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Experimentally Characterizing Quantum Processors Using Modeling and Simulation

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Fitting coarse-grained and application-focused noise models for NISQ devices

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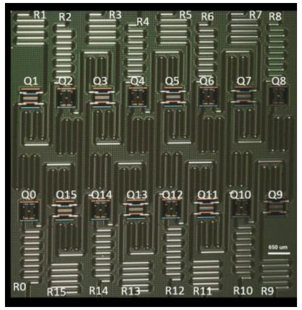
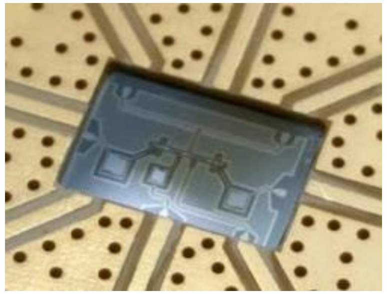
Current Quantum Processing Units

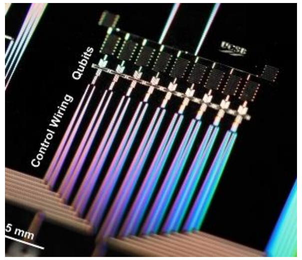
- QPU's are devices that implement the principles of digital quantum computing
  - Several different maturing technologies
  - Small register sizes (1-20)
  - Very high 1-qubit gate fidelities (0.999+)
  - Moderately high 2-qubit gate fidelities (0.99+)
  - Limited connectivity with good addressability
  - Low-depth sequences of reliable operations
  - Applications limited by gate noise, controllability
- Early stage vendors are offering access
  - D-Wave, IBM, IonQ, Google, Rigetti, Alibaba
  - Client-server interaction, "cloud" model
  - Very loose integration with modern computing



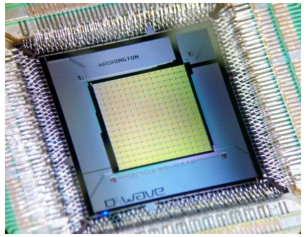
Superconducting chip from IBM



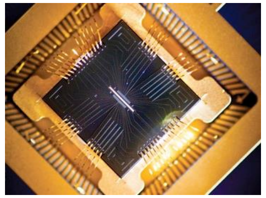
Superconducting chip from Rigetti



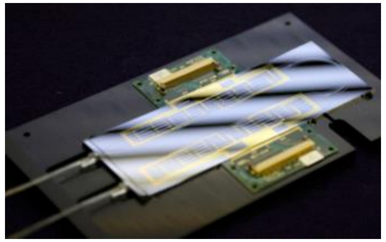
Superconducting chip from Google



Superconducting chip from D-Wave Systems

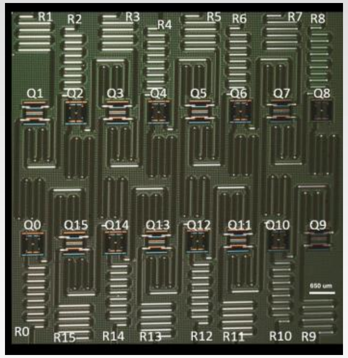
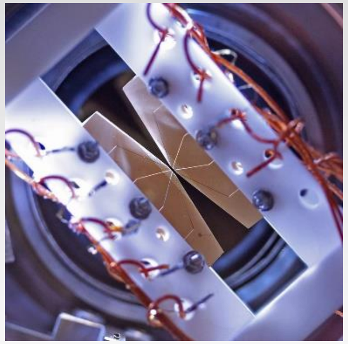
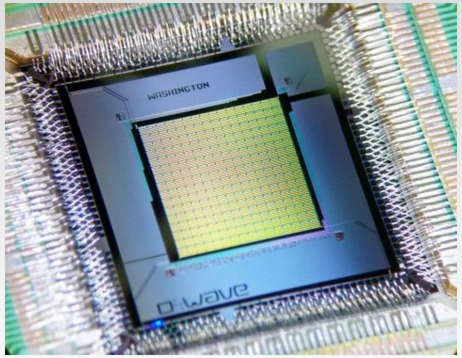


Ion trap chip from Sandia



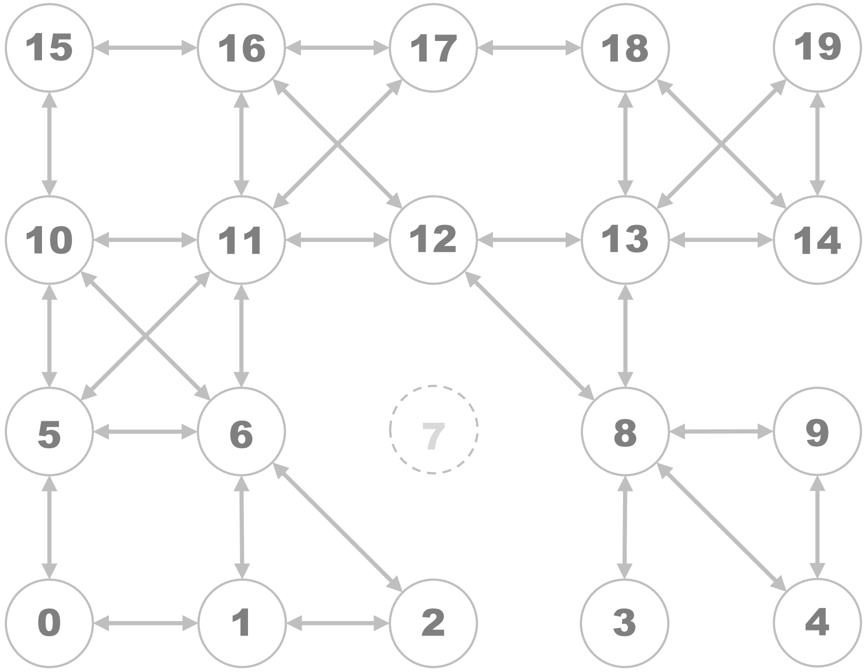
Linear optical chip from Univ. Bristol/QET Labs

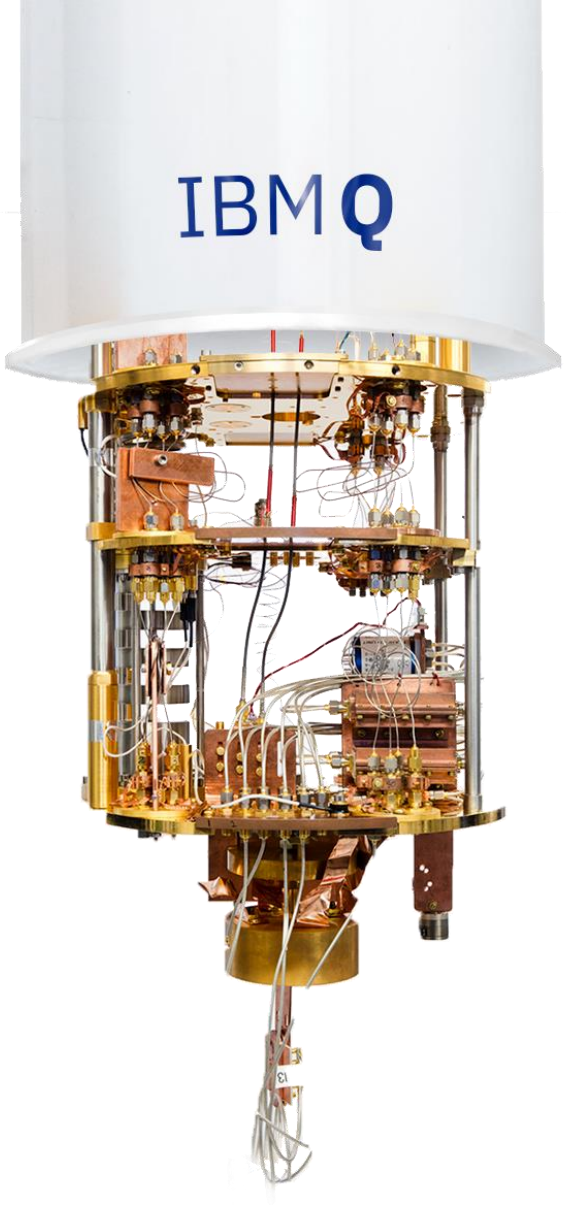
Measuring Quantum Computer Capabilities

Metrics	IBM	IonQ	D-Wave
			
Scale of qubits	5-50	5-79	2048
Initialization fidelity	95%	95%	99.9%
Gate set fidelity	99-95%	99-97%	N/A
Duty cycle	400	2,000	10^(-1)
Measurement fidelity	95%	95%	99.9%
Swap fidelity	98%	97%	N/A
Transport fidelity	N/A	N/A	N/A

