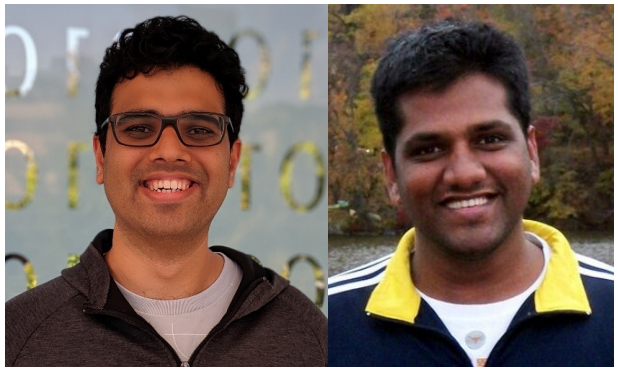
Mitigating Measurement Errors in Quantum Computers by Exploiting State-Dependent Bias

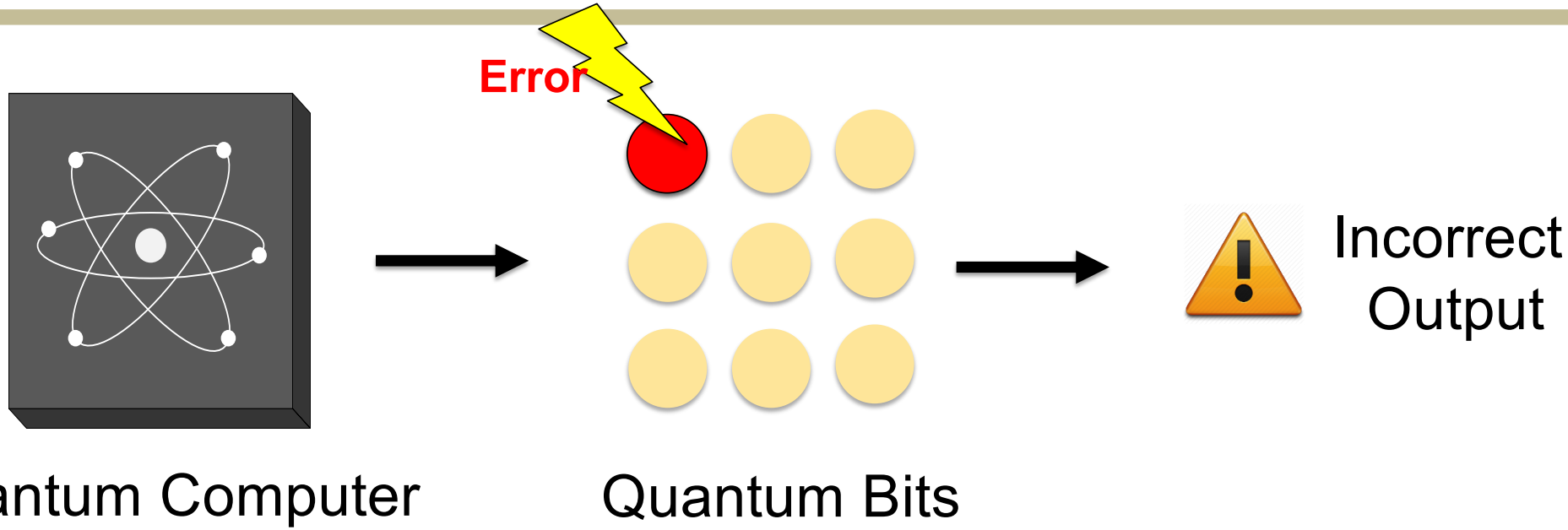
Swamit Tannu and Moinuddin Qureshi



Georgia Tech

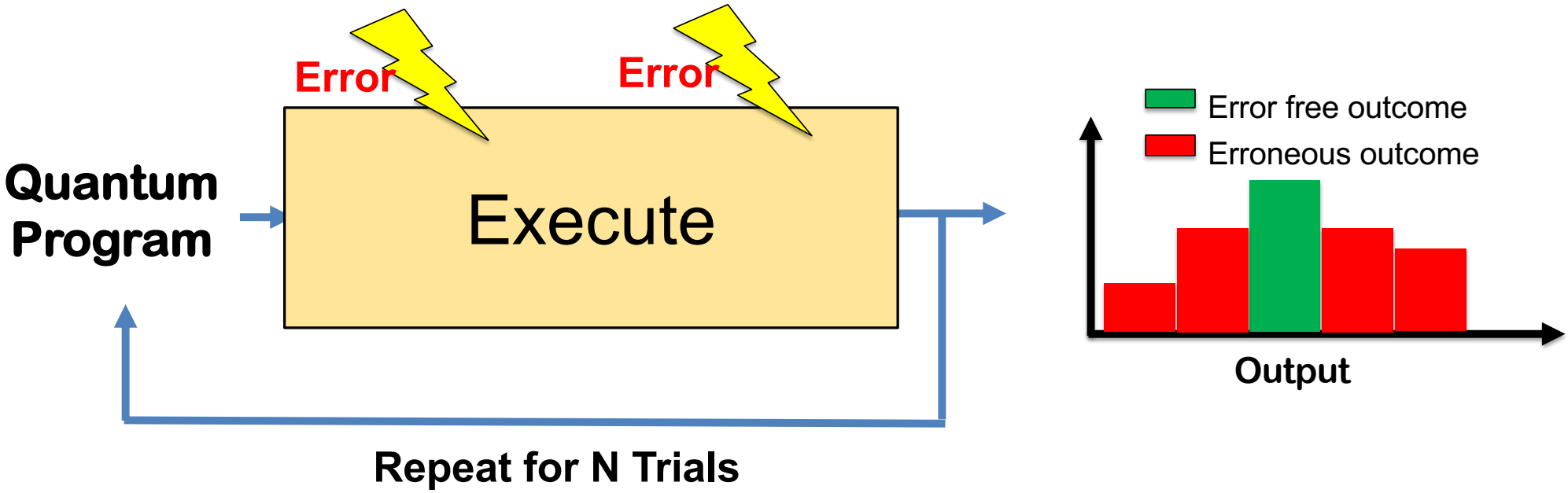
CREATING THE NEXT

Near-term Quantum Computers will be Noisy!



