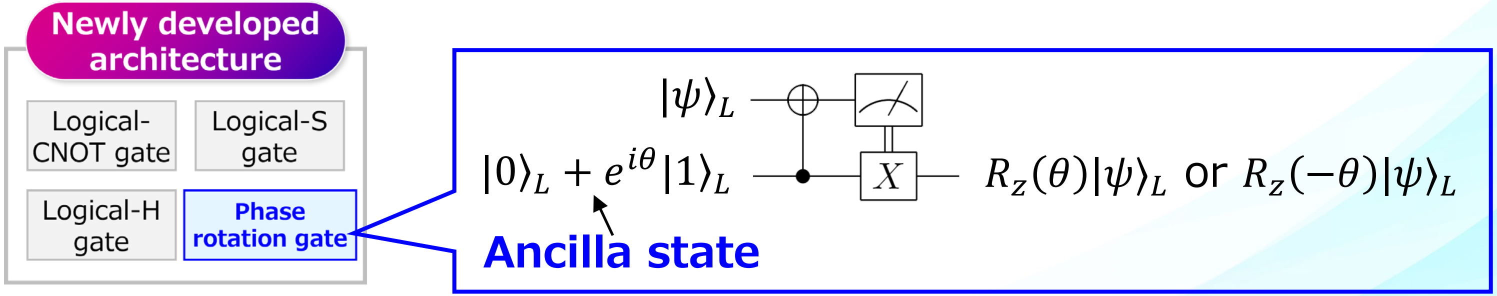
- **Phase rotation gate is implemented with an ancilla state via gate teleportation**
- **The ancilla state is not distilled in our architecture**



No distillation greatly reduces number of physical qubits, however ancilla errors must be minimized

Technical points in phase rotation (1)

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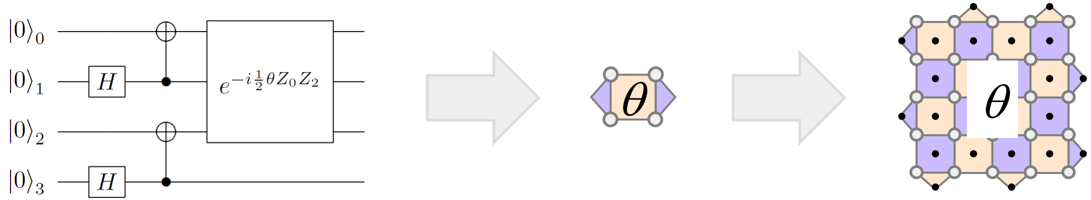
Generate a target angle θ by direct phase rotation of physical qubits and convert them into a logical qubit

