Goal6 Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050.

Research and Development of Theory and Software for Fault-tolerant Quantum Computers

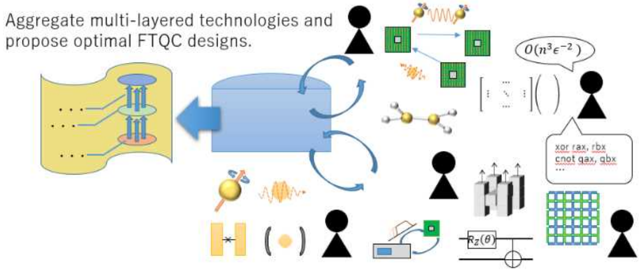
R&D Theme

Development and expansion of cross-layer codesign models

Progress until FY2022

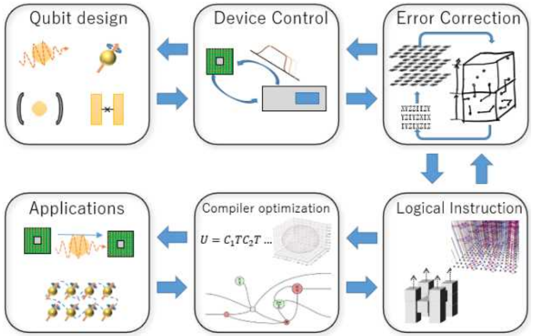
1. Outline of the project

Under this theme, we aim to construct a full-stack framework that enables the efficient and flexible design of fault-tolerant quantum computing (FTQC). While massive software stacks have been developed to optimize and evaluate existing computing, there are no quantum counterparts for this purpose. This makes it difficult to quantitatively plan long-term goals for development. To resolve this issue, we will construct a software foundation to enable co-design beyond multiple technology layers, named “cross-layer codesign (CLCD) models.” With this software, we show optimized FTQC designs and contribute to the long-term planning for FTQC R&D.


Aggregate multi-layered technologies and propose optimal FTQC designs.

Concept of Cross-Layered Co-Design models

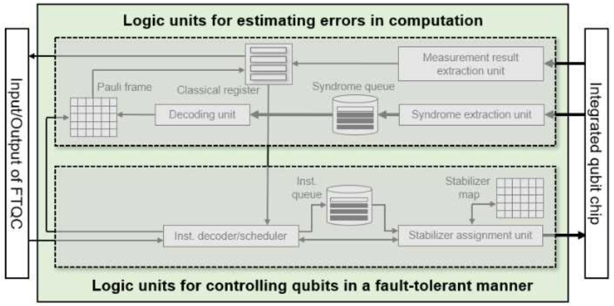
We develop CLCD models with the following steps. First, we list all the components of FTQC in each technological layer without considering their feasibility. We named this mockup as a minimal model. Then, we resolve problems found in minimal models by relaxing the requirement by optimizing designs or proposing architectures. According to these results, we update minimal models and design sophisticated FTQC based on them.



Technology layers in CLCD models

2. Outcome so far

Our current contributions can be summarized in the following four points. 1) We proposed a minimal model for FTQCs. So far, we have targeted FTQCs with superconducting qubits and surface codes. We have enumerated all the relevant components as detailed as possible. 2) We developed software stacks to emulate its behavior and evaluated its performance. Based on this foundation, we revealed the resources required to demonstrate computational advantage. 3) We designed computer architecture and FTQC control circuits. They are now used as a reference for large-scale implementation of FTQCs. 4) We proposed several methods to relax the hardware requirement of FTQC. For example, we proposed methods to cope with temporal and spatial variation of error properties. Our cross-layer designs encouraged deep collaborations with many fields, such as computer architecture, circuit design, and quantum physics, and our results were achieved based on these collaborations.



Schematic diagram of FTQC control units

3. Future plans

We continue developing FTQC based on deep collaborations with basic theory to applications. We also extend our minimal models for superconducting qubits to other devices in Moonshot projects. Based on these efforts, we realize CLCD models that enable flexible design and optimization of FTQCs and will find the fundamental problems in FTQC and solve them.

