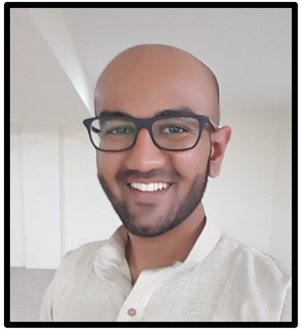
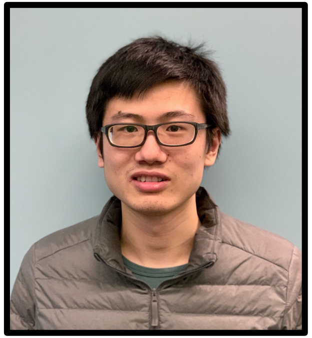
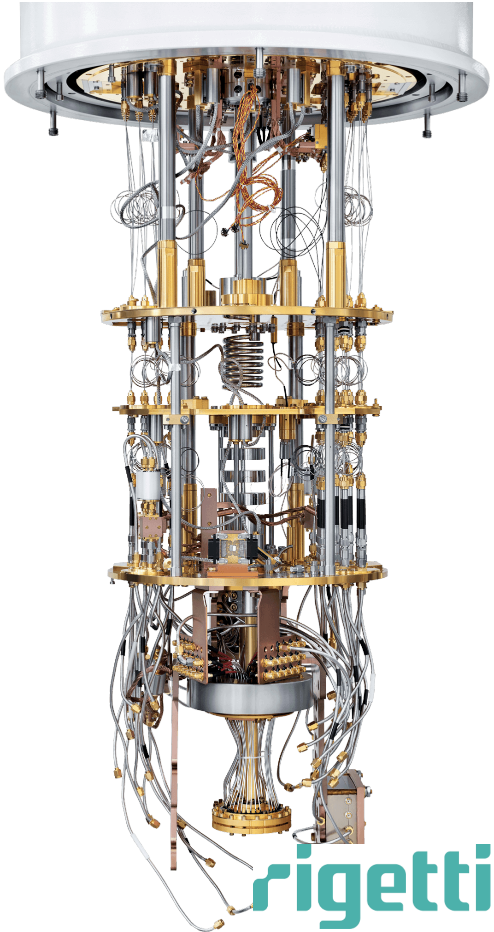
UREQA: Leveraging Operation-Aware Error Rates for Effective Quantum Circuit Mapping on NISQ-Era Quantum Computers

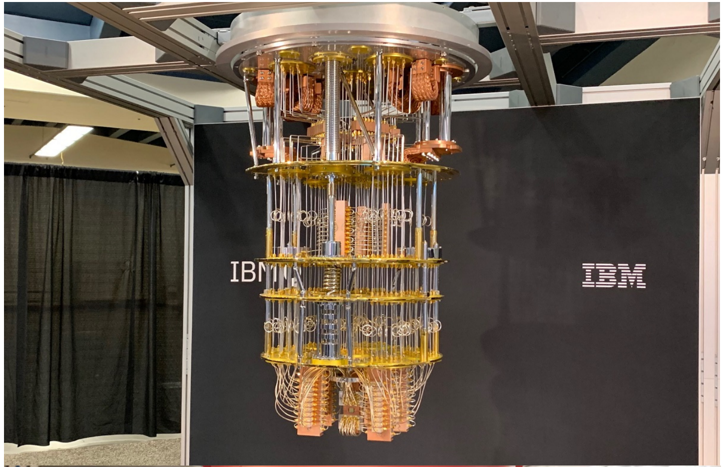



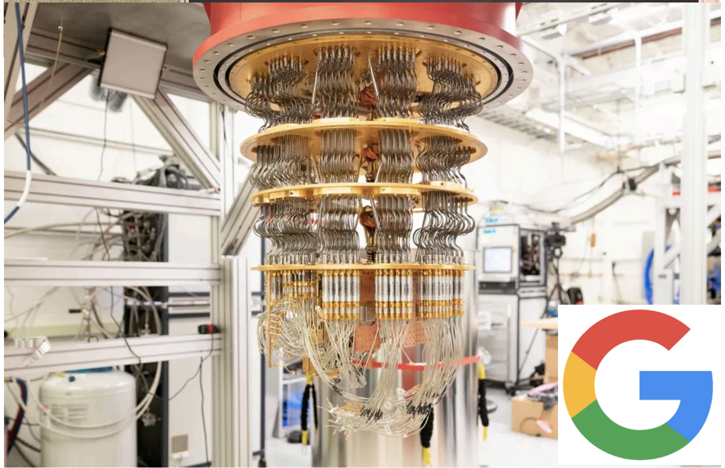
Tirthak Patel Baolin Li Rohan Basu Roy Devesh Tiwari

Northeastern University

Quantum Computing is Coming!








The international journal of science / 24 October 2019

nature

QUANTUM SUPREMACY

Classical supercomputer outperformed by quantum chip for the first time

What is a Qubit (Quantum Bit)?

A classical bit has two states:

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ and } |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

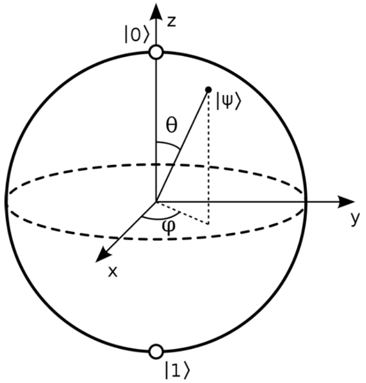
A quantum bit or qubit can be in a superposition of the two basis states:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad |\alpha|^2 + |\beta|^2 = 1$$

Upon measurement, the qubit superposition collapses, and the qubit can be found in one of the two basis states.

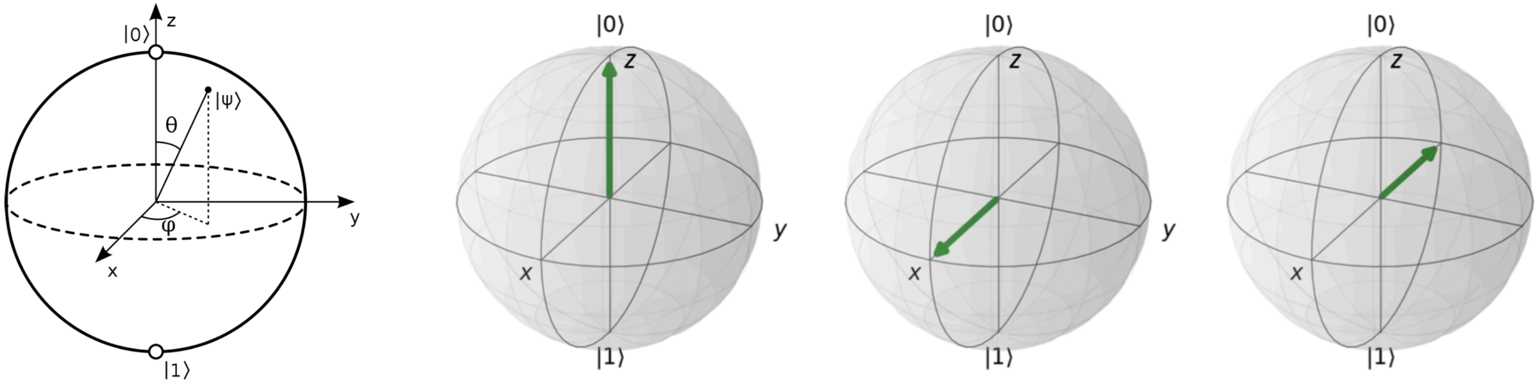
Manipulating Qubit States

A qubit can be put in a desired superposition by applying quantum operations which can be represented as rotations on the Bloch sphere.