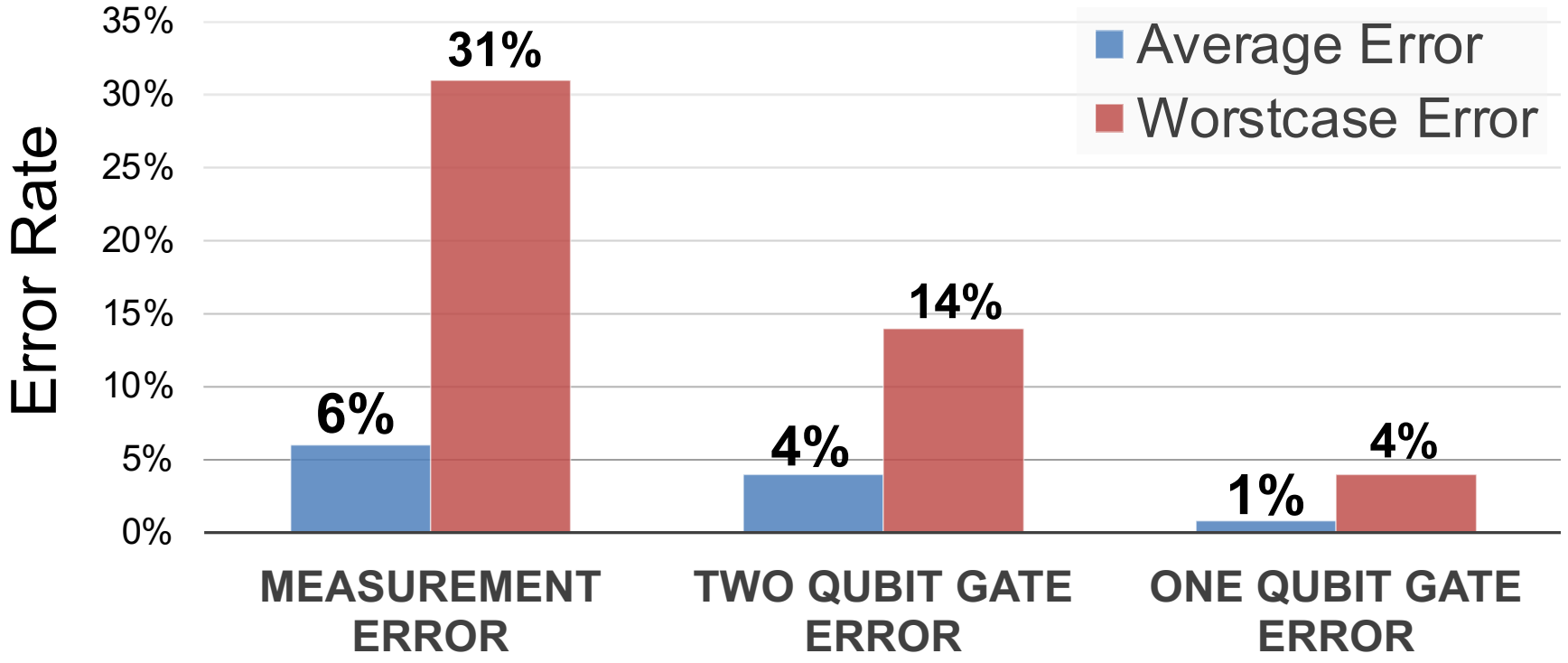
Can’t enable fault-tolerance using quantum error correction→ Noisy Intermediate Scale Quantum (NISQ) Computers

Execution Model for NISQ



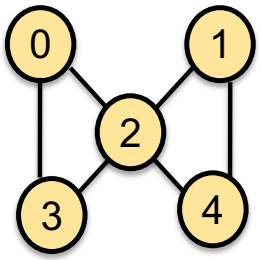
Quantum gates and measurements introduce errors

Error on IBMQ14 Quantum Computer

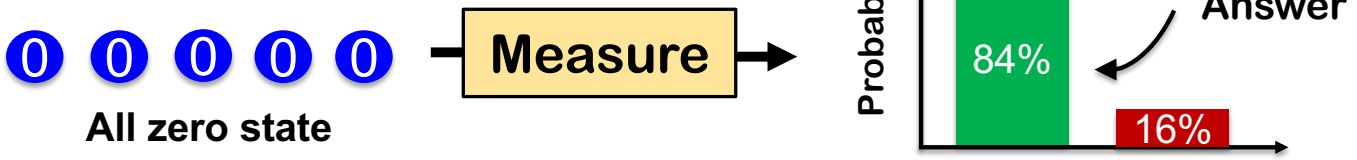


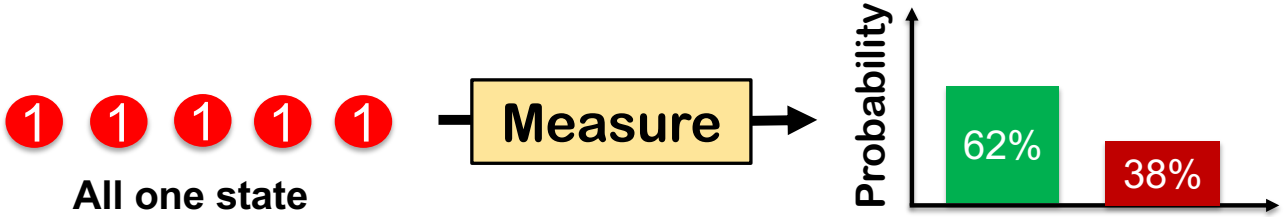
Qubit measurement error → dominant error