R&D Theme

Development of hardware control methods and analysis of performance

Progress until FY2022

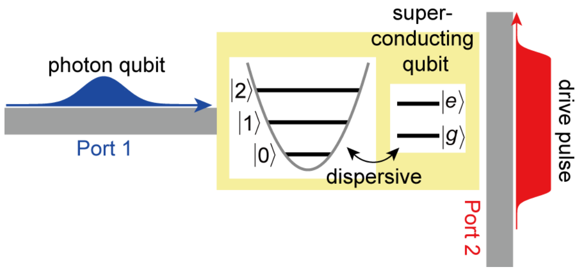
1. Outline of the project

Under this R&D theme, we focus on several physical systems suited for building a fault-tolerant quantum computer. We are trying to capture the unique features of each system quantitatively and to exploit them for proposals of novel implementation methods. We are also developing software such as simulator tools that help to accelerate research on device technology.

2. Outcome so far

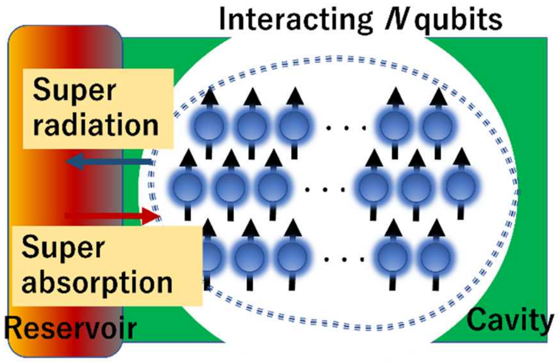
1) SWAP gate between superconducting and microwave-photon qubits

To realize a truly useful quantum computer, it is necessary to connect stationary qubits by using propagating qubits. We theoretically proposed a method to confirm the state exchange (SWAP gate) between a superconducting qubit and a microwave-photon qubit and demonstrated it in collaboration with an experimental group. The proposed gate can be easily operated by simply reflecting photon qubits onto the superconducting qubits. The average fidelity of photon to atom (atom to photon) state transfer reached 0.829 (0.801). This value can be further improved by extending the qubit lifetime.



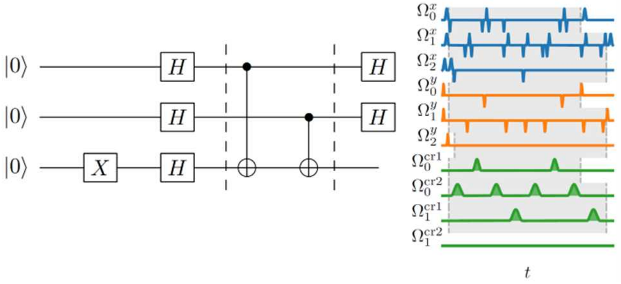
2) Exploring novel physical process useful for quantum computing

Controlling heat exchange between a system and its environment becomes important as qubits are densely integrated. Super-radiance is a quantum phenomenon that many qubits emit photons synchronously. We have theoretically proved that the reverse process, called “super-absorption,” is possible by a proper design of the qubit interaction and the external system. Moreover, for N qubit system, there is a fundamental limit of heat flux that scales with cubic power of N. This process has possible application to the cooling or initialization of qubits in quantum computers [Phys. Rev. Lett. 2022; Phys. Rev. Lett. 2023].



3) Expanding supporting tools for development of quantum computers

QuTiP (the Quantum Toolbox in Python) is an open-source numerical package for the general simulation of open quantum systems. It has become one of the top quantum numerical packages in the world, surpassing a total of 1,000,000 downloads by the end of 2022. To expedite the use of QuTiP in the research of quantum computers, we released a new package (qutip-qip), which addresses pulse-level simulation of noisy quantum circuits [Quantum 2022].



3. Future plans

We will explore more efficient methods of gate manipulation and state readout with a longer lifetime by applying quantum optical effects for superconducting qubits. We will explore the speed limit of control and measurements and decoherence process of the qubits. We will also continue to develop supporting tools.