Quantum Processing Unit (QPU)

IBM Q "Tokyo"





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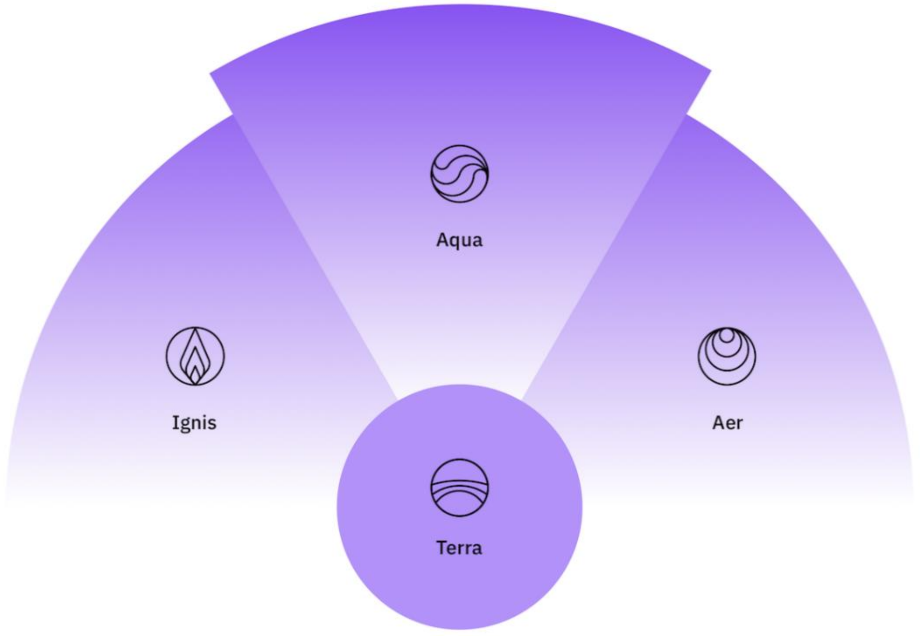
Right Image: IBM

Interfacing with the QPU

- IBM's Qiskit framework
- Software support for quantum computing
  - Running experiments on QPUs (Terra)
  - Simulating quantum circuits (Aer)
  - Draw from quantum algorithm libraries (Aqua)
  - Study and mitigate quantum noise (Ignis)



Images: Qiskit Docs

Example Programs

Qiskit Code

```
# Create a Quantum Register with 2 qubits
q = QuantumRegister(2)
# Create a Classical Register with 2 bits
c = ClassicalRegister(2)
# Create a Quantum Circuit
qc = QuantumCircuit(q, c)

#Create Bell state and measure
qc.h(q[0])
qc.cx(q[0], q[1])
qc.measure(q, c)

# See a list of available devices
print("IBMQ backends: ", IBMQ.backends())

# Compile and run the quantum circuit on a device
backend = IBMQ.get_backend('tokyo')
job_bellstate = execute(qc, backend, shots=8192)
result = job_bellstate.result()
```

QASM Code

```
OPENQASM 2.0;
include "qelib1.inc";
qreg q[3];
creg c0[1];
creg c1[1];
creg c2[1];
h q[1];
cx q[1],q[2];
y q[0];
x q[0];
measure q[0] -> c0[0];
measure q[1] -> c1[0];
measure q[2] -> c2[0];
```

Methods of Characterizing QPUs

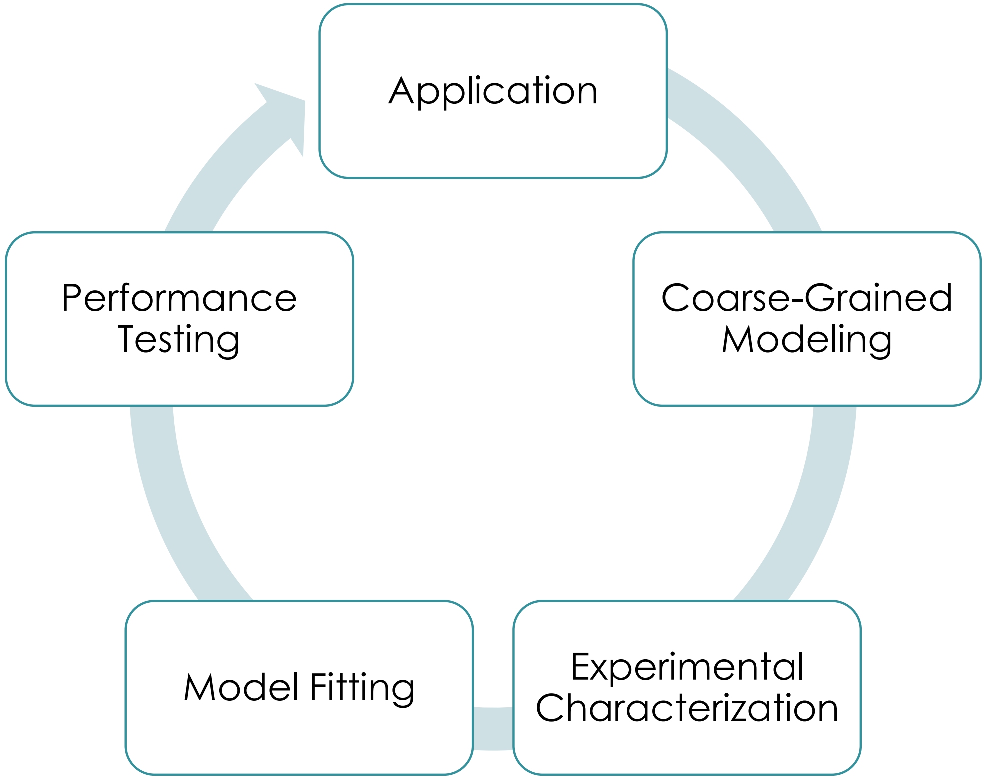
Fine-grain physics models

- Examples: quantum state tomography (QST), quantum process tomography (QPT), gate set tomography (GST), randomized benchmarking (RB)
- Very accurate and detailed description of the processor
- Computationally expensive
- Scales poorly with size of QPU

Coarse-grain circuit models

- Noisy circuit descriptions with reduced dimensionality
  - Empirical approach to inform descriptions of the processor
  - Varies depending on the experiment
- Approximate and effective description of the processor
- Computationally efficient
- Scales well with size of QPU

Experimental Characterization Workflow

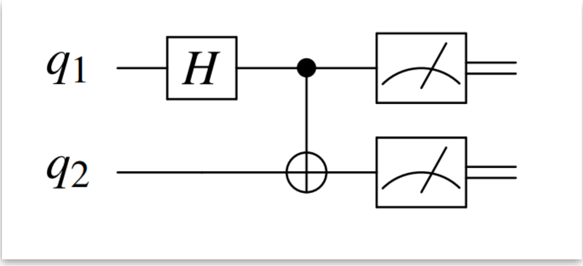


- The needs of the application determine what components we characterize.
- We run experiments on quantum hardware to perform these characterizations.
- We use simulation to test selected noise models.
- By comparing these simulations to the experimental results, we build noise models with the best fit to the experimental data.
- This process can be performed iteratively based on performance testing.