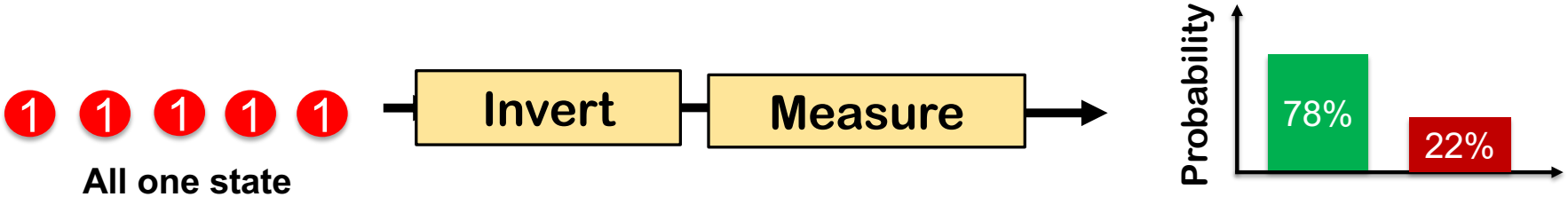
Experiments on IBM Quantum Computer



ibmqx4







Measurement errors have directional bias

Insight

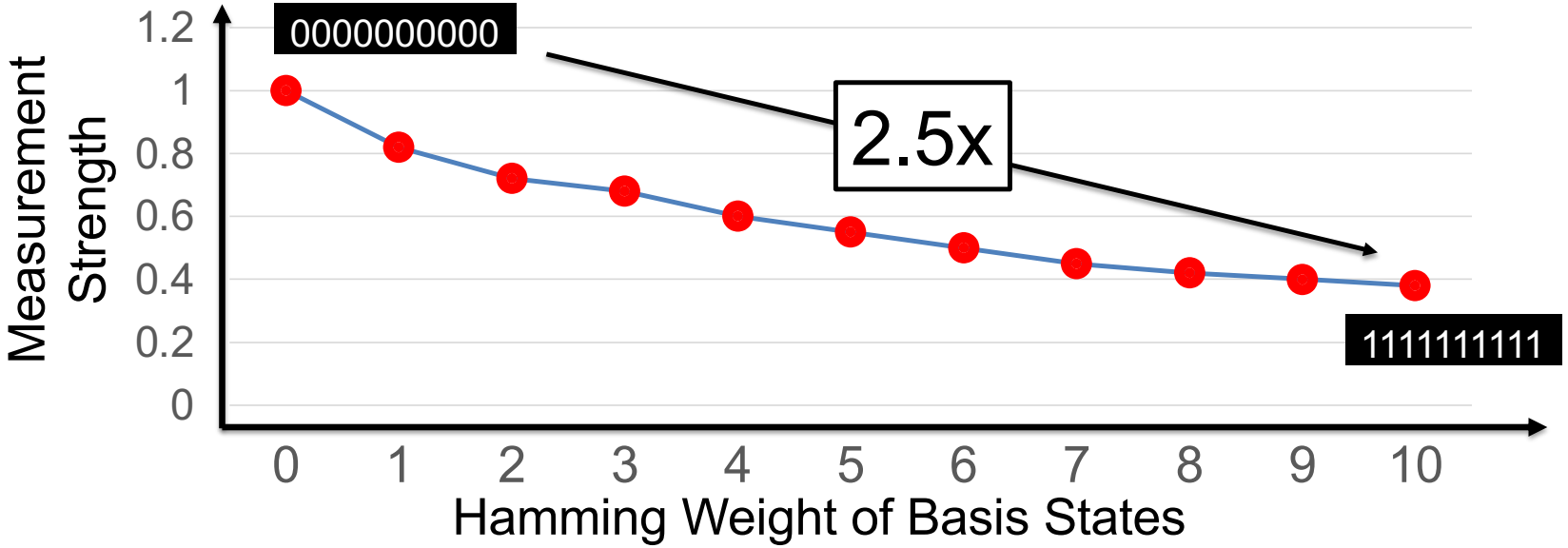
Exploit the state-dependent bias to reduce the impact of measurement errors

OUTLINE

- Introduction
- Characterization of Measurement Bias
- Static Invert and Measure (SIM)
- Adaptive Invert and Measure (AIM)
- Evaluations

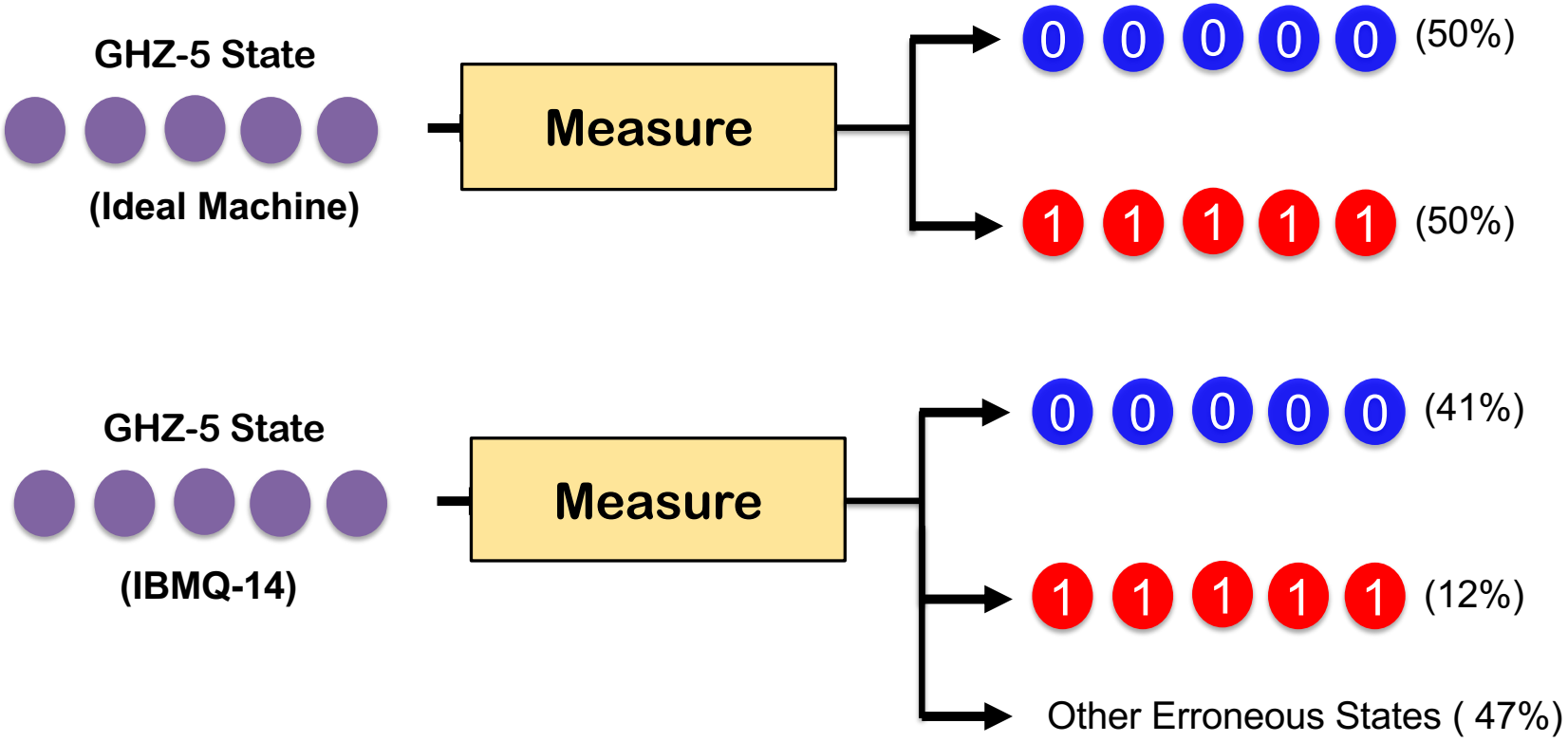
Measurement Bias on IBM Machine (IBMQ-14)

- We measure all 10 bit basis states (2^{10}) on fourteen qubit machine



Measurement Strength is negatively corelated to Hamming weight of data

Impact of Bias on Superposition State



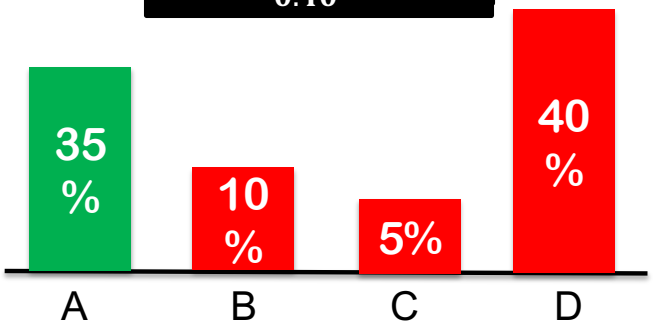
Measurement Bias Effects Quantum States with Superposition

Figure of Merit: Inference Strength (IST)

$$IST = \frac{Probability\ of\ Erorr\ Free\ Output}{Probability\ of\ Erroneous\ Output\ with\ Highest\ Frequency}$$