Ancilla state preparation: $|0\rangle + e^{i\theta}|1\rangle$



Rotations of physical qubits

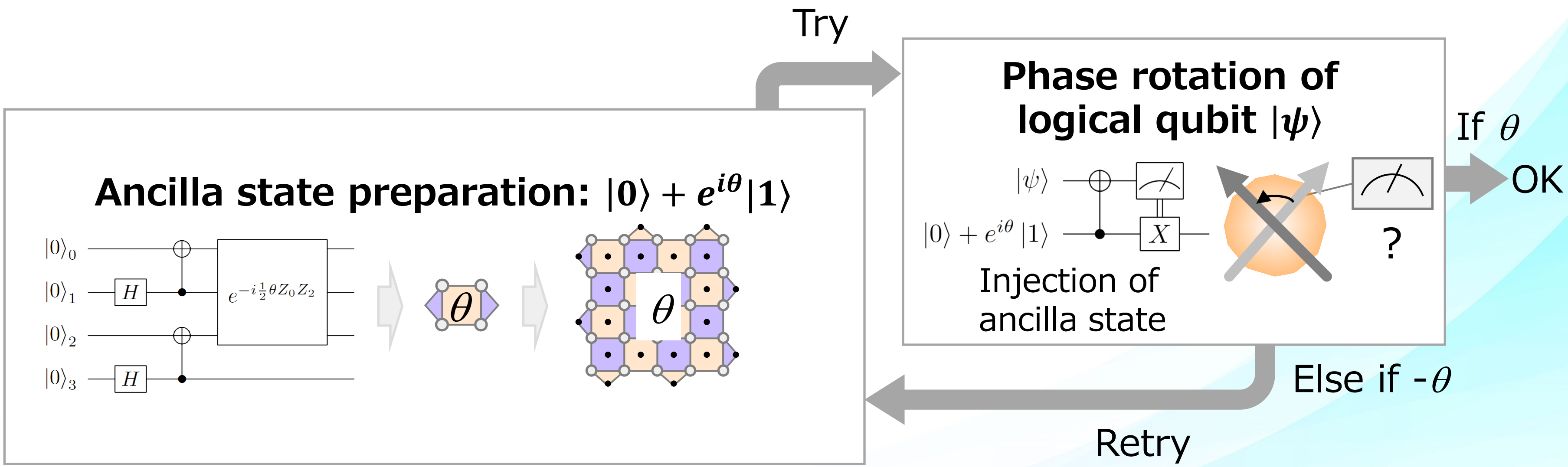
Ancilla state in 4-qubit code

Ancilla state in the surface code

High accuracy: approximately 1/8 of the physical error rate

Technical points in phase rotation (2)

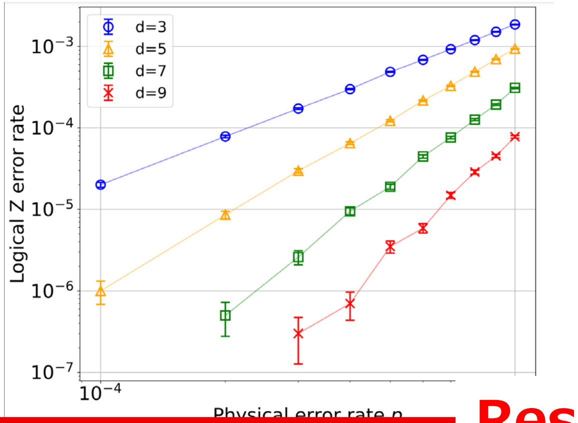
Repeat until success with the logical qubit



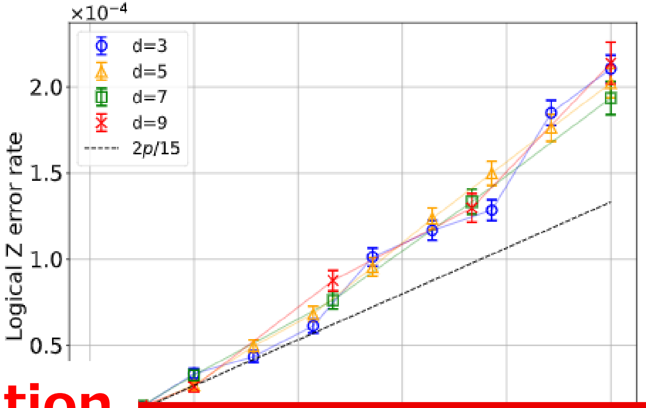
High efficiency: Success in an average of 2

Numerical simulations

➢ QEC simulation



➢ Ancilla state preparation



Resource estimation

Under the assumption of 10^4 physical qubits with error rate $p = 10^{-4}$,
Our architecture can perform
Clifford (CNOT, S, H) gates : 1.72×10^7 times
Phase rotation gates : 3.75×10^4 times
on 64 logical qubits

Achievement of newly developed architecture (1)