Manipulating Qubit States

A qubit can be put in a desired superposition by applying quantum operations which can be represented as rotations on the Bloch sphere.



Initially, the qubit is in the ground state. Then, it first gets manipulated by an *H* gate in an equal superposition state, then by a R_z gate.

Multi-qubit Gate Operations

Basis states of a two-qubit system can be expressed as

$$|00\rangle = \begin{bmatrix}1\\0\\0\\0\end{bmatrix},\ |01\rangle = \begin{bmatrix}0\\1\\0\\0\end{bmatrix},\ |10\rangle = \begin{bmatrix}0\\0\\1\\0\end{bmatrix},\ \text{and}\ |11\rangle = \begin{bmatrix}0\\0\\0\\1\end{bmatrix}$$

$$|\psi_0\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle, \quad |\psi_1\rangle = \beta_0|0\rangle + \beta_1|1\rangle$$

$$|\psi_0\rangle|\psi_1\rangle = \alpha_0\beta_0|00\rangle + \alpha_0\beta_1|01\rangle + \alpha_1\beta_0|10\rangle + \alpha_1\beta_1|11\rangle$$

Multi-qubit Gate Operations

Two qubits can be entangled using two-qubit gates. E.g., Bell State

$$\left|\psi_0\,\psi_1\right\rangle = \frac{1}{\sqrt{2}}\,|00\rangle + 0\,|01\rangle + 0\,|10\rangle + \frac{1}{\sqrt{2}}\,|11\rangle$$

$$\neq$$

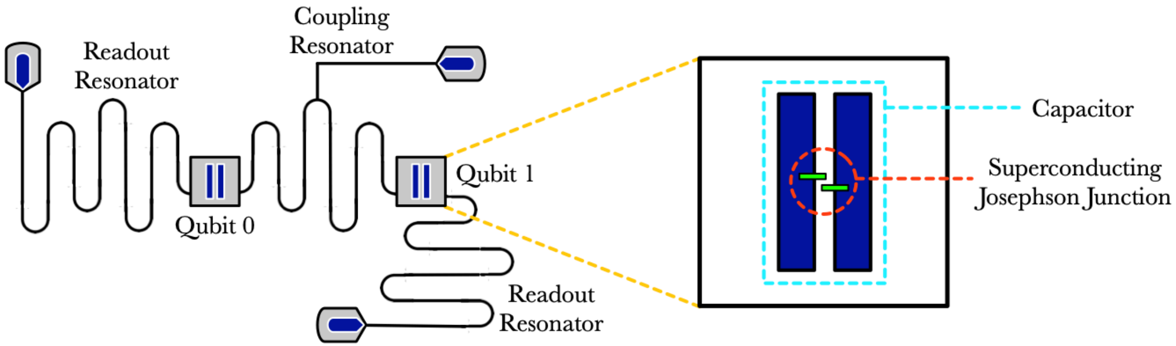
$$\left|\psi_0\right\rangle\left|\psi_1\right\rangle = \alpha_0\beta_0\left|00\right\rangle + \alpha_0\beta_1\left|01\right\rangle + \alpha_1\beta_0\left|10\right\rangle + \alpha_1\beta_1\left|11\right\rangle$$

In 2-qubit gates (CH, CR_x, CR_y and CR_z), one qubit is the control qubit and the other is the target qubit.

The respective 1-qubit gate is applied to the target qubit depending on the superposition of the control qubit.

All quantum algorithm circuits can be broken down into one- and two- qubit basis gates.

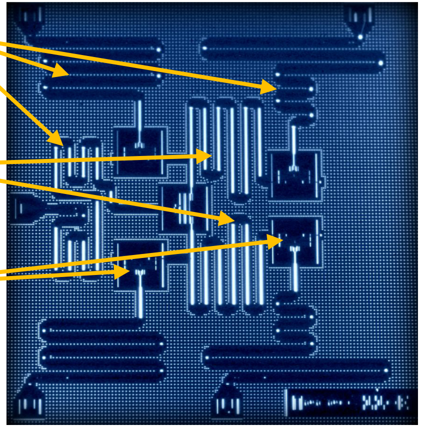
Engineering a Quantum Computing Device



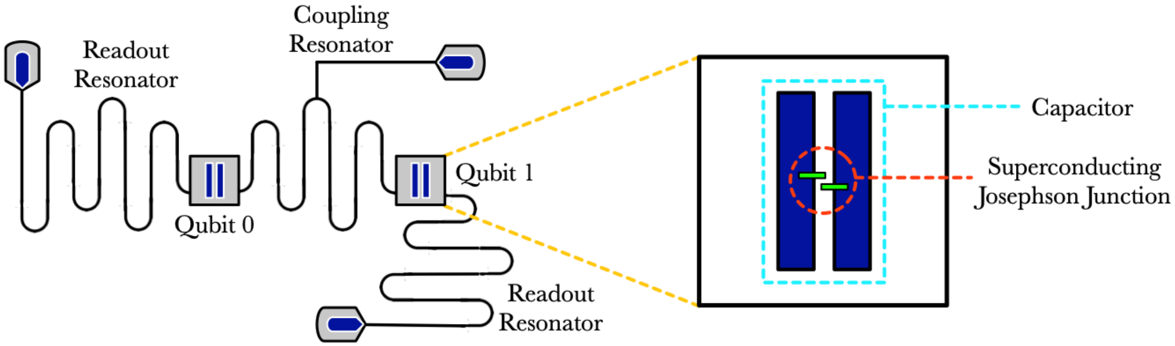
Readout/Control Resonators

Coupling Resonators

Qubits



NISQ Devices are Highly Erroneous!



Errors in applying microwave pulses cause 1-qubit gate errors.