R&D Theme

Development of quantum error correction schemes and analysis of performance

Progress until FY2022

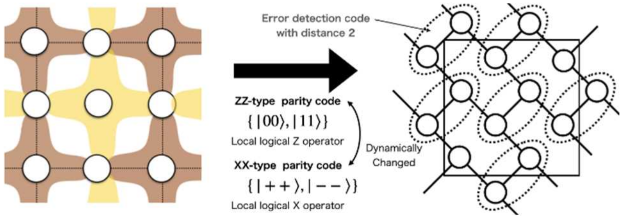
1. Outline of the project

In order to relax hardware requirements and improve the performance of fault-tolerant quantum computers (FTQC), it is essential to add new options at each layer, not just a combination of existing schemes. Under this theme, we will pioneer new schemes for quantum error correction and fault-tolerant quantum computation architectures through various approaches.

2. Outcome so far

1) New quantum error correction scheme to relax physical constraints

By reducing the connectivity of the qubits, the frequency assignment of each superconducting qubit becomes easier, and high-precision quantum operations can be achieved. In this research, we proposed a new method to perform quantum error correction by connecting each qubit to only three adjacent qubits by combining a small error detection code. Numerical simulations confirmed that the proposed method is also highly error tolerant because of the additional error detection functionality. Using the knowledge obtained here, we aim to improve the error tolerance of the color codes, which has a good property for transversal logical operations, providing a new alternative to surface codes.

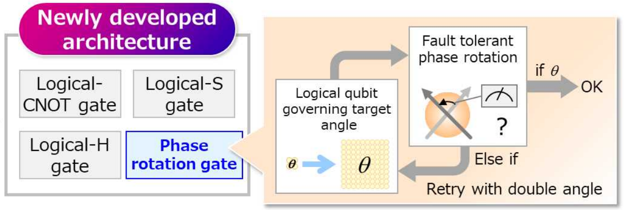


2) Bridging the gap between NISQ and FTQC

There is a gap of several orders of magnitude in the number of qubits that can be meaningfully utilized or necessarily required for NISQ (Noisy Intermediate-Scale Quantum computer) (around 100 qubits) and FTQC (around 1 million qubits). In this research, we have been working to fill those gaps.

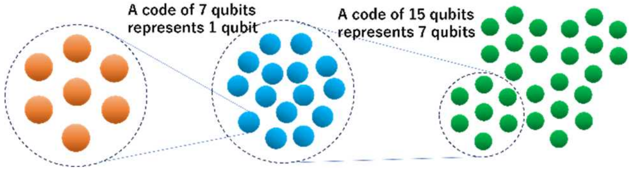
As a software approach, we have developed a framework for applying quantum error mitigation method conventionally applied for NISQ to logical qubits encoded in error-correcting codes and have shown that sufficiently high computational accuracy can be achieved even with small size codes. Then, the number of physical qubits required can be reduced by as much as 80% in the area where the proposed method works most effectively [PRX Quantum, 2022].

As an architectural approach, we developed a new concept, early-FTQC architecture. There, only Clifford operations, which are relatively easy to be protected, are protected by error correction, and non-Clifford operations are performed by generating special ancilla states with high accuracy via error detection. It was shown that even with an error probability of 10^4 and 10,000 physical qubits, a quantum volume of 2^{64} can be achieved (QV=2^{37} is the limit in NISQ). This indicates that deeper quantum computation, which is difficult to simulate even with a classical supercomputer, can be achieved even on a 10,000-qubit scale.



3) Ultimate efficiency of FTQC in the large-scale limit

The FTQC fights against errors by using redundant qubits and carrying out extra computational steps. Seeking the minimum of these overheads in space and time is one of the fundamental questions on FTQC. We have proposed a new architecture based on concatenation of simple error correcting codes with growing sizes and showed that its space and time overheads are smaller than any other known architectures.



3. Future plans

We seek to provide new options for cross-layer co-design by not only improving surface codes but also exploring new quantum error correction codes such as topological color codes and more general quantum LDPC codes. For the application of quantum error mitigation to FTQC, we aim to further reduce the overhead by investigating application of other NISQ-aware techniques. For early-FTQC architecture, we will start research to find feasible and quantum advantageous applications with the near-future goal of 10,000 qubit scale.