Application Example

Bell state

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|0_1 0_2\rangle + \ |1_1 1_2\rangle)$$

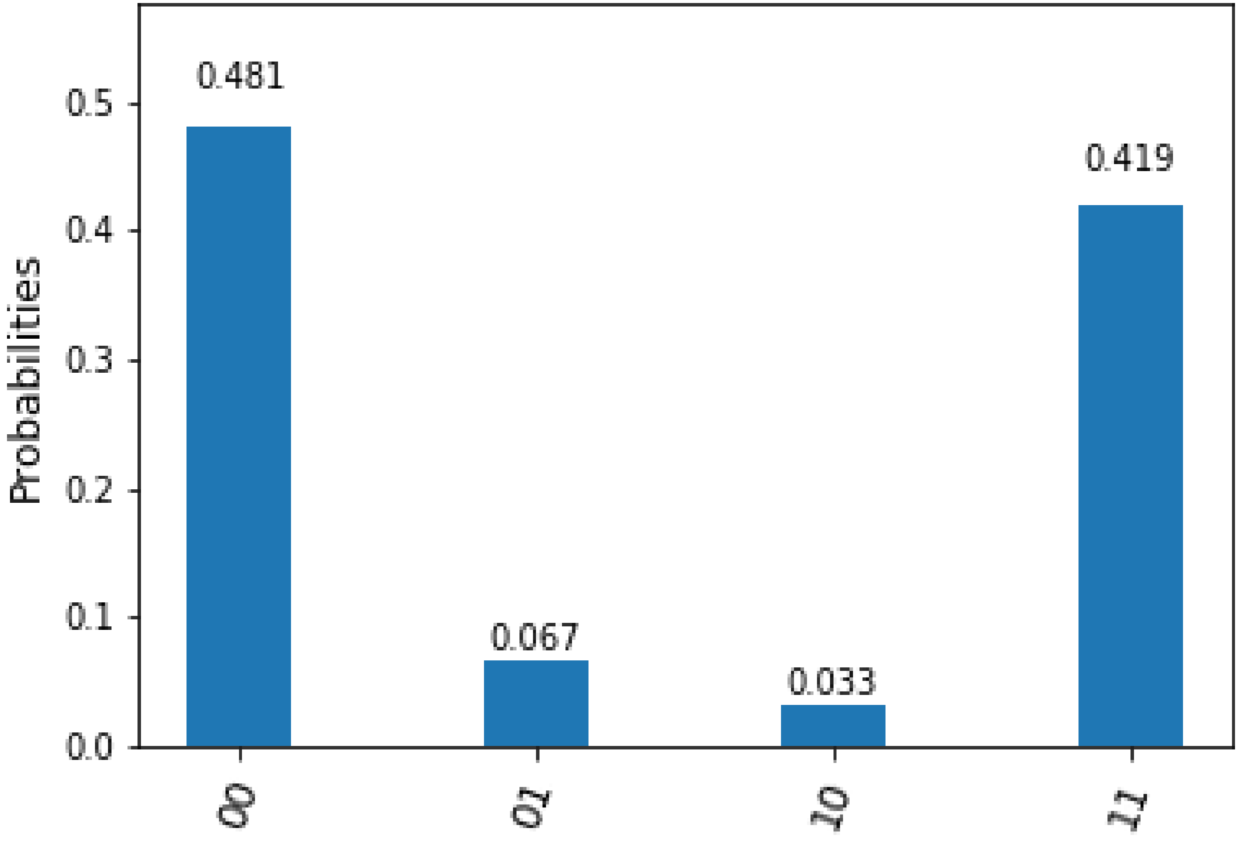


The Bell state represents an example of quantum superposition and entanglement in a simple circuit that can be implemented on existing hardware.

We characterize the pieces of this circuit – H, CNOT, and measurement – to find a noisy composite description of the hardware that closely matches experimental data.

Example of Bell state data from "Tokyo"

Probabilities of bit string results out of 8192



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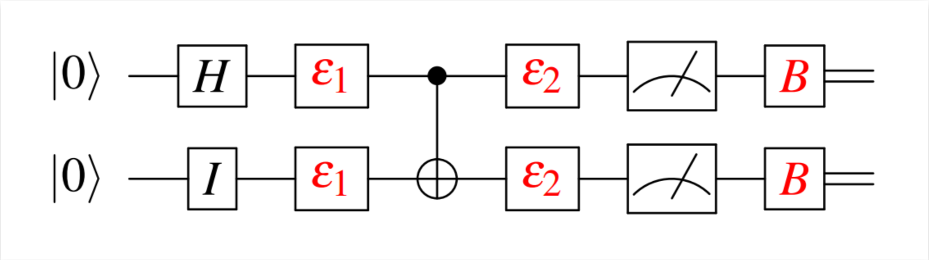
Noise Models



Using a bootstrapping approach, we can piece together a composite model for this circuit by considering smaller circuit examples.

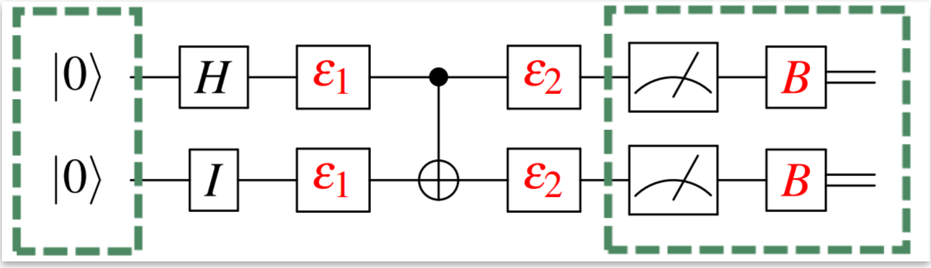
Error models:

- Depolarizing error
- Unitary rotations
- Symmetric/asymmetric bit flip

Components:

- Single qubit gates
- Two-qubit gates
- Readout

Noise Models



Starting with initialization and measurement, we characterize readout.

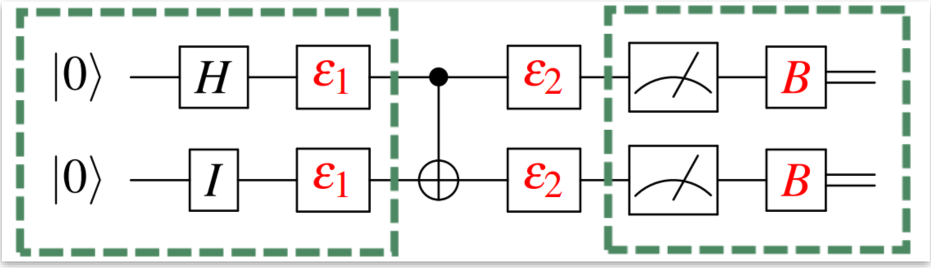
Error models:

- Depolarizing error
- Unitary rotations
- Symmetric/asymmetric bit flip

Components:

- Single qubit gates
- Two-qubit gates
- Readout

Noise Models

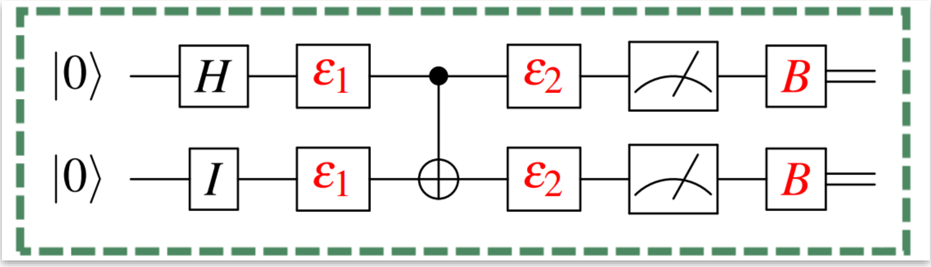


Using the description of readout noise we find from the previous example, we find a noise model that characterizes *H* gates.