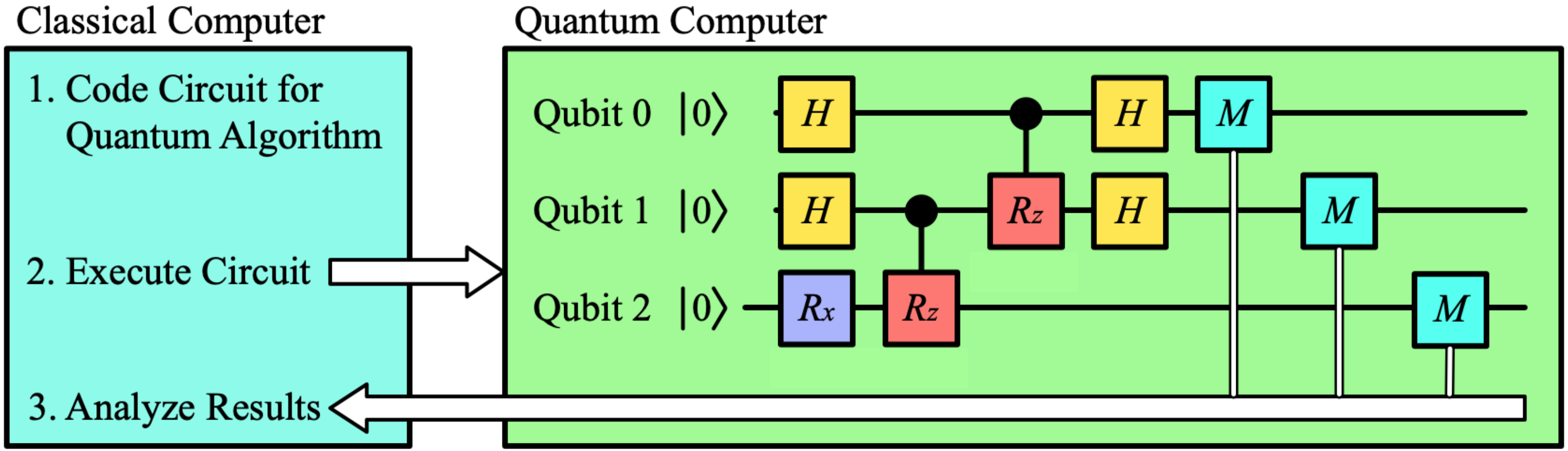
Coupling resonators can be highly erroneous causing 2-qubit gate errors.

The readout resonators are also highly error-prone and cause readout errors.

T1 coherence time: energy decay to the ground state.

T2 coherence time: phase damping due to env. factors.

Execution Flow on a Quantum Computer



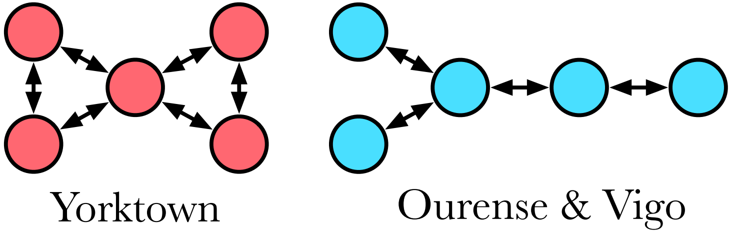
Classical Computer

1. Code Circuit for Quantum Algorithm
2. Execute Circuit
3. Analyze Results

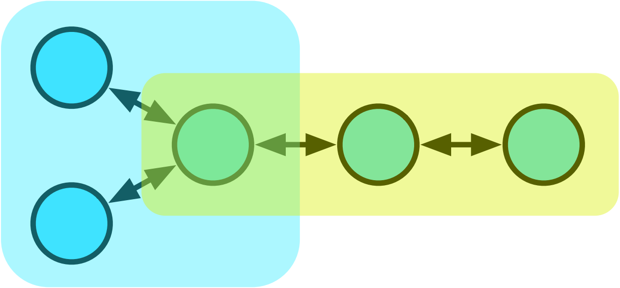
Quantum Computer

Quantum Circuit Maps

Every quantum computers is composed of multiple qubits – each with potentially different number of qubits and topological structure



A single quantum algorithm can be "mapped" in different ways on the same quantum computer – each mapping is referred as "circuit map".

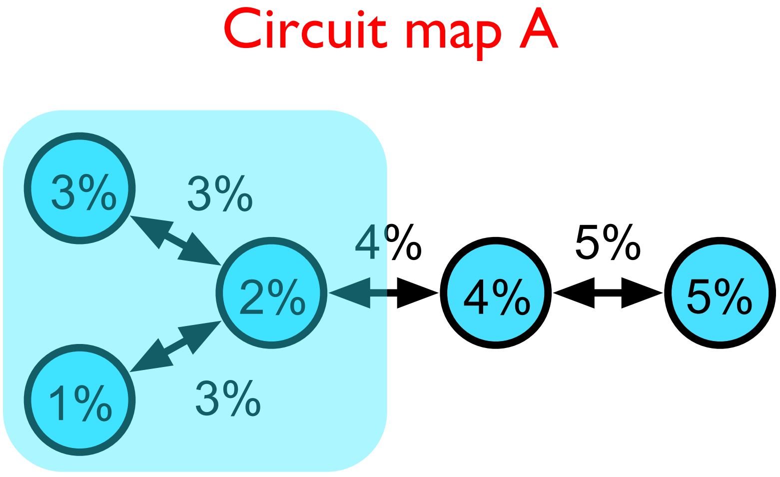


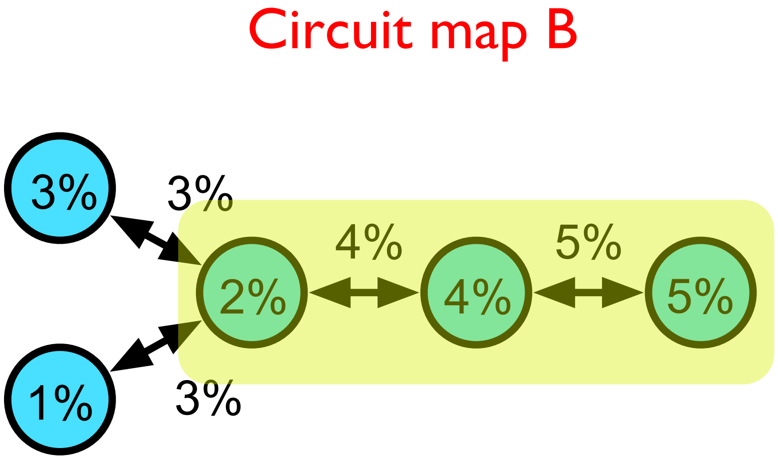
Circuit map A for a 3-qubit algorithm

Circuit map B

Quantum Circuit Map Selection

Quantum circuit map selection is affected by the error rate of different quantum gates, readout measurements, and qubit connectivity.