R&D Theme

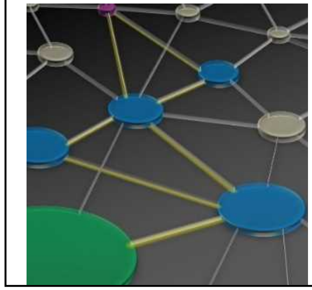
Research and development of distributed fault-tolerant quantum computers

Progress until FY2022

1. Outline of the project

Under this theme, we aim to explore the possibility of distributed architecture of fault-tolerant quantum computers. In particular, the goal is to open up the possibilities of quantum computation with physical systems that cannot be scaled up without having a distributed structure and of further scaling up by connecting quantum computers that are developed in a monolithic form. This will present new guidelines for the design of fault-tolerant quantum computers, eventually contributing to the realization of a fault-tolerant quantum computer in 2050, i.e., the goal of the Moonshot Goal 6.

Toward the goal, we have started to consider the design of a basic module to connect distant qubits or integrated chips with quantum communication, as well as the exploration of quantum error-correcting codes and fault-tolerant quantum computing schemes which fit distributed architecture.

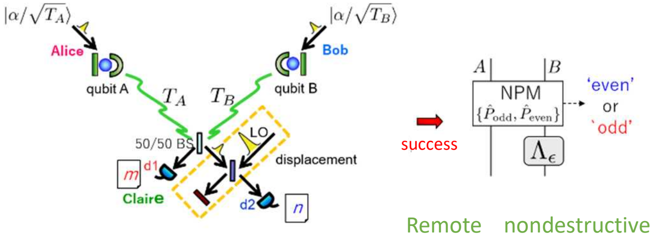


Distributed fault-tolerant quantum computer

2. Outcome so far

1) Optimal supplier of single-error type entanglement via coherent-state transmission [K. Azuma *et al.*, PRA **105**, 062432 (2022)]

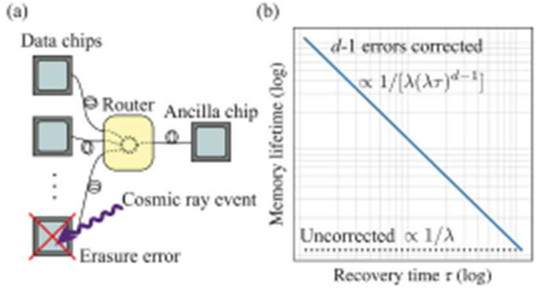
The basis of distributed quantum computation is to apply a high-fidelity controlled-not gate to distant qubits, which is achieved by supplying them with high-fidelity entanglement. In this research, we derive an upper bound on achievable rates of protocols that supply single-error type entanglement via coherent-state transmission over lossy channels. This upper bound coincides with the performance of an existing protocol based on a remote nondestructive parity measurement. Our result suggests that if we perform distributed quantum computing based on such an efficient entanglement distribution protocol, entanglement distillation may not be necessary in terms of performance, in contrast to what was thought to be required in existing proposals.



Remote nondestructive parity measurement

2) Distributed quantum error correction for chip-level catastrophic errors [Q. Xu *et al.*, PRL **129**, 240502 (2022)]

It has been pointed out that a large-scale quantum computer may suffer from cosmic ray events that cause chip-level catastrophic errors. We proposed to implement quantum error correction across separate chips in a distributed quantum-computing setup. Even if arbitrary data in a chip is destroyed, by connecting data chips and an ancilla chip, the data as a whole can be retrieved with an erasure quantum error correcting code. Our scheme can, for example, suppress the rate of such catastrophic errors from 1 per 10 s to less than 1 per month.



(a) Proposed scheme; (b) Recovery time vs memory lifetime

3. Future plans

We will develop a blueprint of a distributed fault-tolerant quantum computer, by building a found practical basic module into distributed architecture of quantum computing.