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World's First Quantum Error Correction Method Developed for Cryogenic Environments Enabling Operations between Logic Qubits ―A Major Step Toward the Realization of Large-Scale Quantum Computers―

Professor Masaaki Kondo and Visiting Research Fellow Yosuke Ueno (regular affiliation: Graduate School of Information Science and Technology, The University of Tokyo) from the Keio University Faculty of Science and Technology; Yasunari Suzuki, a researcher at NTT Computer and Data Science Laboratories; Assistant Professor Masamitsu Tanaka of the Graduate School of Engineering, Nagoya University; Yutaka Tabuchi, a unit leader at RIKEN Center for Quantum Computing have developed the world's first quantum correction algorithm capable of decoding not only single logical qubits but also multiple interacting logical qubits. This is accomplished while satisfying the required levels of power consumption, implementation scale, speed, and error correction performance in cryogenic environments to control a practical large-scale quantum computer. Our results improve the scalability of superconducting quantum computers and fault-tolerance of superconducting qubits, which contribute to the development of fault-tolerant quantum computers.

The team's results were published at the 28th IEEE International Symposium on High-Performance Computer Architecture (HPCA-28) to be held from April 2, 2022.

1. Points

- The team proposed a novel quantum error correction algorithm that enables error decoding and fault-tolerant logical operations on interacting multiple logical qubits.

- They implemented a decoding unit based on the proposed algorithm with single-flux-quantum circuits. Due to their high operating frequency and low power consumption, their quantum error correction scheme can protect multiple logical qubits under logical operations from errors within the restricted power consumption in cryogenic environments.

- This technology is expected to contribute to the development of fault-tolerant quantum computers.

2. Background

Quantum computers are a technology that can perform calculations by making use of quantum mechanics phenomena such as superposition and entanglement. Quantum computers are actively developed in the world due to their ability to solve vital problems in cryptography and quantum chemistry faster than previously existing computers.

Since the elements of the quantum computers, qubits, have high error rates, the framework of quantum error correction has been investigated to correct errors during the computation by constructing a logical qubit with several noisy physical qubits, as shown on the left side of Figure 1.

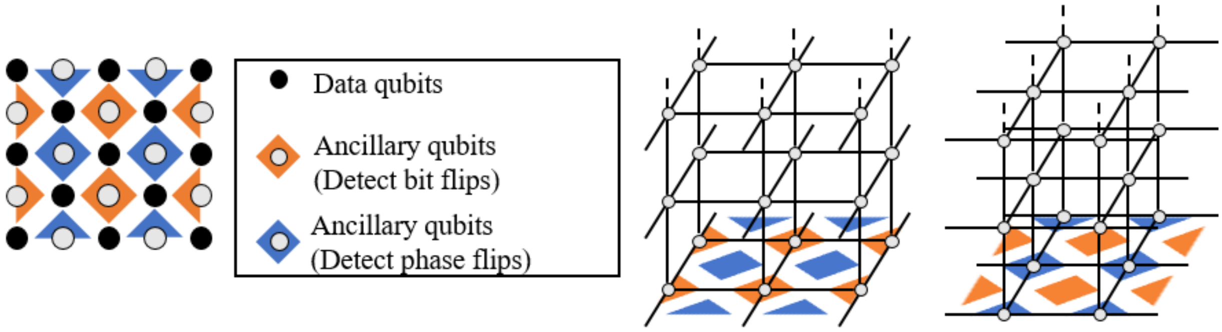

Figure 1. Left: Surface code; Right: Three dimensional lattices by stacking measurement values of surface codes

Surface codes, which are one of the most popular quantum error-correcting codes, consists of data qubits and ancillary qubits (left side of Figure 1). Values called syndromes are obtained from the ancillary qubits in each cycle of computation, and the decoding process of surface codes is attributed to the graph matching problem on syndrome values. Classical computers that solve the graph matching problems to estimate the errors in quantum devices are called decoding units. High-performance decoding units are required to construct fault-tolerant quantum computers. In practice, errors may also occur in the measurements of ancillary qubits. Even such cases, one can reliably estimate errors by solving a graph matching problem on a three-dimensional lattice constructed by stacking the obtained syndrome values in several cycles in the time direction (right side of Figure 1).

To perform quantum computation using logical qubits protected by surface codes, it is necessary to perform logical operations in a fault-tolerant manner. Lattice surgery enables fault-tolerant operations between logical qubits by merging and splitting the codes of multiple logical qubits encoded with surface codes, and this operation is known to be one of the essential operations in realizing arbitrary quantum operations. The decoding process during the lattice surgery corresponds to solving a complicated graph matching problem in which the boundary of logical qubits dynamically changes due to the merge and split of logical qubits (Figure 2). However, the existing decoding methods can only decode independent single logical qubits and cannot perform error correction of logical qubits during lattice surgery.