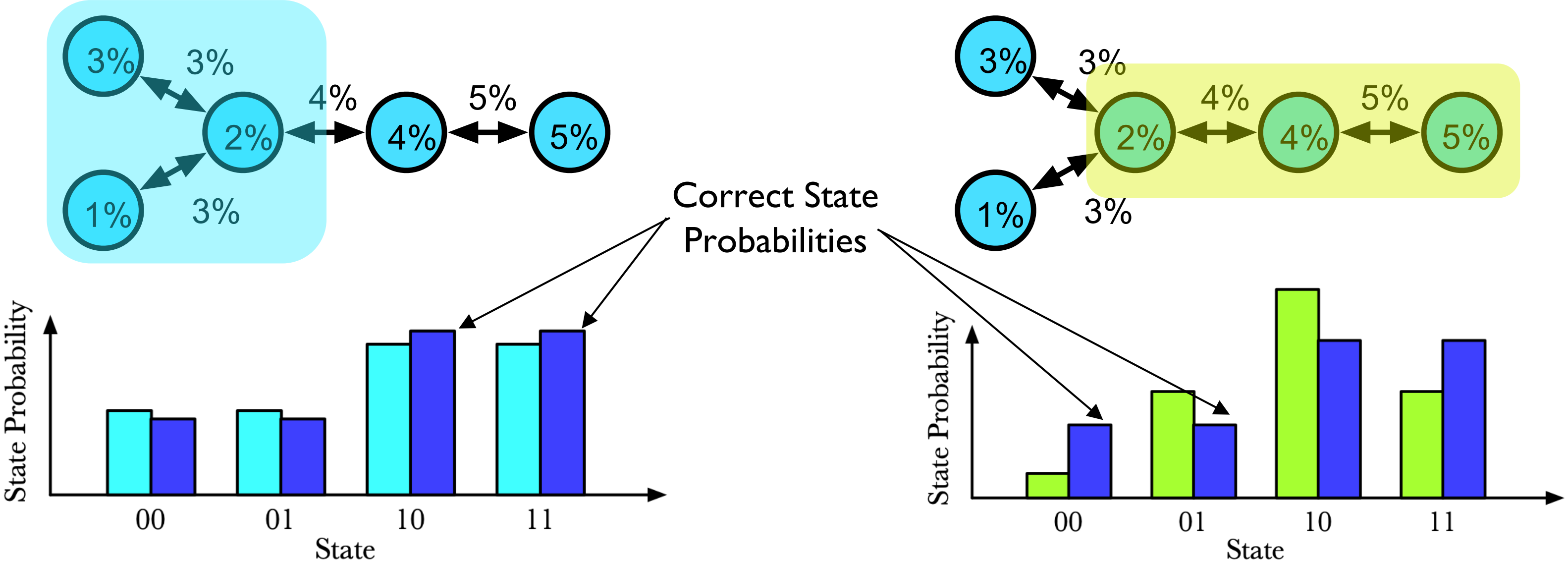


Effect of Circuit Maps on Program Output

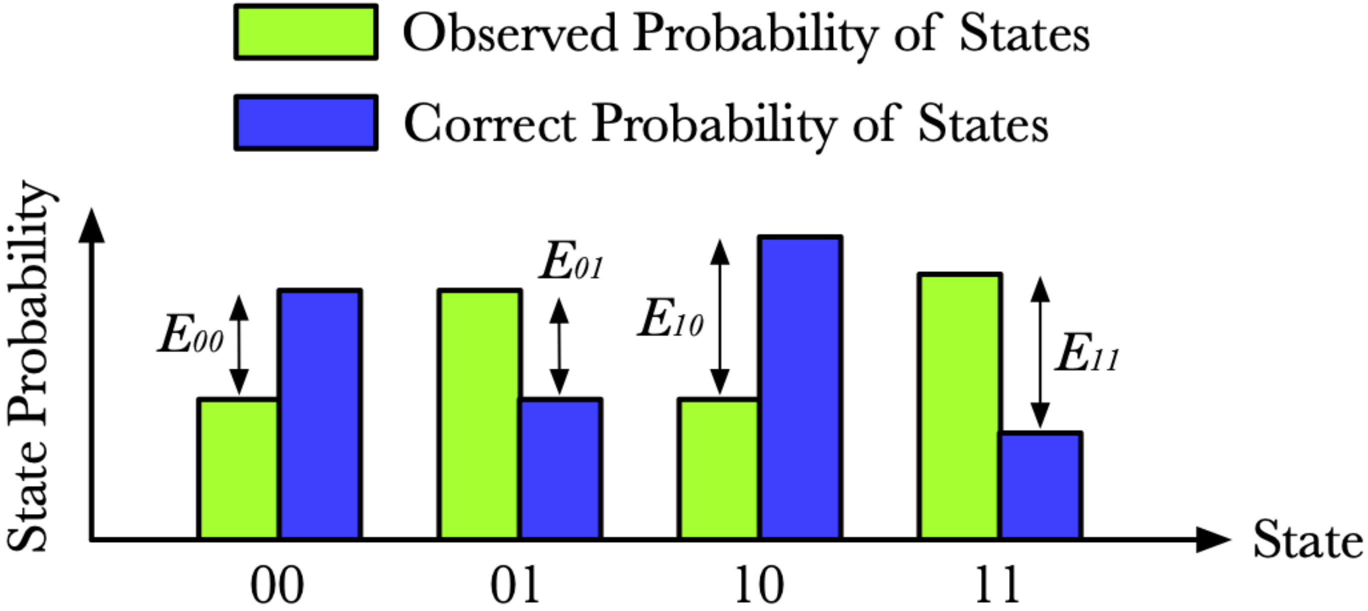
Execution of a circuit map produces the program output. Due to errors in operations, each circuit map suffers from error in its program output.

Circuit map A

Circuit map B


Correct State Probabilities

Error in the Program Output

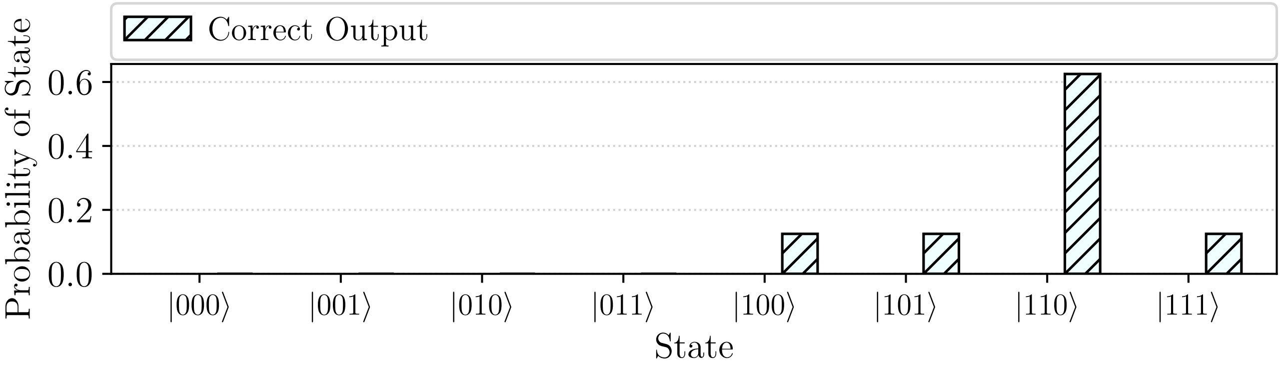


$$\text{Output Error} = (E_{00} + E_{01} + E_{10} + E_{11})/2$$

A real quantum algorithm example!