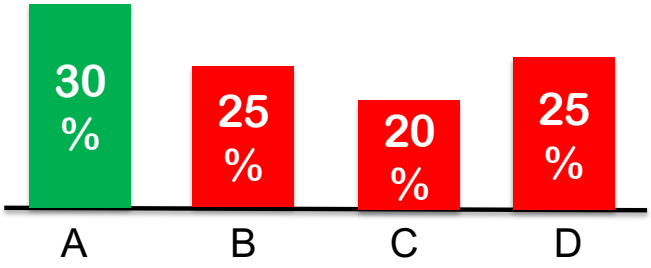
Incorrect Inference

IST = $\frac{0.35}{0.40}$ = 0.87



Correct Inference

IST = $\frac{0.3}{0.25}$ = 1.25



IST captures quality of inference. IST > 1 ensures correct answer is strongest

IST of Baseline

Benchmark	Platform	Baseline
BV-4A	IBMQX2 (5 Qubits)	1.22 ✓
BV-4B		0.9
QAOA-4A		0.73
QAOA-4B		0.72
BV-4A	IBMQX4 (5 Qubits)	0.46
BV-4B		4.8 ✓
QAOA-4A		0.82
QAOA-4B		0.72
BV-6	IBMQ-Melbourne (14 Qubits)	0.70
BV-7		0.62
QAOA-6		0.23
QAOA-7		0.18

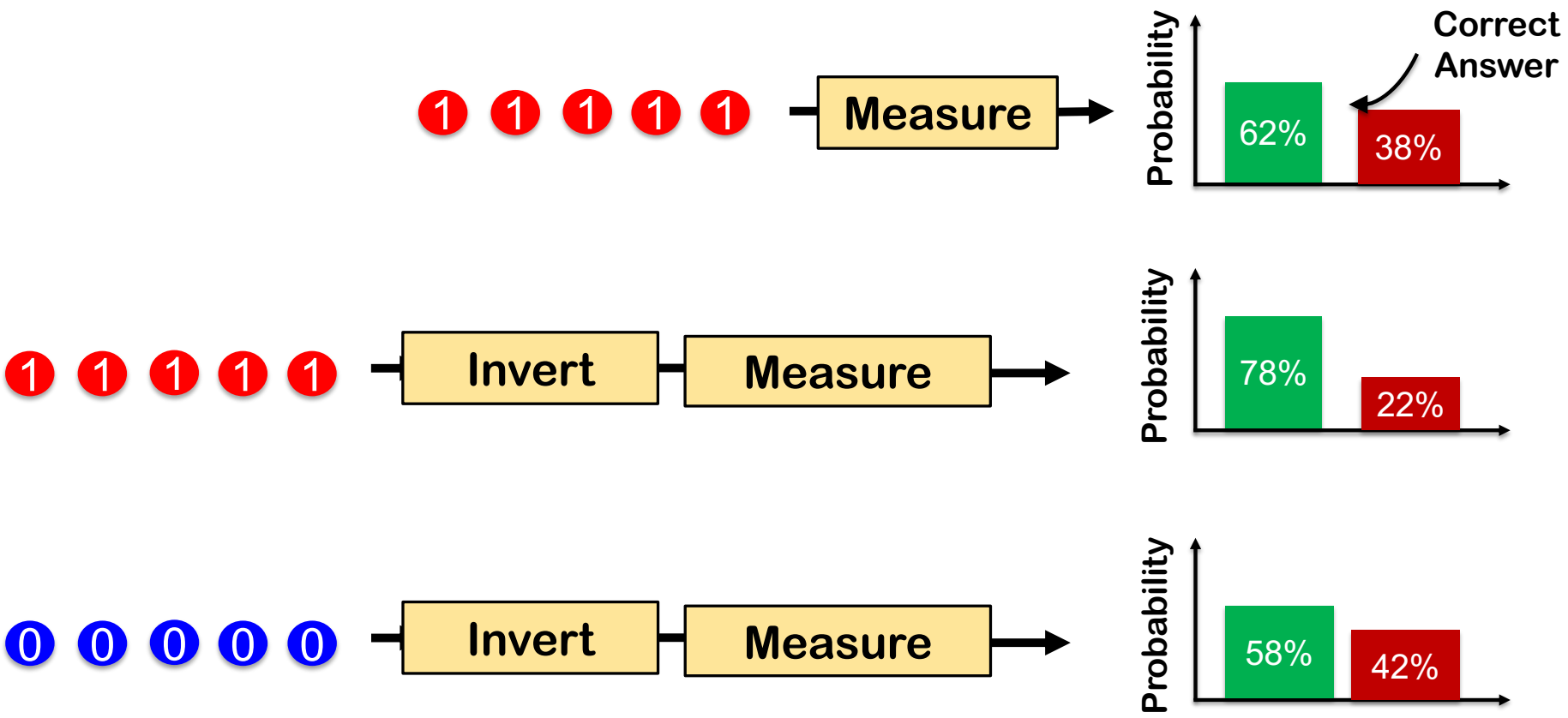
IST captures quality of inference. IST > 1 ensures correct answer is strongest

Goal: Improve NISQ reliability by exploiting measurement bias

OUTLINE

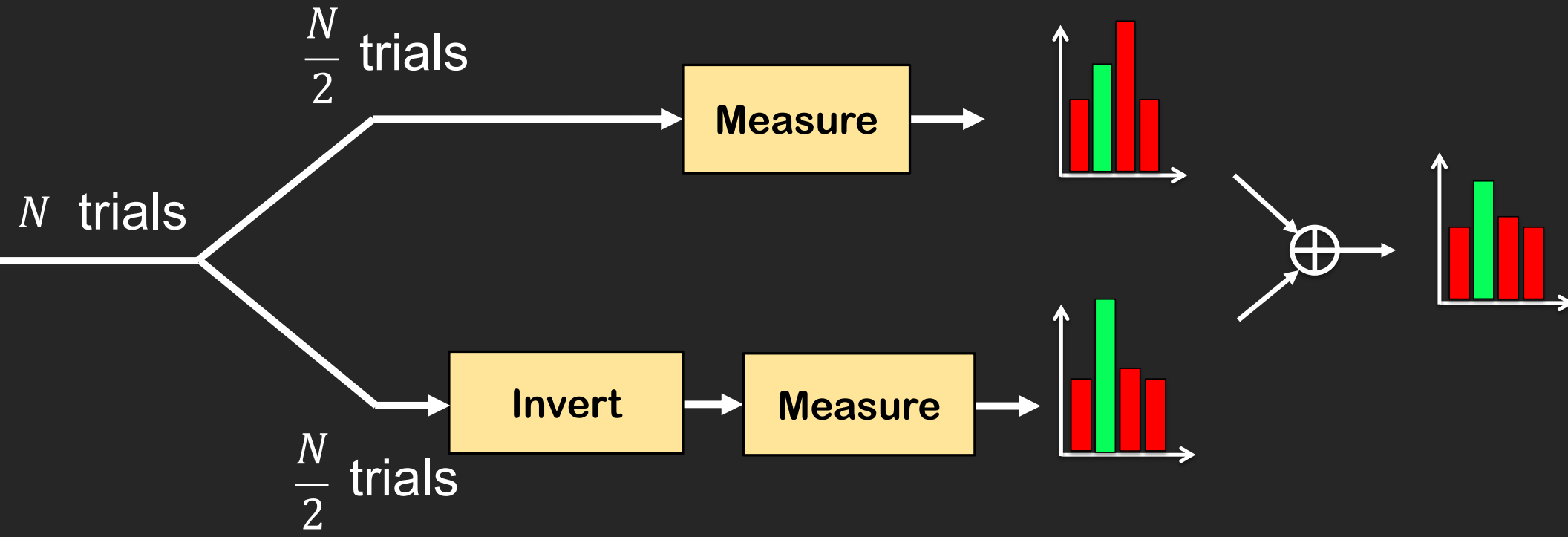
- Introduction
- Bias Characterization
- Static Invert and Measure (SIM)
- Adaptive Invert and Measure (AIM)
- Evaluations

To Invert or Not to Invert?