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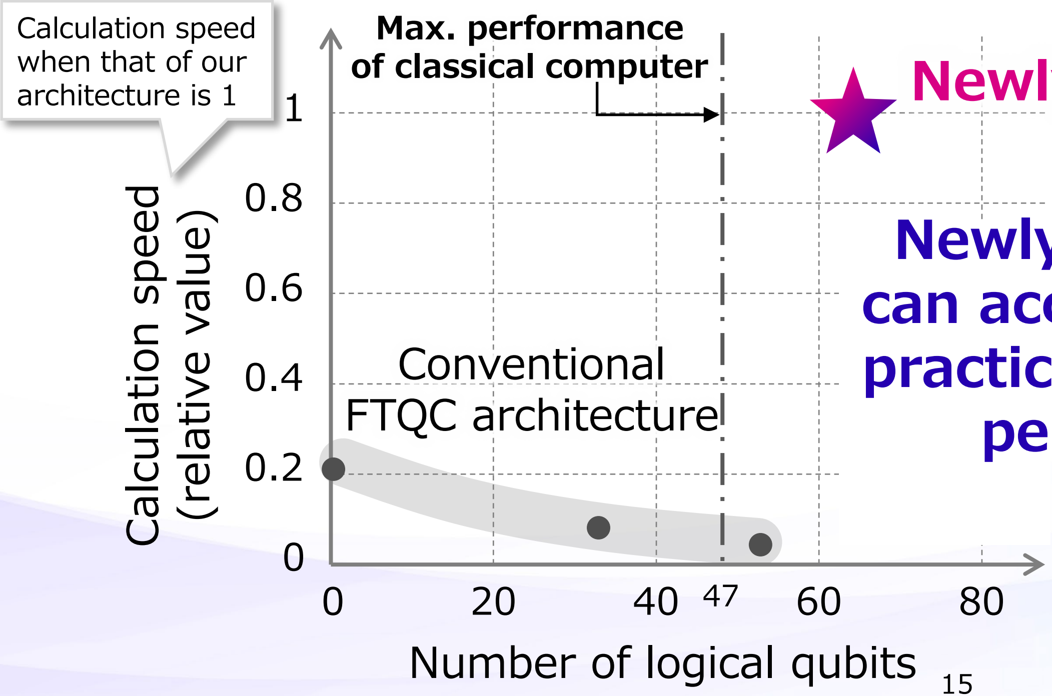
Estimated at QC with 10,000 physical qubits

- Calculation speed is the number of gate operations per unit time

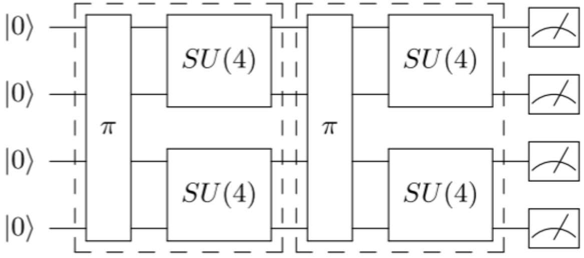


Newly developed architecture: 64 logical qubits

Newly developed architecture can accelerate the realization of practical QC with computational performance exceeding classical computer

Achievement of newly developed architecture (2)

Comparing quantum volume to NISQ computing



Benchmark circuit（4 qubits, depth 2）

Quantum volume

If the benchmark circuit (left figure) with n qubits and n depth is reasonably performed, **we say the quantum volume (QV) is 2^n**

- With the same assumption discussed the last slide, naive NISQ computing gives[1] QV = $\mathbf{2^{37}}$
- On the other hand, our architecture achieves QV = $\mathbf{2^{64}}$

[1] A. W. Cross et al., Phys. Rev. A 100, 032328 (2019)

Summary

- For forthcoming **early-FTQC era**, new quantum computing architecture is essential to achieve useful computation

- We propose a quantum computing architecture which replaces T gate by phase rotation gate

- By numerical estimation, **our architecture can surpass existing architectures on 10^4 physical qubit device**

Future plans

We plan to further refine this new architecture to advance the developments of QC in early-FTQC era, with the aim of applying to a wide range of practical social issues

New material development

Financial applications

Thank you!