Quantum Phase Estimation (QPE)

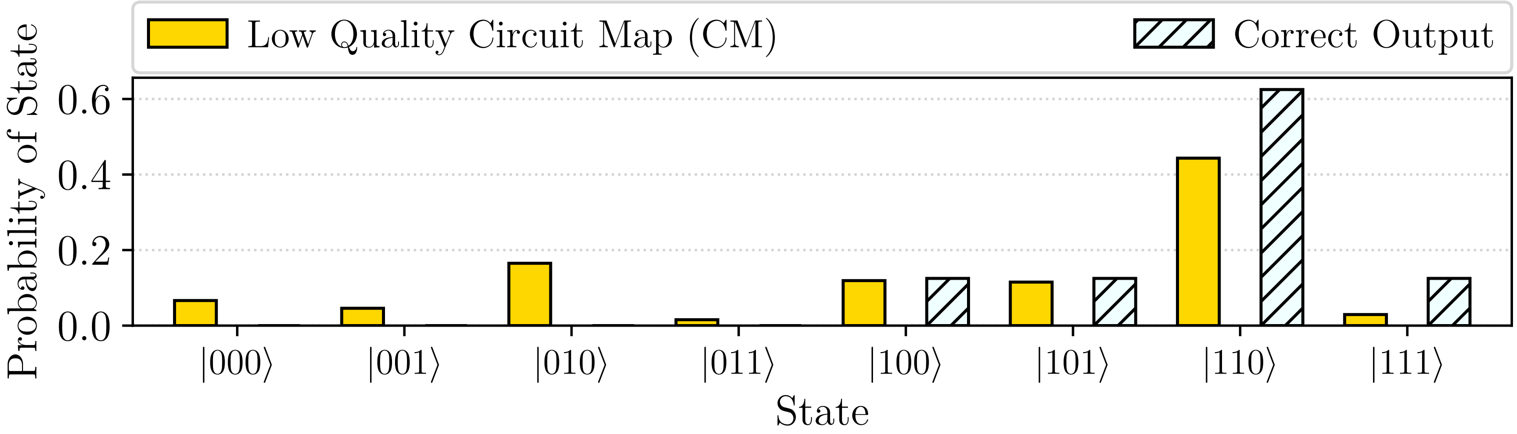
QPE algorithm running on three qubits has eight program output states with correct output state probabilities as shown below.



An ideal circuit map would produce the program output such that the probability of each output state is the same as error-free execution.

Quantum Phase Estimation (QPE)

QPE algorithm running on a low-quality circuit map produces erroneous output probability for each output state. The error is 28%.

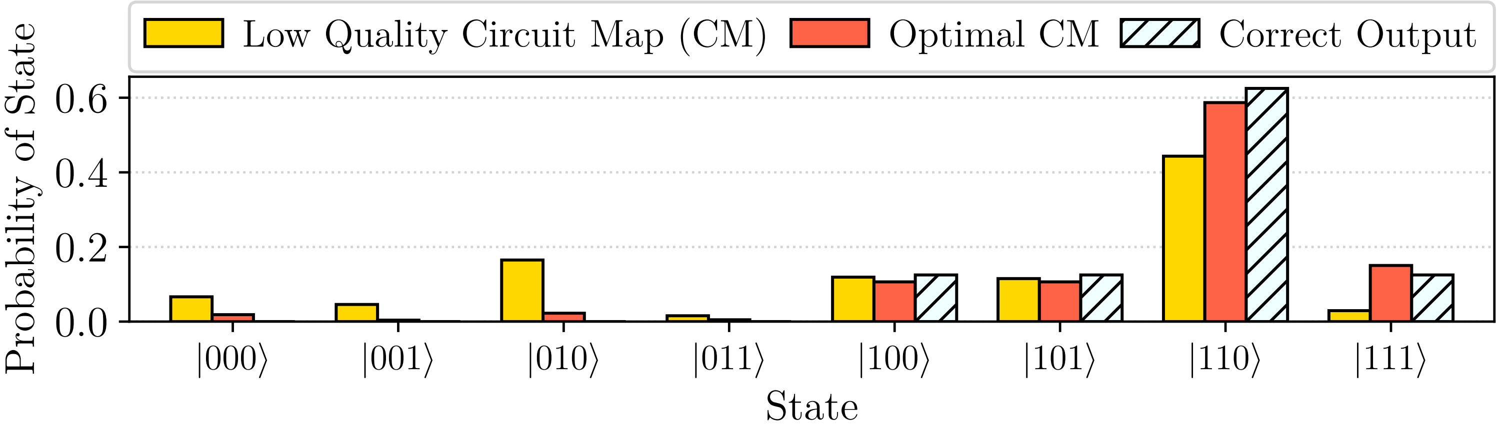


Optimal Circuit Map

Optimal circuit map is the set of operations and qubits which achieve the lowest output error (highest success rate) for a given algorithm (6% here).

$$\prod_{i=1}^{N_{gates}} g_i * \prod_{j=1}^{N_{readout}} m_j$$

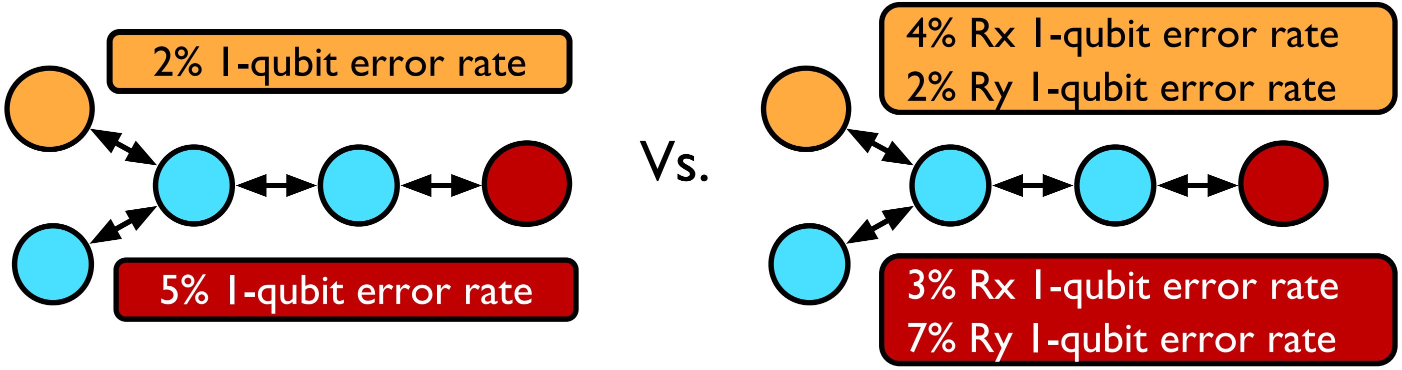
Where *g* is the success rate of gates and *m* is the success rate of readout (success rate = 1 - error rate)



What is Missing from Existing Solutions?

