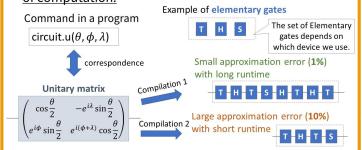
### Improving the reliability of quantum computation

Converting a program into a gate sequence is required for performing fault-tolerant quantum computation. The process of this conversion is called compilation. However, to ensure the reliability of the computation, it is usually necessary to increase the gate length, which results in a longer computational time. In this work, we have developed a compilation method that can enhance reliability without increasing the gate length.

We have developed an efficient compiler that probabilistically generates a gate sequence from a list of short gate sequences with an optimal probability distribution that maximizes reliability. Our research has shown that our compiler can achieve the fundamental limit of reliability, both in theory and through numerical simulations. It is imperative to develop a cutting-edge compiler to achieve the full potential of quantum computation, which has the power to revolutionize our society. We believe that our compiler provides a practical foundation for realizing quantum computation.

### Compilation of quantum program

- We implement a physical operation on multiple qubits and obtain a computation result by measuring them.
- The physical operation consists of unitary matrices, which are primitive commands of a quantum program.
- Since only a very restricted subset of unitary matrices, called elementary gates, is implementable in a real quantum device, each unitary matrix must be compiled use this gate into a sequence of elementary gates.
- Compilation causes an approximation error, reducing success probability of computation. Increasing gate length can reduce the error but increases the runtime of computation.



The objective is to minimize the approximation error by using the short gate sequences.

# Error reduction by probabilistic compilation

- We have verified numerically that the error reduction achieves the fundamental limit ( $\epsilon \rightarrow \epsilon^2$ ) when compiling a random 2x2 unitary matrix.
- This means that our probabilistic compiler can reduce gate length by approximately 50% to achieve a certain level of approximation error, resulting in shorter computation runtime.

## Our approach: probabilistic compilation

Standard approach: Compile a Our approach: Significantly reduce the unitary matrix into the gate approximation error by compiling a sequence with the minimum error in unitary matrix into a probabilistically gate sequences with a fixed length. chosen gate sequence. Approximation error 10% Approximation error 1% T - H - T - S -Approximation error 11% Every time when the same unitary matrix is used in a program, it is converted into one of T - S - H - T the following gate sequences: T - H - T - S — with probability 50% Approximation error 9%

■ We have demonstrated that the error can be significantly reduced by sophisticatedly designing a probability distribution p for choosing a gate sequence.

H - T - H - S -

H T H S

— with probability 30%

T - S - H - T — with probability 20%

\_\_\_\_ Approximation error

- While a primitive idea of probabilistic compilation can be found in a few previous researches, we have developed the world's first probabilistic compiler that can efficiently compile any unitary matrix and achieve the minimum approximation error.
- We have <u>completely revealed the fundamental limit</u> on the reduction rate of approximation error owing to any kind of probabilistic compilers.

#### Comparison of standard approach and probabilistic compilation. Target unitary matrix Number of T gates (=T-count) $-\sin\frac{1}{2}$ 120 $\cos \frac{\pi}{2}$ Standard approach Halving 100 (=without probabilistic gate length compilation) 80 uadratic $\theta$ is randomly chosen reduction of erro We plot the number of T 60 gates (=T-count) since a T gate is hard to implement. Probabilistic compilation The total gate length is proportional to the T-count.

[1] S. Akibue, G. Kato, S. Tani, "Probabilistic state synthesis based on optimal convex approximation," npj Quantum Information 10, 3, 2024. [2] S. Akibue, G. Kato, S. Tani, "Probabilistic unitary synthesis with optimal accuracy," under review.

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