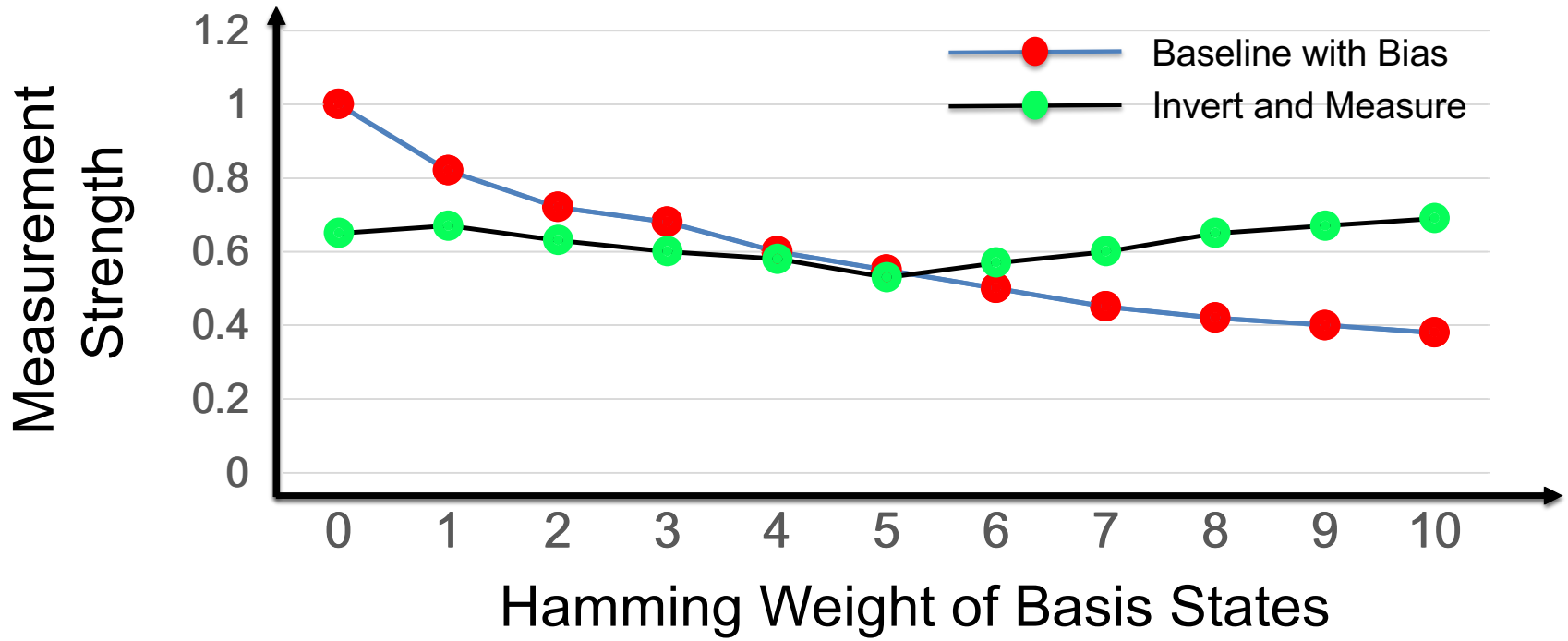
If done naively, inversion can degrade reliability

Static Invert and Measure (SIM)



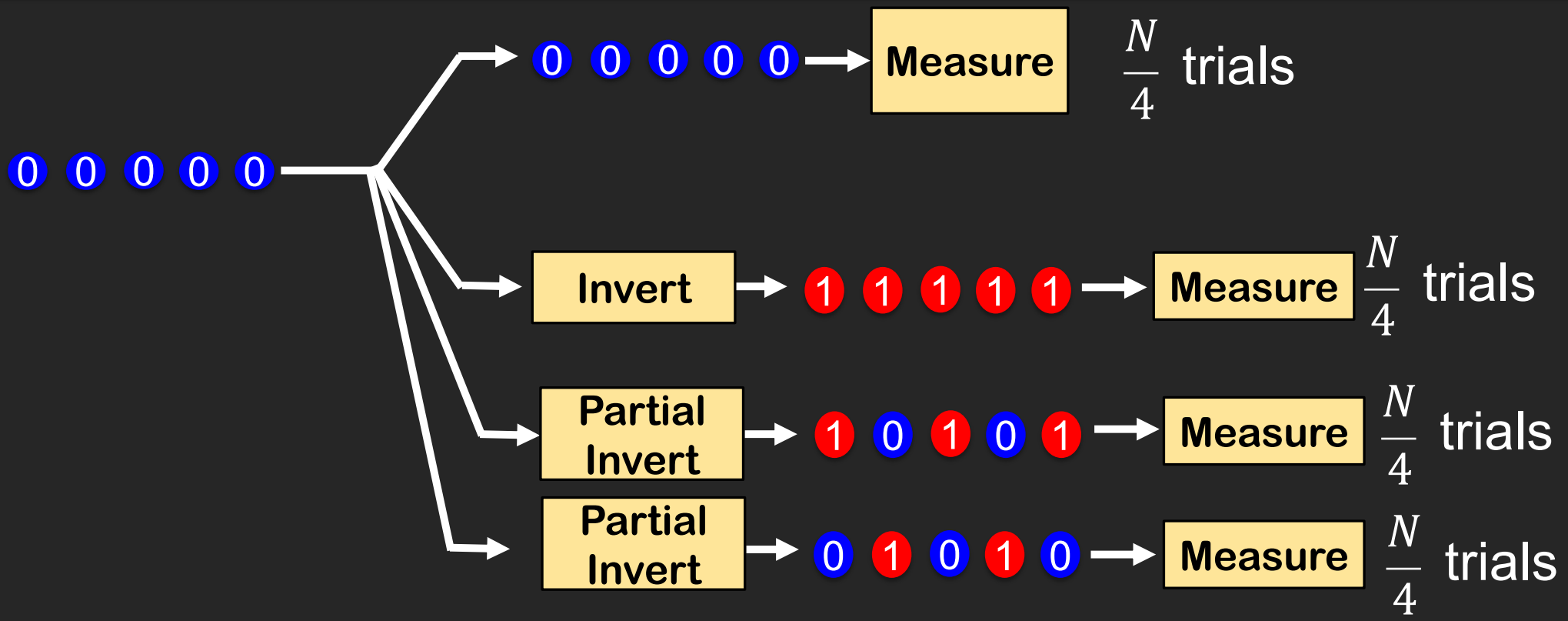
Create two copies of program: one with inverted measurement and other with standard measurement