Previous solutions determine the optimal circuit map using qubit error rates identified during calibration to calculate circuit map success rate.

However, these single per-qubit error rates do not distinguish the difference in error rate among all the quantum operations that can be performed on a given qubit.



2% 1-qubit error rate

5% 1-qubit error rate

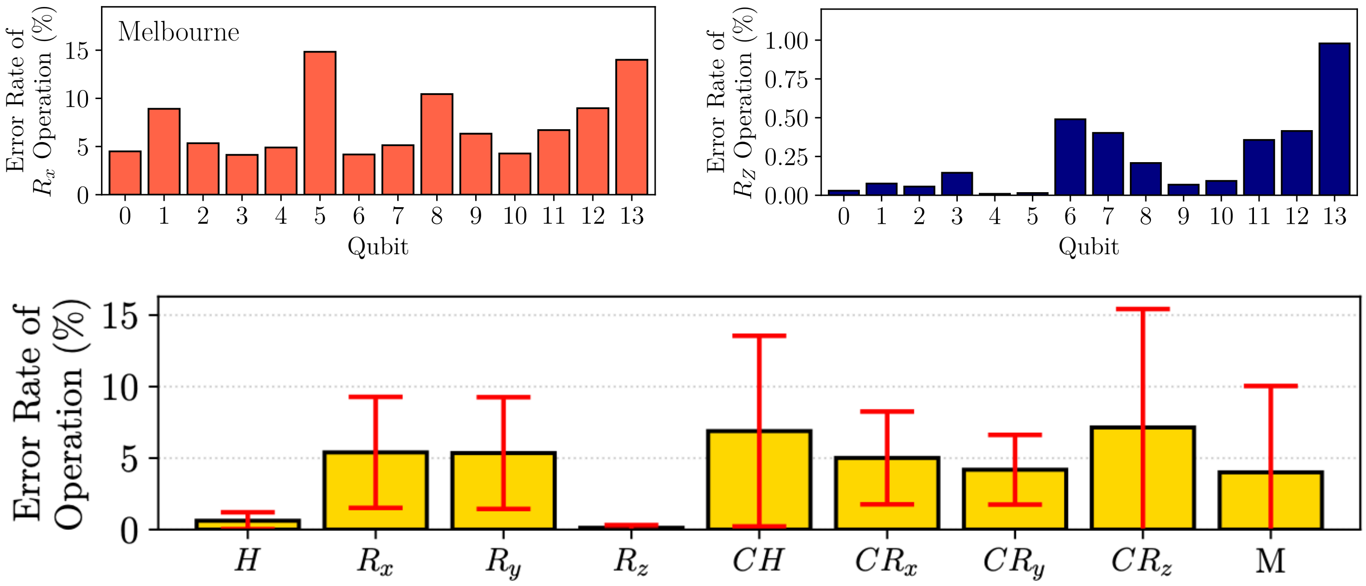
Vs.

4% Rx 1-qubit error rate
2% Ry 1-qubit error rate

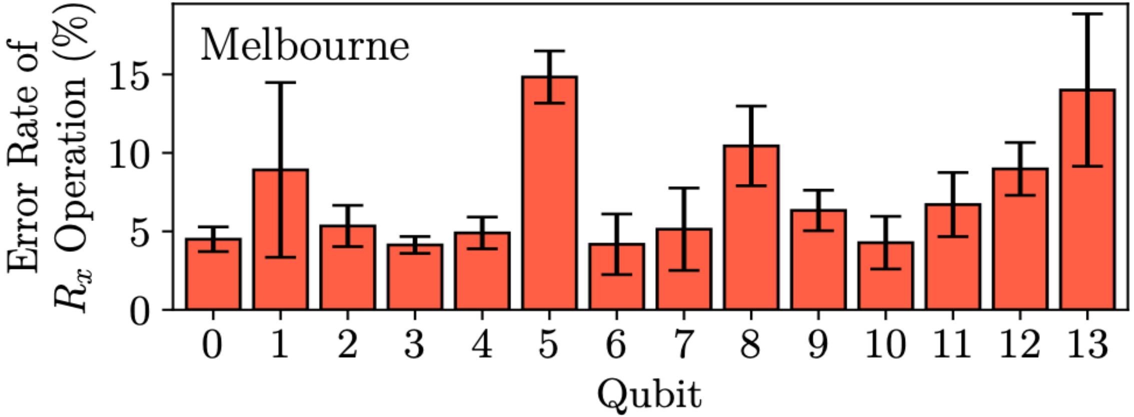
3% Rx 1-qubit error rate
7% Ry 1-qubit error rate

UREQA Observation 1: Different Quantum Operations have Different Error Rates

Different operations *on the same qubit* have over 5x different error rates.

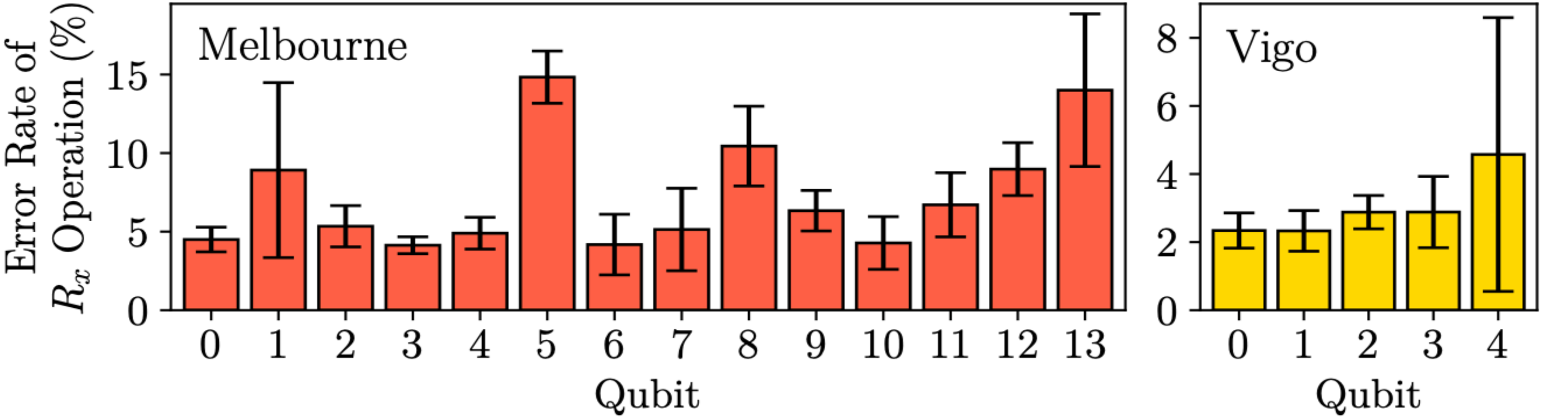


UREQA Observation II: Operation-Specific Error Rates Vary Significantly Temporally and Spatially



The operation-specific error rates vary *across* different qubits <u>within</u> the same machine and *over time*.