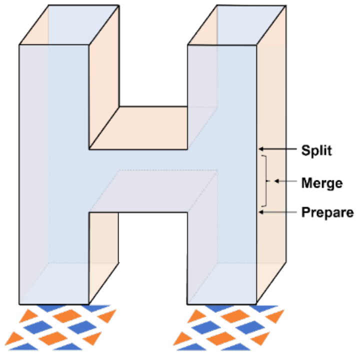

Figure 2. The shape of a lattice of graph matching problem during a lattice-surgery operation

3. Results

In this research, the team proposed a decoding algorithm compatible with lattice surgery. This was based on a decoding scheme previously proposed by the same group called "online decoding," which follows the occurrence of errors in qubits and prevents the accumulation of errors by estimating errors in real-time. [1]This is expected to enable fast correction of errors on logical qubits during quantum operations.

Superconducting qubits are promising candidates as quantum computer devices due to their scalability. Since they can only be operated in cryogenic environments, they are usually installed in dilution refrigerators. Meanwhile, it is supposed that decoders operate at room temperature because conventional CMOS-based implementations consume too much energy in cryogenic environments. Therefore, the large amount of wiring between a room and cryogenic temperatures limits the scalability of superconducting quantum computers (left side of Figure 3).

This team has designed a decoder based on the proposed algorithm that can be operated in a cryogenic environment using single-flux-quantum (SFQ) circuits. The SFQ circuits are superconductor circuits that can be operated at a high frequency with low power consumption. This can dramatically improve the scalability of quantum computers (right side of Figure 3). Furthermore, their decoder can finish the decoding process in less than 1 microsecond per cycle, which is fast enough to prevent accumulation of errors. These improvements are expected to contribute to the development of fault-tolerant quantum computers with superconducting qubits. [2]

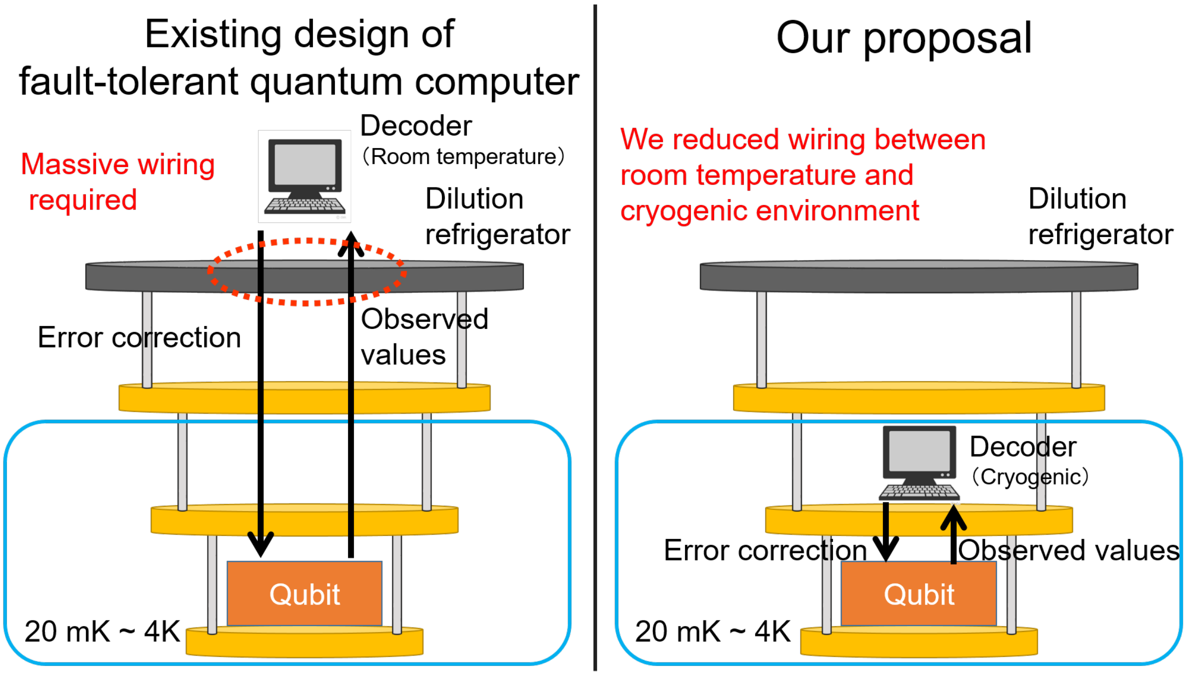

Figure 3.Structures of superconducting fault-tolerant quantum computing (Left: existing approach, Right: Our proposal)

4. Perspective

This team has proposed a fast error-correction method for multiple logical qubits with performing logical operations in a cryogenic environment, thereby improving the scalability of superconducting quantum computers and the fault-tolerance of qubits. These results are expected to contribute to the development of fault-tolerant quantum computers.

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<References>

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2.Press release "Development of Quantum Error Correction Method for Superconducting Quantum Computers in Cryogenic Environments - World's First Realization of a Key Technology for the Development of Large-Scale Quantum Computers -" (November 8 , 2021)
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