Impact of SIM on Measurement Bias



For monotonically decreasing measurement fidelity with Hamming weight, Invert and Measure reduces gap between worst case and average error rate

Generalization of Static Invert and Measure



Using partial inversions, transform any input state to any other state

IST of Baseline and SIM

Benchmark	Platform	Baseline	SIM
BV-4A	IBMQX2 (5 Qubits)	1.22 ✓	**1.12** ✓
BV-4B		0.9	**1.25** ✓
QAOA-4A		0.73	0.86
QAOA-4B		0.72	0.96
BV-4A	IBMQX4 (5 Qubits)	0.46	**2.85** ✓
BV-4B		**4.8** ✓	**6.4** ✓
QAOA-4A		0.82	**1.94** ✓
QAOA-4B		0.72	**2.67** ✓
BV-6	IBMQ-Melbourne (14 Qubits)	0.70	0.93
BV-7		0.62	0.84
QAOA-6		0.23	0.72
QAOA-7		0.18	0.36

IST captures quality of inference. IST > 1 ensures correct answer is strongest

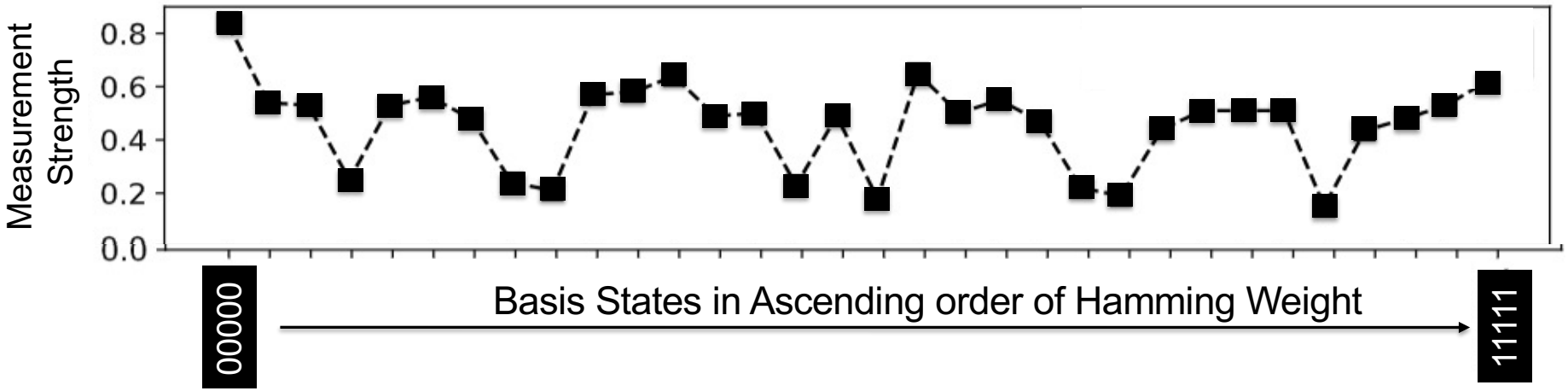
SIM operates at average-case. Can we do better?

OUTLINE

- Introduction
- Bias Characterization
- Static Invert and Measure (SIM)
- Adaptive Invert and Measure (AIM)
- Evaluations

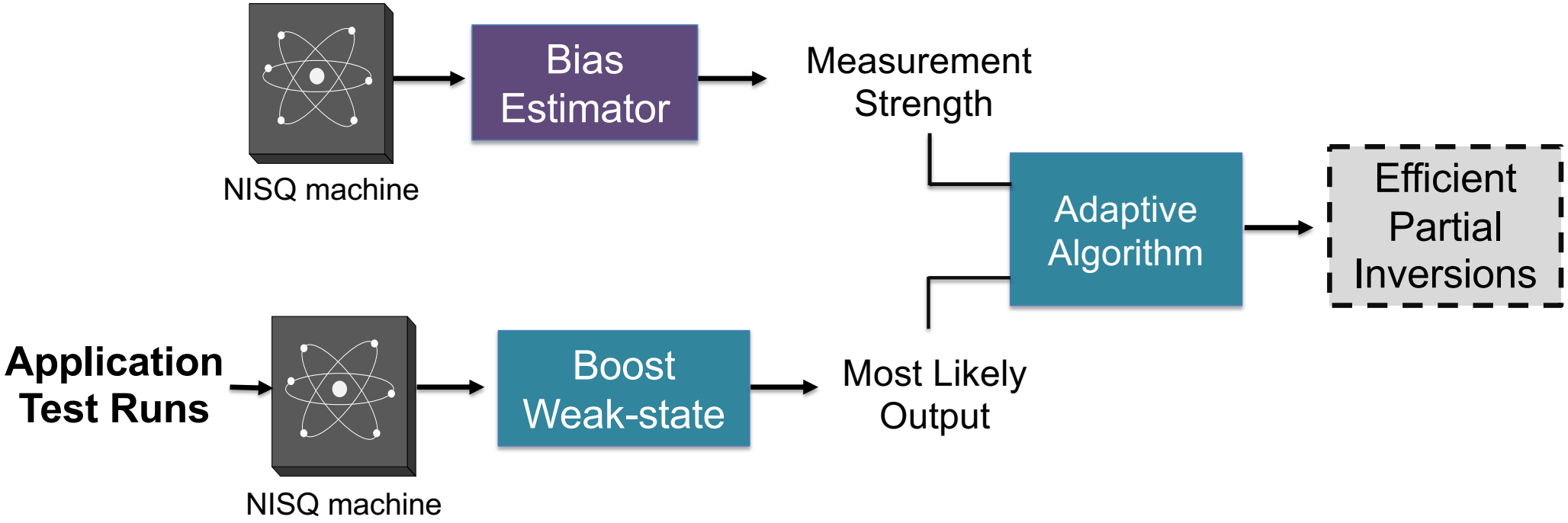
Presence of Arbitrary Measurement Bias

- We measure all basis states on IBM's five qubit machine – ibmqx4
- For five qubit machine we have 2^5 (32) basis states (00000 to 11111)