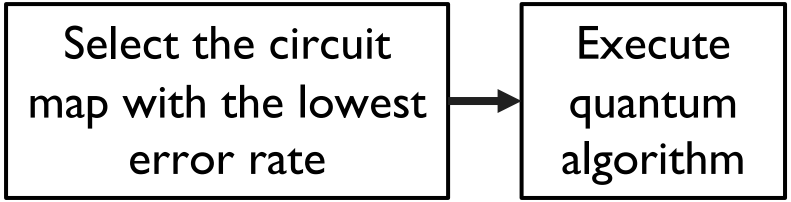
UREQA Observation II: Operation-Specific Error Rates Vary Significantly Temporally and Spatially



The degree of operation-specific error variance is different across quantum computers and exists even on newest quantum computers.

Machine-Learning-based Approach to Predict Error Rates of Quantum Operations

The goal of UREQA is to select the best circuit map
to execute a quantum algorithm.



Select the circuit map with the lowest error rate

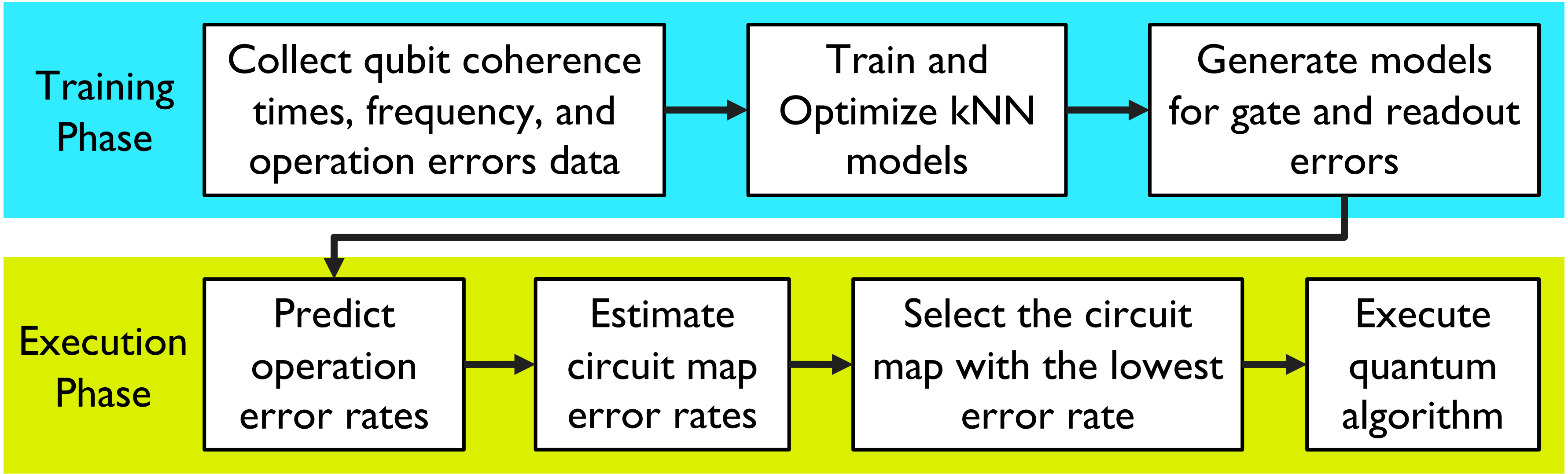
Execute quantum algorithm

Machine-Learning-based Approach to Predict Error Rates of Quantum Operations

To achieve this goal it needs to be able to estimate the error rates of different circuit maps by predicting the error rates of the underlying operations.

Predict operation error rates → Estimate circuit map error rates → Select the circuit map with the lowest error rate → Execute quantum algorithm

UREQA: A Machine-Learning-based Approach to Predict Error Rates of Quantum Operations



Training Phase

Collect qubit coherence times, frequency, and operation errors data

Train and Optimize kNN models

Generate models for gate and readout errors

Execution Phase

Predict operation error rates

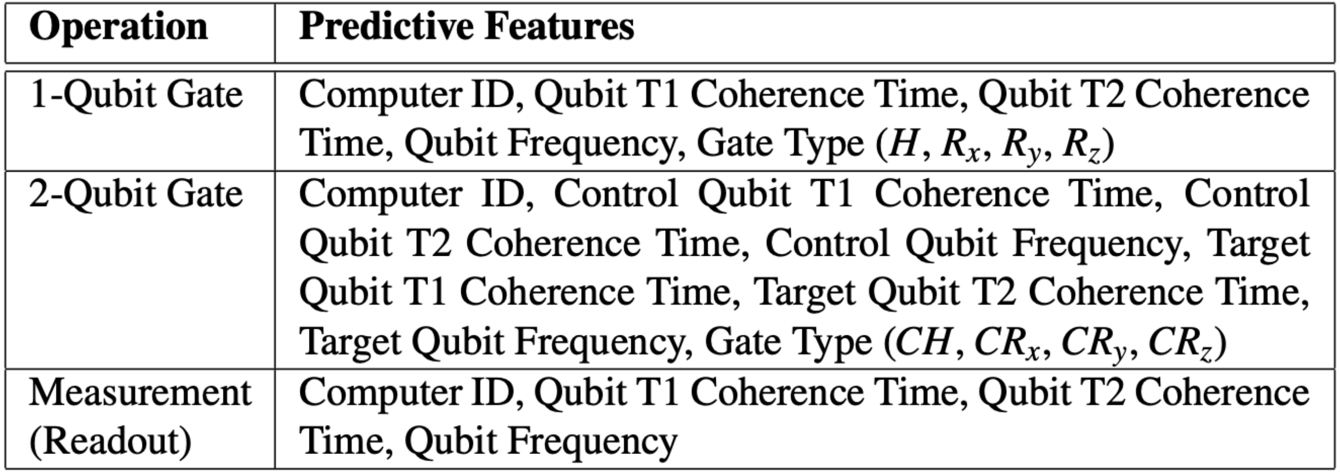
Estimate circuit map error rates

Select the circuit map with the lowest error rate

Execute quantum algorithm

What Predictive Features does UREQA Model Use?

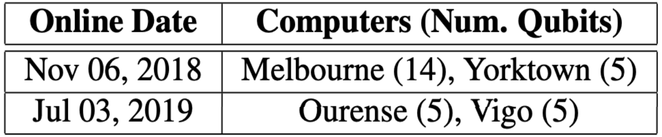
UREQA uses the following features for training the kNN models as they are readily available from daily qubit calibration. They account for over 95% of the variance based on PCA. Refer to the paper for model details.