- Depolarizing error
- Unitary rotations
- Symmetric/asymmetric bit flip

- Single qubit gates
- Two-qubit gates
- Readout

Noise Models

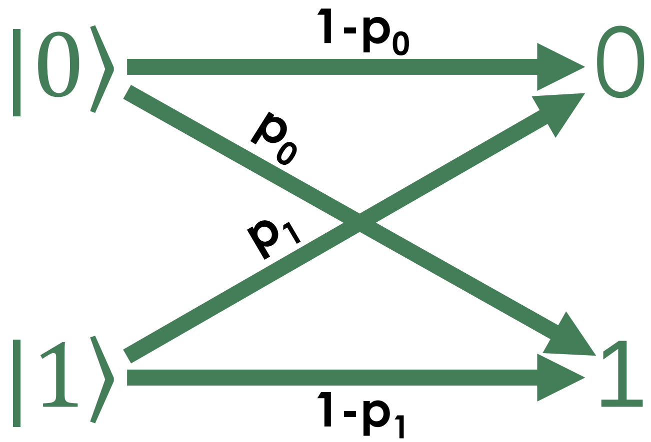


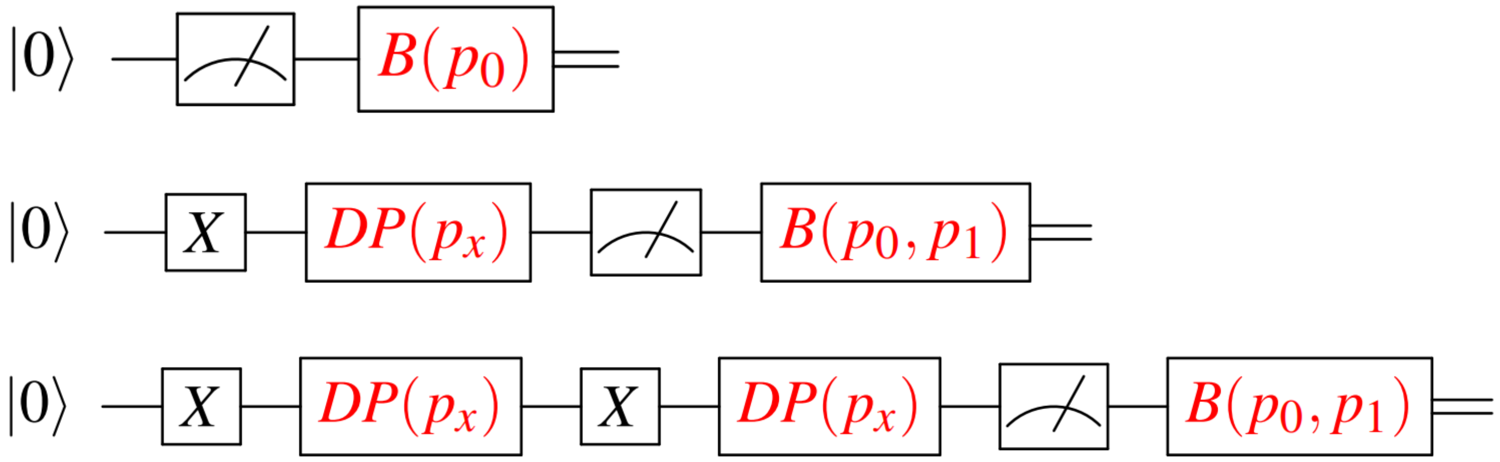
Finally, we characterize CNOT error using a full Bell state circuit.

- Depolarizing error
- Unitary rotations
- Symmetric/asymmetric bit flip

- Single qubit gates
- Two-qubit gates
- Readout

Asymmetric Readout (ARO) Parameters





$$p^{obs}_{X\ gate}(0) = \frac{2p_X}{3}(1-p_0) + \left(1 - \frac{2p_X}{3}\right)p_1$$

$$p^{obs}_{XX\ gates}(0) = \left[\left(1 - \frac{2p_X}{3}\right)^2 + \left(\frac{2p_X}{3}\right)^2\right](1-p_0) + \left[\frac{4p_X}{3}\left(1 - \frac{2p_X}{3}\right)\right]p_1$$

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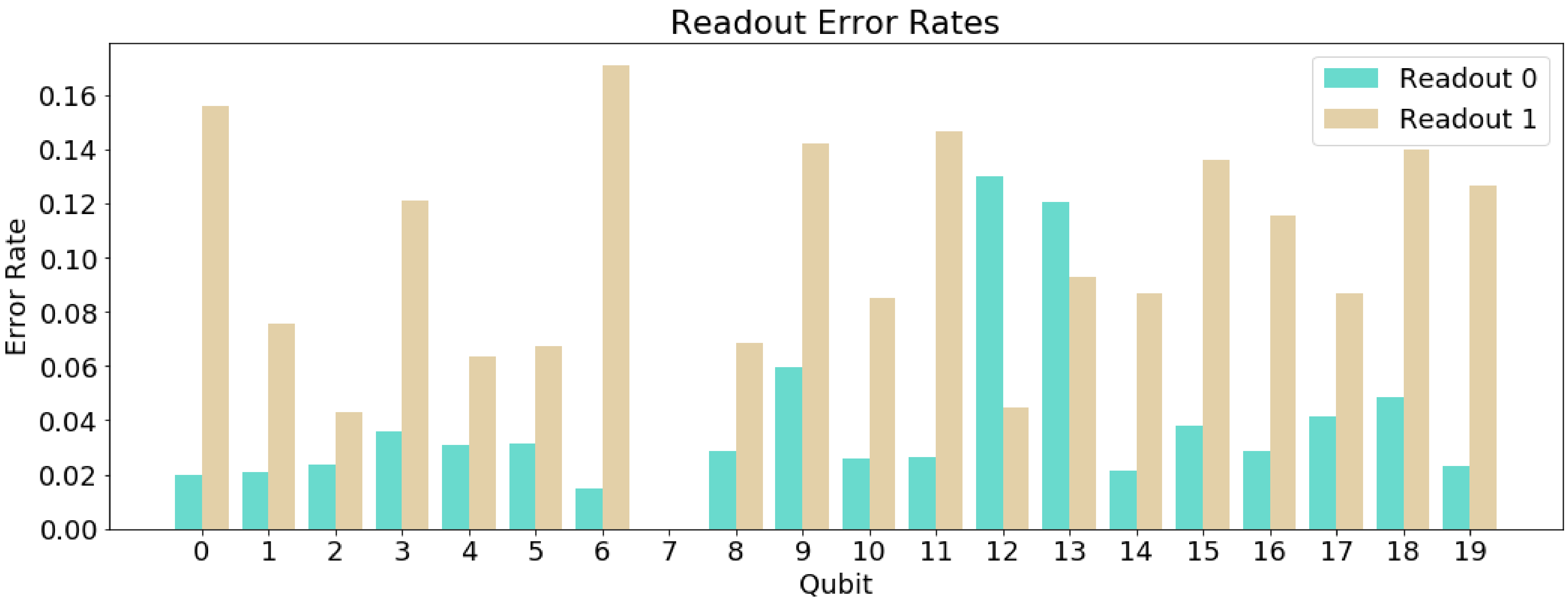


Readout Error Rates
Readout 0
Readout 1
Error Rate
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Qubit

19-qubit averages: $p_0 = 0.0385$

$p_1 = 0.0984$


X Gate Error Rates
Error Rate
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Qubit

CNOT Depolarizing Parameters

For depolarizing noise, defined as a probability p_{DP} of a Pauli X, Y, or Z operation, we label results after the depolarizing channel with ij and after measurement with asymmetric readout error (ARO) as kl; we obtain a value for p_{DP} that makes $p^{obs}(kl) = \sum_{ij} p_{ij}(kl)$ true.

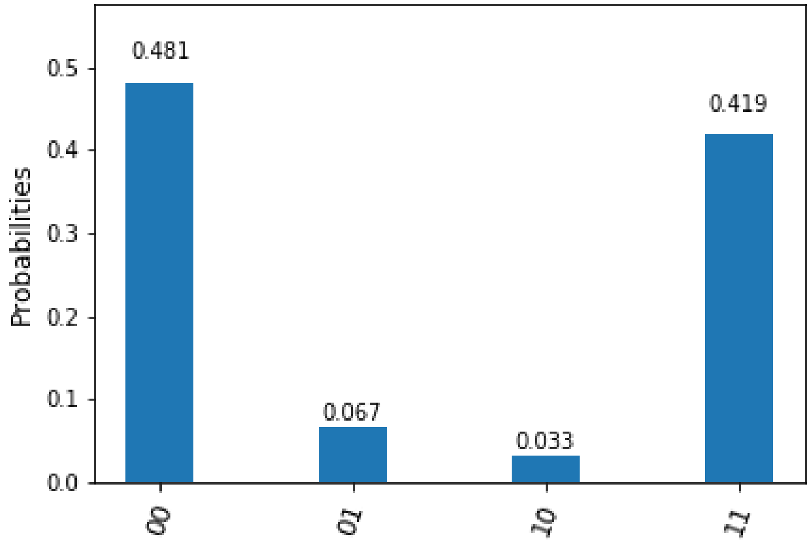
$$p(ij) = Tr\left[\Pi_{ij}\epsilon_{DP}\left(U_{BS}|0\rangle\langle 0|U_{BS}^{\dagger}\right)\right],\ p_{ij}(kl) = ARO\left(p(ij)\right)$$