Measurement Bias may not be predictable

Adaptive Invert and Measure (AIM): Design



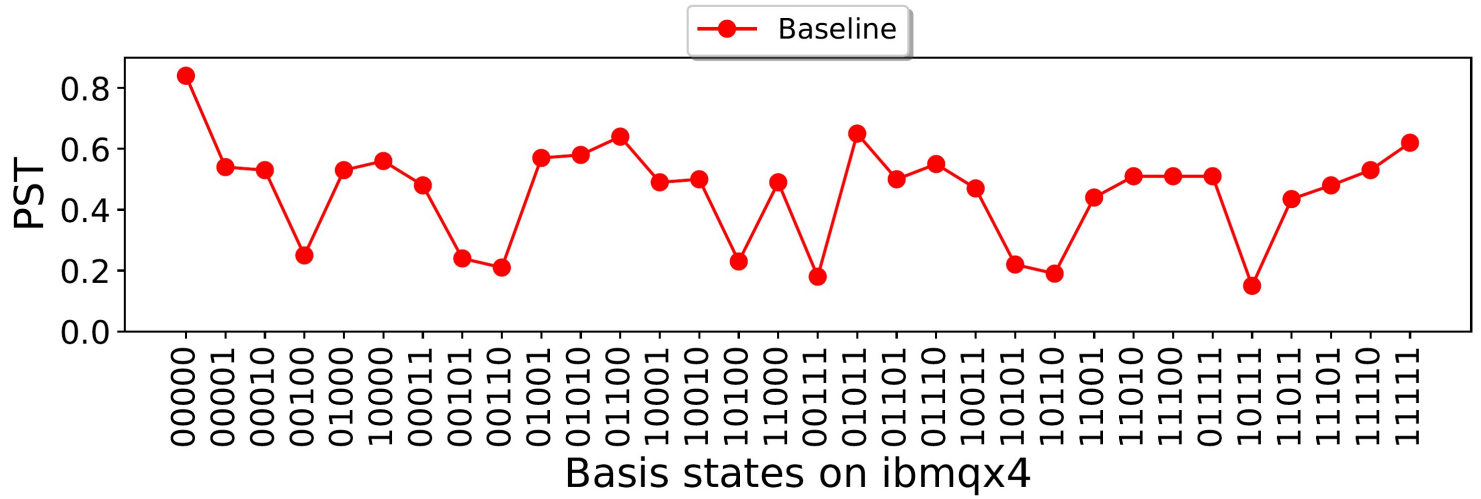
Measurement bias can be learned, and we use it to find inversions that will ensure strong to weak transformation

Evaluations: Improvement in Inference Strength

Benchmark	Platform	Baseline	SIM	AIM
BV-4A	IBMQX4 (5 Qubits)	1.22 ✓	**1.12** ✓	**1.32** ✓
BV-4B		0.9	**1.25** ✓	**1.83** ✓
QAOA-4A		0.73	0.86	**1.27** ✓
QAOA-4B		0.72	0.96	**1.12** ✓
BV-4A	IBMQX4 (5 Qubits)	0.46	**2.85** ✓	**10.38** ✓
BV-4B		**4.8** ✓	**6.4** ✓	**5.7** ✓
QAOA-4A		0.82	**1.94** ✓	**2.03** ✓
QAOA-4B		0.72	**2.67** ✓	**1.98** ✓
BV-6	IBMQ-Melbourne (14 Qubits)	0.70	0.93	**1.02** ✓
BV-7		0.62	0.84	**1.09** ✓
QAOA-6		0.23	0.72	0.86
QAOA-7		0.18	0.36	0.78

Inference Strength (IST) captures quality of inference. IST > 1 ensures correct answer is most likely

Impact of Bias on Bernstein Vazirani (BV) Algorithm



Adaptive Invert and Measure mitigate the measurement bias such that all basis states have better than average measurement fidelity

OUTLINE

- Introduction
- Bias Characterization
- Static Invert and Measure (SIM)
- Adaptive Invert and Measure (AIM)
- Evaluations
- Conclusion

Summary

- Measurement is a dominant source of errors on NISQ
- Measurement errors have state dependent bias
- We mitigate the measurement bias using Static Invert and Measure (SIM) and Adaptive Invert and Measure (AIM)
- SIM and AIM improves the reliability by up to 2x and 3x on IBMQ and significantly improve the ability to do correct inference.

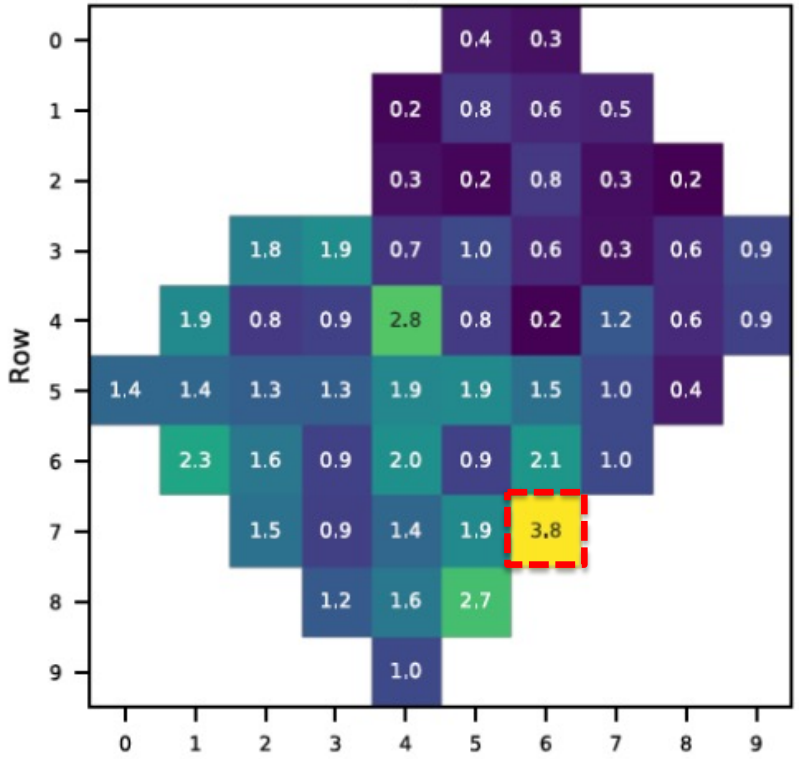
Thank you

IBM 20 Qubit Machine → Measurement Bias

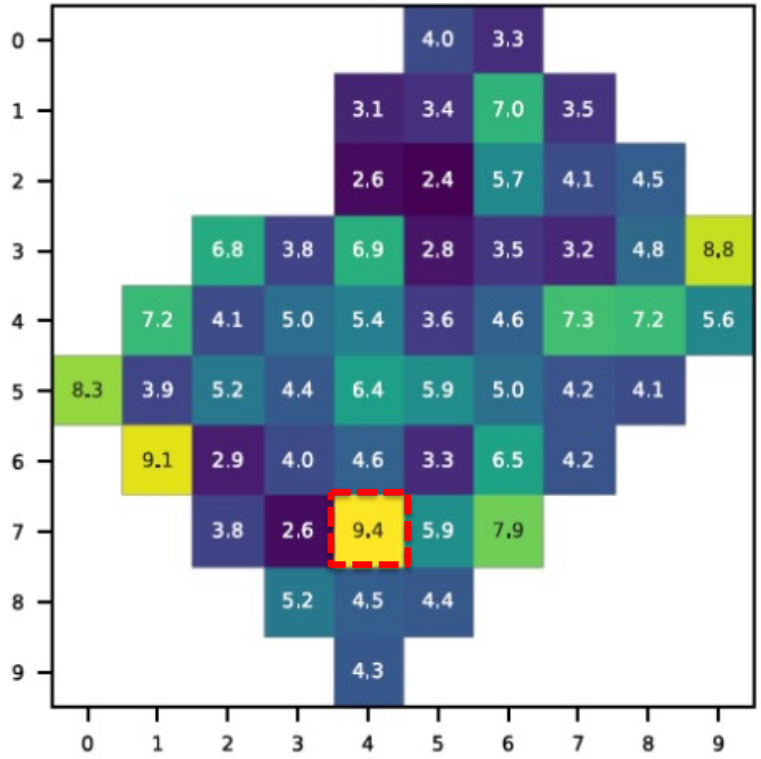
Source: "Experimentally Characterizing IBM Quantum Processors" Megan Lily and Travis Humble (Oak Ridge) , at QRE2019