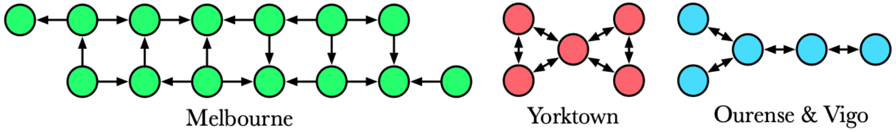
Operation	Predictive Features
1-Qubit Gate	Computer ID, Qubit T1 Coherence Time, Qubit T2 Coherence Time, Qubit Frequency, Gate Type (H, R_x, R_y, R_z)
2-Qubit Gate	Computer ID, Control Qubit T1 Coherence Time, Control Qubit T2 Coherence Time, Control Qubit Frequency, Target Qubit T1 Coherence Time, Target Qubit T2 Coherence Time, Target Qubit Frequency, Gate Type (CH, CR_x, CR_y, CR_z)
Measurement (Readout)	Computer ID, Qubit T1 Coherence Time, Qubit T2 Coherence Time, Qubit Frequency

UREQA Evaluation Methodology

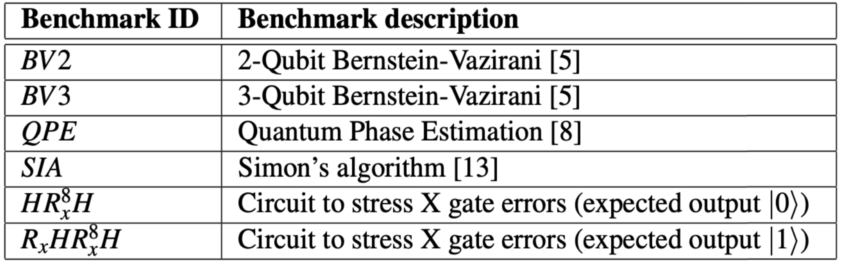
Experimental Platforms



Online Date	Computers (Num. Qubits)
Nov 06, 2018	Melbourne (14), Yorktown (5)
Jul 03, 2019	Ourense (5), Vigo (5)



Benchmarks



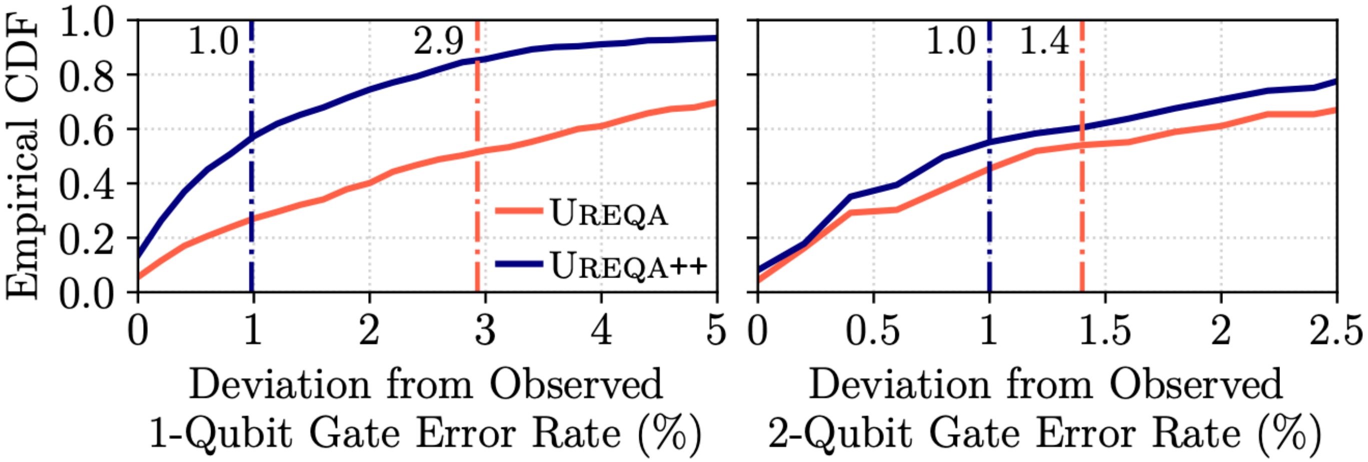
Benchmark ID	Benchmark description
$BV2$	2-Qubit Bernstein-Vazirani [5]
$BV3$	3-Qubit Bernstein-Vazirani [5]
QPE	Quantum Phase Estimation [8]
SIA	Simon's algorithm [13]
HR_x^8H	Circuit to stress X gate errors (expected output $\|0\rangle$)
$R_xHR_x^8H$	Circuit to stress X gate errors (expected output $\|1\rangle$)

Base Method Circuit map is selected using the best estimate when all operations are assumed to have the same error rate.

UREQA Circuit map is selected with KNN models trained without operation-specific information.

UREQA++ Circuit map is selected with KNN models trained with operation-specific information.

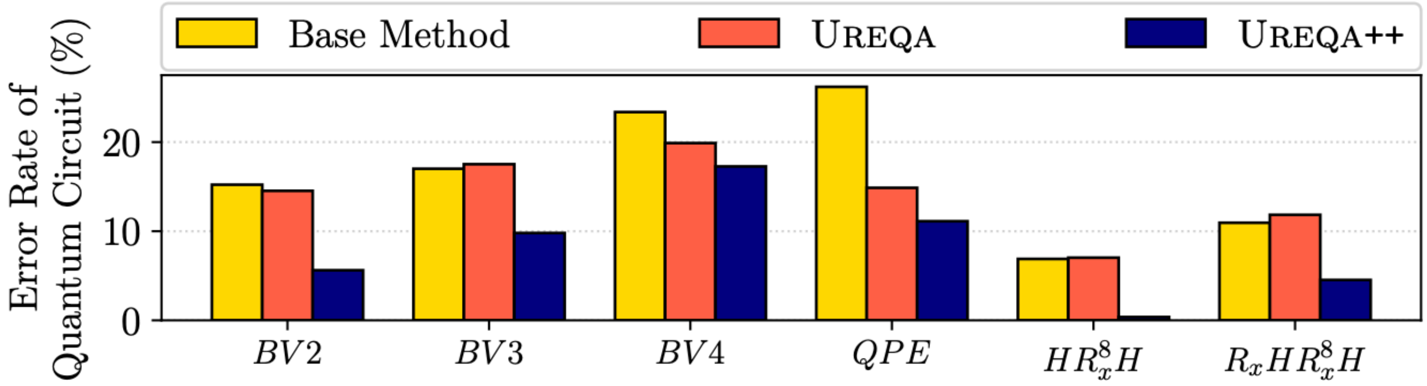
Operation-Aware UREQA++ Achieves the Lowest Deviation from Observed Error



UREQA++ reduces the deviation of the predicted error rate from the observed error rate which can be used for better quantum circuit mapping.

Operation-Aware UREQA++ Achieves the Lowest Error Rates Across Algorithms

By reducing the deviation of the predicted error from the observed error, UREQA++ successfully select better circuit maps, which in turn, reduce the output error rates across all algorithms.



Thank you!

UREQA is open-sourced at

https://github.com/GoodwillComputingLab/UREQA