$$p_{00}(kl) = p_{11}(kl) = ARO\left(\left[\frac{1}{2}(1-p_{DP})^2 + p_{DP}(1-p_{DP}) + \frac{3}{2}p_{DP}^2\right]\right)$$

$$p_{01}(kl) = p_{10}(kl) = ARO\left(2p_{DP}(1-p_{DP})\right)$$

Example of CNOT Model Fitting

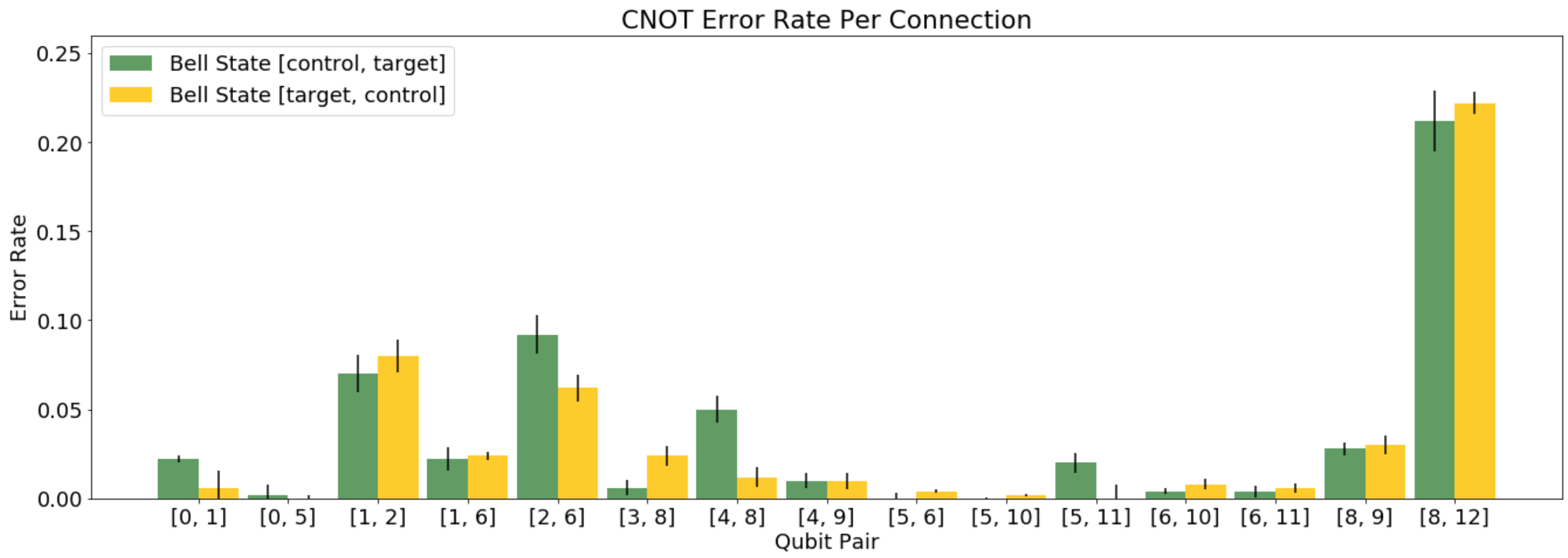
Experimental results for a single coupling

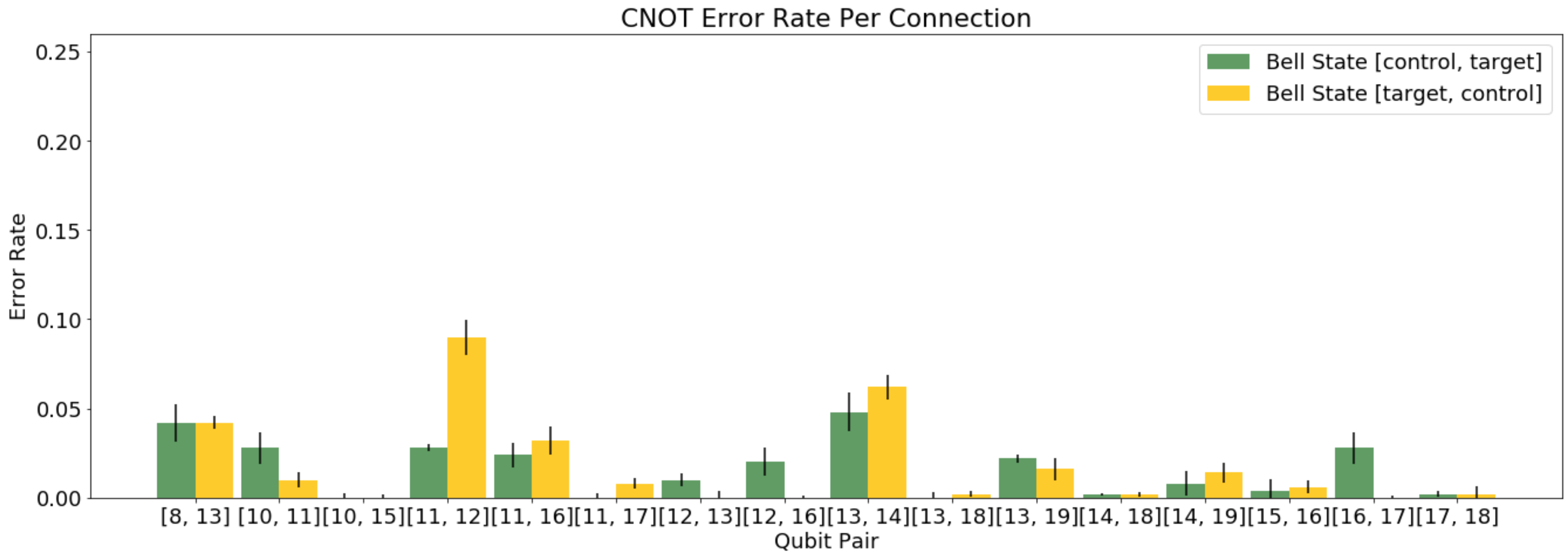


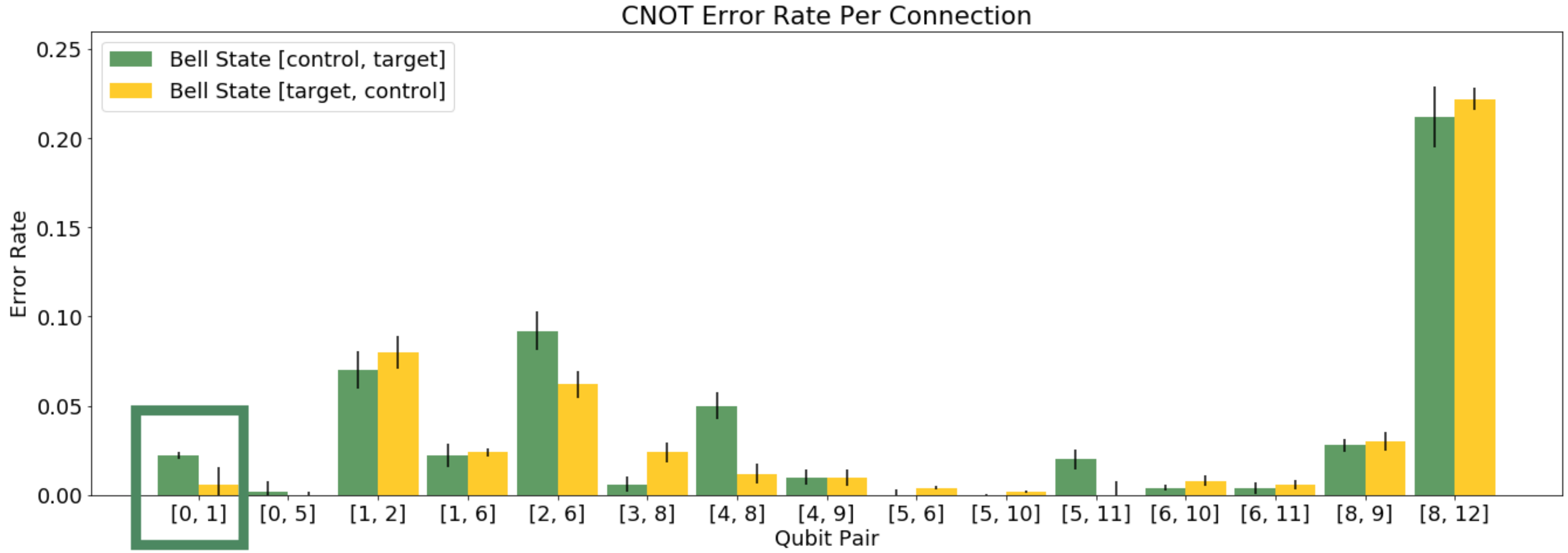
- Inject noise into simulations of quantum circuits and perform measurement
- Compare simulation results to experimental results using the expression for **model error**:

$$E_{model} = \sum_i \left(\frac{h_i^{exp}}{N} - \frac{h_i^{sim}}{N} \right)^2$$

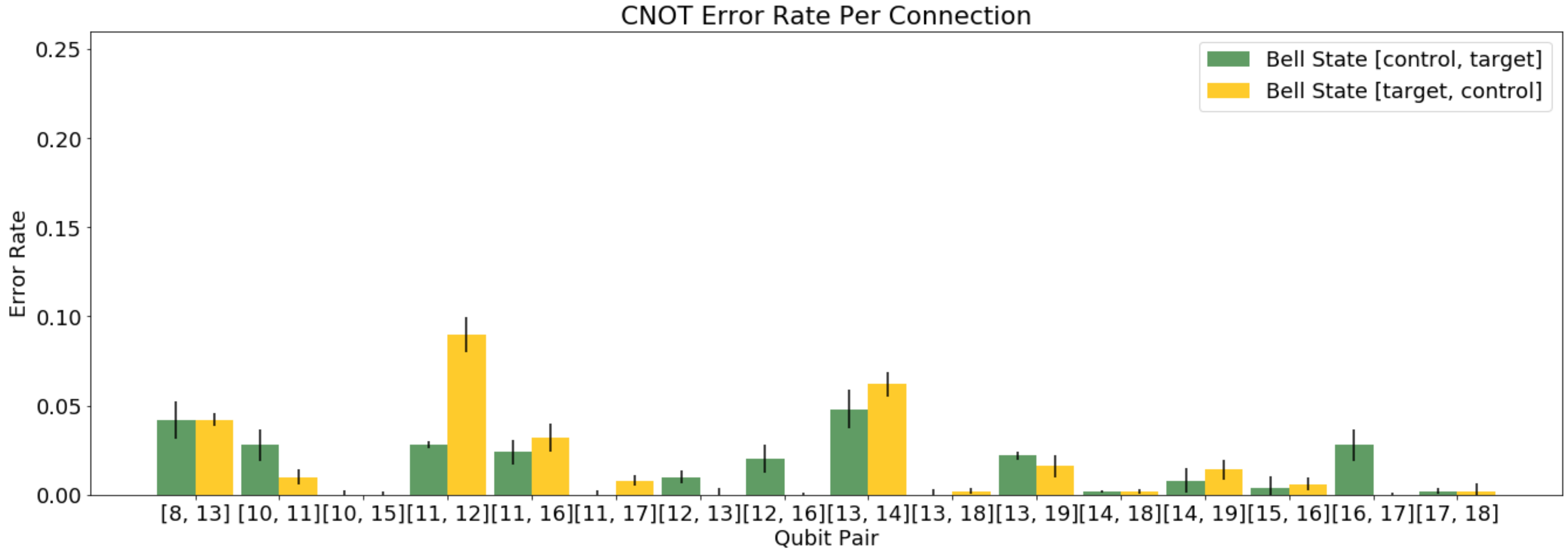
- Minimize this quantity to determine best fit


CNOT Error Rate Per Connection
Bell State [control, target]
Bell State [target, control]
Error Rate
0.25
0.20
0.15
0.10
0.05
0.00
[0, 1]
[0, 5]
[1, 2]
[1, 6]
[2, 6]
[3, 8]
[4, 8]
[4, 9]
[5, 6]
[5, 10]
[5, 11]
[6, 10]
[6, 11]
[8, 9]
[8, 12]
Qubit Pair


CNOT Error Rate Per Connection
Bell State [control, target]
Bell State [target, control]
Error Rate
0.25
0.20
0.15
0.10
0.05
0.00
[8, 13]
[10, 11]
[10, 15]
[11, 12]
[11, 16]
[11, 17]
[12, 13]
[12, 16]
[13, 14]
[13, 18]
[13, 19]
[14, 18]
[14, 19]
[15, 16]
[16, 17]
[17, 18]
Qubit Pair



Average over all 62:
$p_{DP} = 0.0255$



Numerical Simulations of Quantum Circuits

- Classical computer optimized for quantum circuit simulation on site at ORNL
  - TBs of RAM
  - Up to ~40 qubits
- QPU emulator
  - Write quantum circuits in AQASM language
  - Compile to simulator

Image: Atos

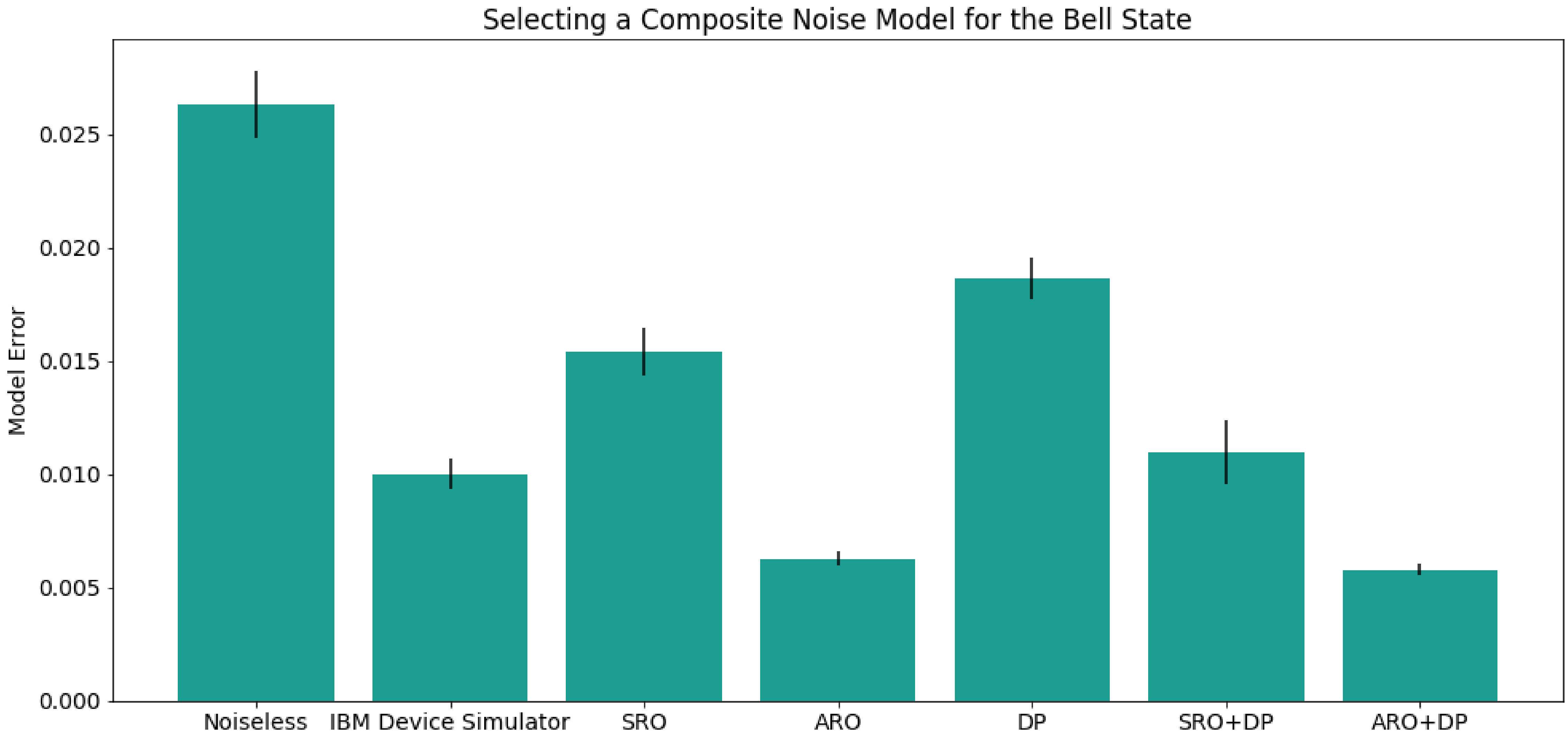
Interfacing with the QLM

- Python control “PyAQASM”
- Create AQASM circuit descriptions
- Execute on chosen simulator
  - Linear algebra
  - Stabilizer
  - MPS
  - Feynman path integral
  - Density matrix