Google's 53 Qubit Machine → Measurement Bias

Measurement Error for reading State "0"



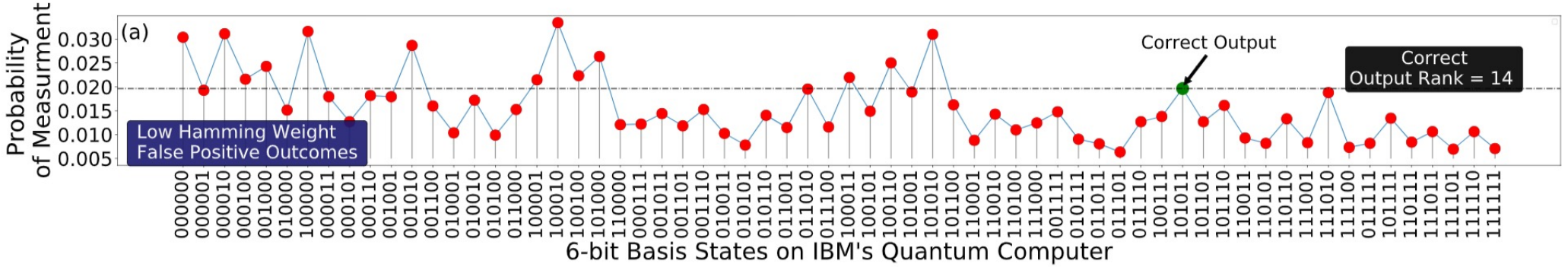
Measurement Error for reading State "1"



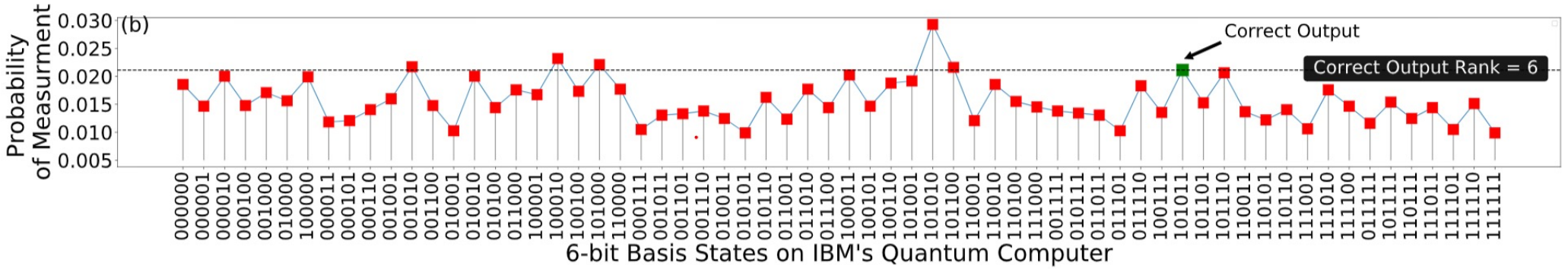
Source: "Quantum supremacy using a programmable superconducting processor"

Invert and Measure on IBMQ

Baseline

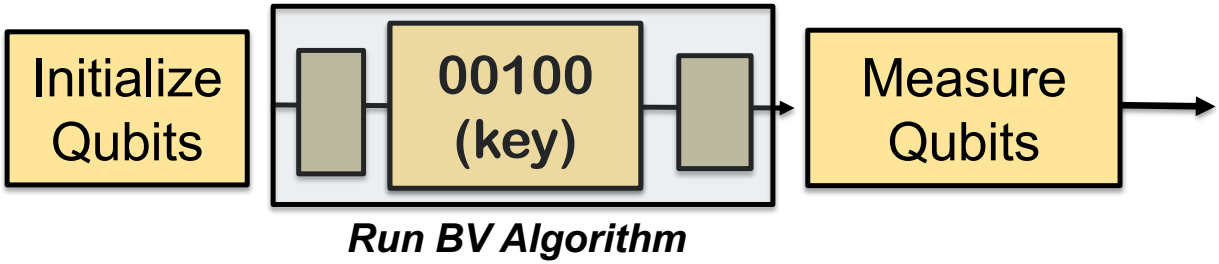


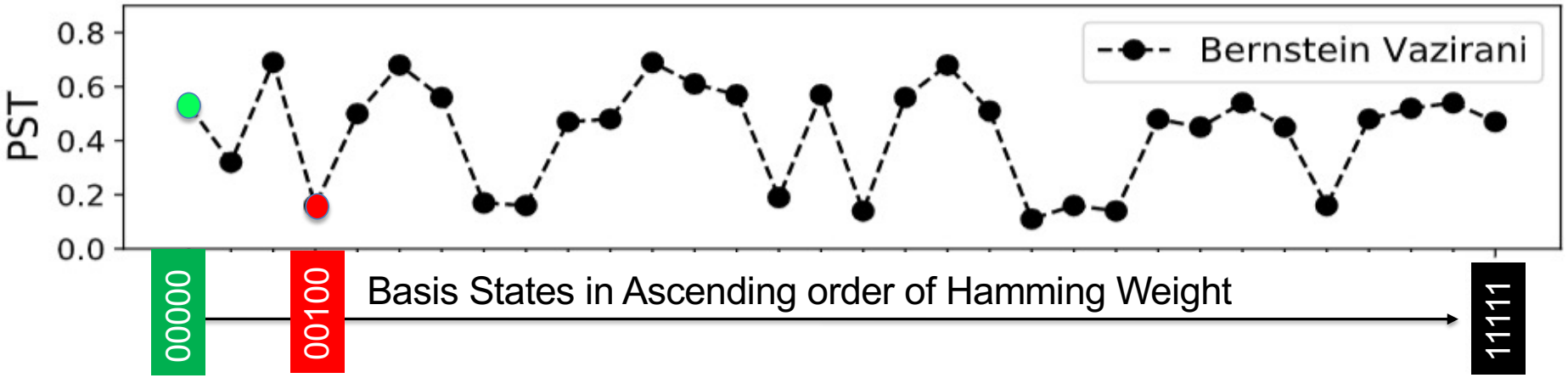
Invert and Measure



Impact of Bias on Bernstein Vazirani (BV) Algorithm

❖ Run BV algorithm with all five bit keys on "ibmqx4" machine





Bias can make some answers more vulnerable than others