AQASM file example

```
BEGIN
qubits 13
cbits 10

RY[1.7401524607843557] q[3]
PH[1.7150018525366089] q[3]
H q[4]
H q[5]
H q[6]
CNOT q[3],q[2]
CNOT q[3],q[1]
END
```

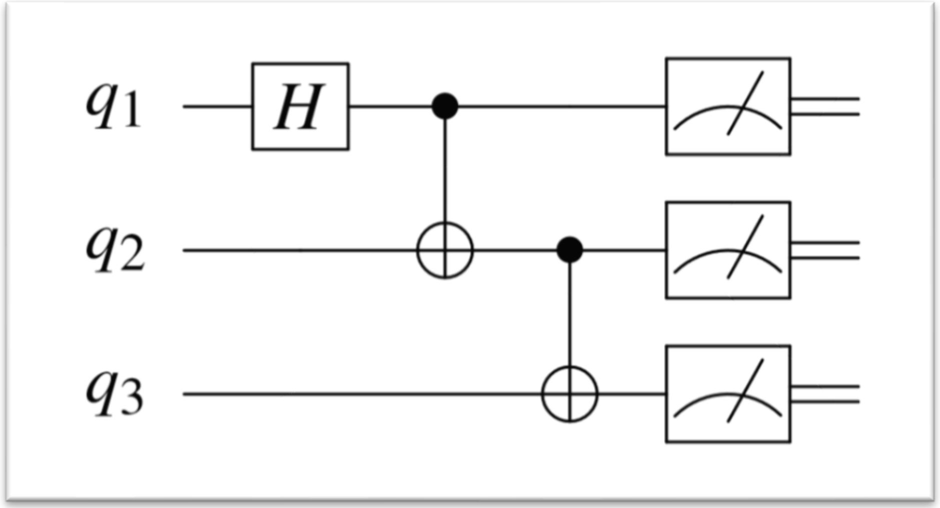


Selecting a Composite Noise Model for the Bell State
Model Error
0.025
0.020
0.015
0.010
0.005
0.000
Noiseless
IBM Device Simulator
SRO
ARO
DP
SRO+DP
ARO+DP

GHZ States

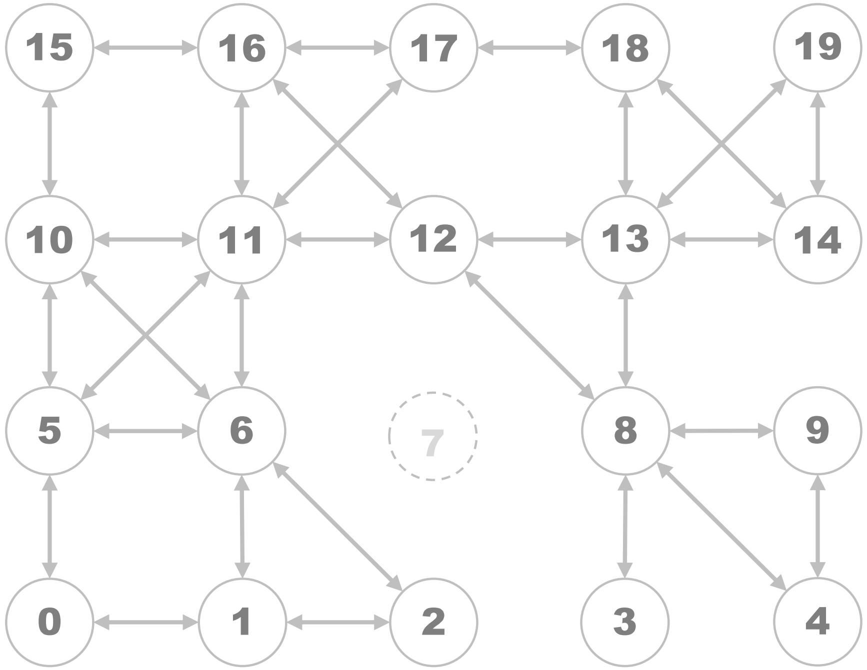
n-qubit GHZ for *n* = {2, 3, …, 20}

$$|GHZ(n)\rangle = \frac{|0\rangle^{\otimes n} + |1\rangle^{\otimes n}}{\sqrt{2}}$$



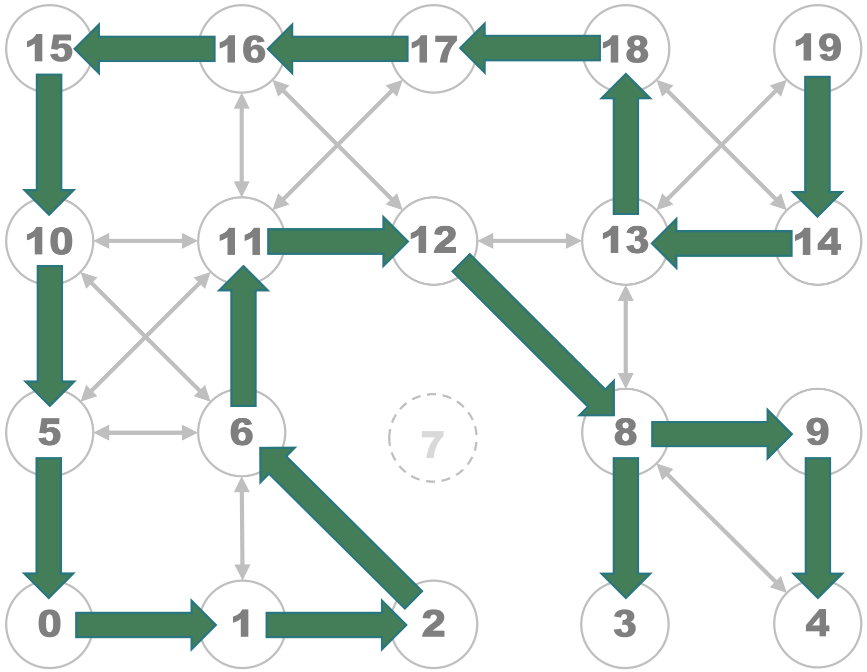
GHZ on Tokyo

"Tokyo" layout at time of data collection.



GHZ on Tokyo

For $n = \{2, 3, \ldots, 20\}$, we map the GHZ circuits onto the chip as shown (arrow from control to target).



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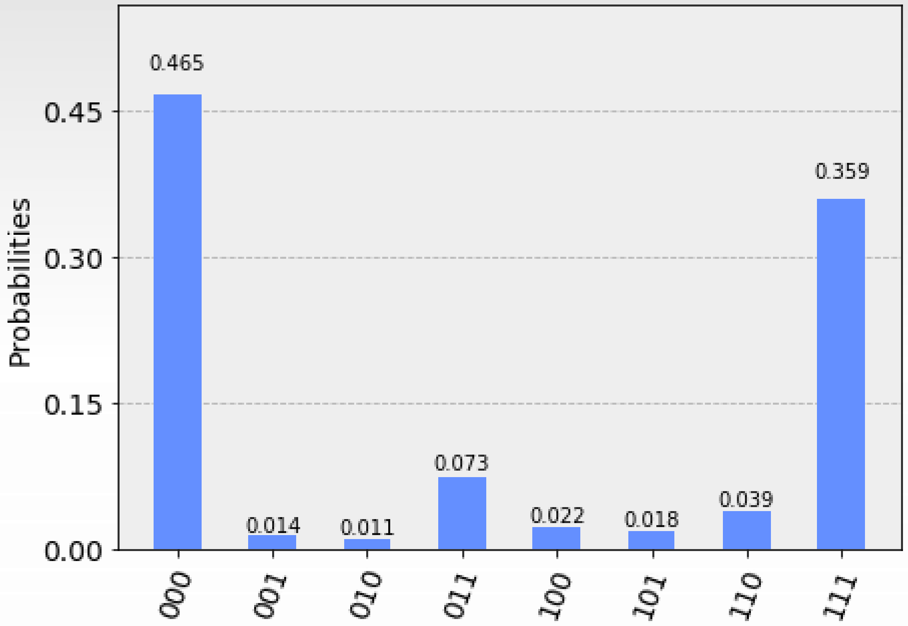
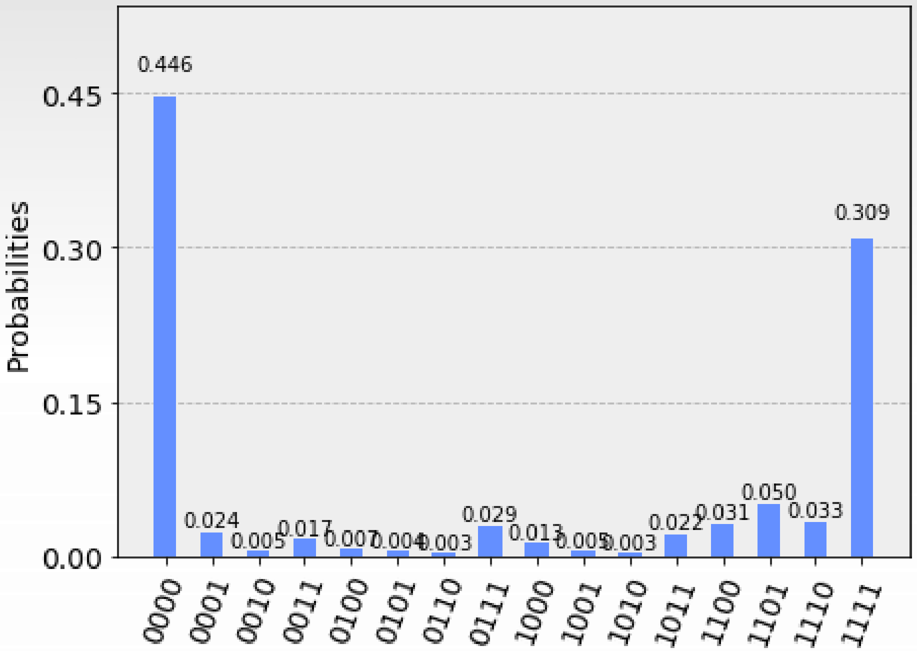
Examples of Experimental Results from QPU

3-qubit GHZ results

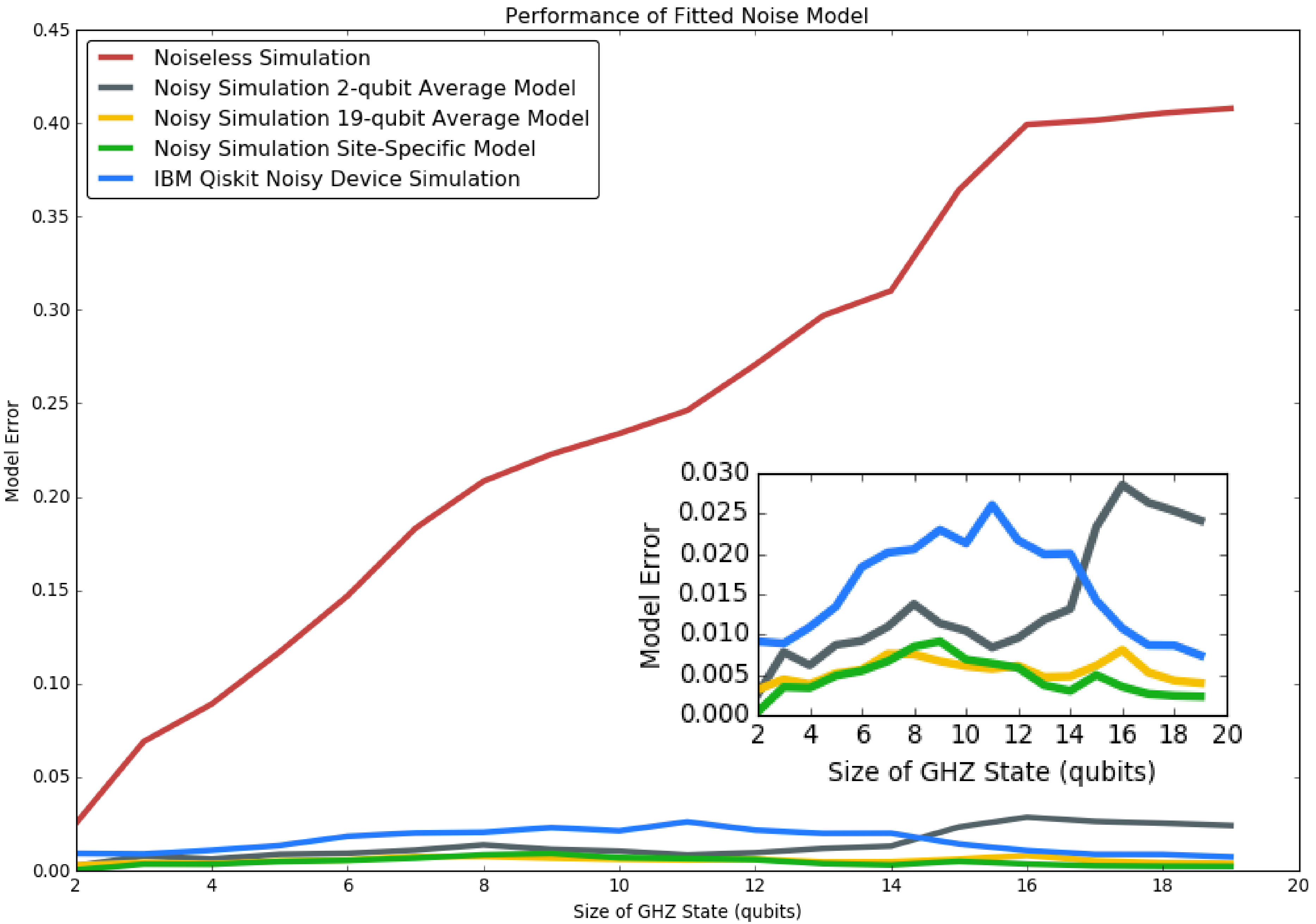


4-qubit GHZ results



GHZ on Tokyo

For GHZ states of increasing size, model error in noisy simulation increases far less dramatically than noiseless and remains under 3% even for the largest circuits.



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Conclusions

- Coarse-grained, application-focused noise models can be used to predict the performance of NISQ devices.
- Development of these noise models requires few computational resources.
  - Needs as few as 4 characterization circuits
  - Yields as few as 3 noise parameters
- Coarse-graining is an iterative process driven by required accuracy.
- Future work will include more refined noise models, exploration of other applications, and comparisons to other characterization methods.

Thank you

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Bonus Slides

Aer “Basic Device Noise Model”

- Input RB error rates from daily calibration and device properties from selected backend
- One- and two-qubit gate errors
  - Determine thermal relaxation error from T1, T2, and gate times
  - Add a depolarizing probability parameter such that the error rates of DP+TR=RB
- Readout error
  - Use reported readout error from RB protocol as symmetric bit flip channel

Code example

```
'''Qiskit-provided basic device noise model'''
# Choose a real device to simulate
device = IBMQ.get_backend('tokyo')
properties = device.properties()
coupling_map = device.configuration().coupling_map

# Generate an Aer noise model for device
noise_model = noise.device.basic_device_noise_model(properties)
basis_gates = noise_model.basis_gates

#Define registers
q = QuantumRegister(20)
c = ClassicalRegister(20)
#Circuit list
bell = QuantumCircuit(q, c)
bell.h(q[0])
bell.cx(q[0],q[1])
bell.barrier()
bell.measure(q, c)

pm = PassManager()
pm.append(Unroller(['u1', 'u2', 'u3', 'cx', 'id']))

# Perform noisy simulation
backend = Aer.get_backend('qasm_simulator')
job_sim = execute(circuits, backend, shots=8192,
                  pass_manager = pm,
                  coupling_map=coupling_map,
                  noise_model=noise_model,
                  basis_gates=basis_gates)
```

Aer "Basic Device Noise Model"

- Input RB error rates from daily calibration and device properties from selected backend
- One- and two-qubit gate errors
  - Determine thermal relaxation error from T1, T2, and gate times
  - Add a depolarizing probability parameter such that the error rates of **DP=RB**
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#Circuit list
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                  noise_model=noise_model,
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```