Tolerating Crummy Hardware with Intelligent Software: Making Progress in the NISQ Era

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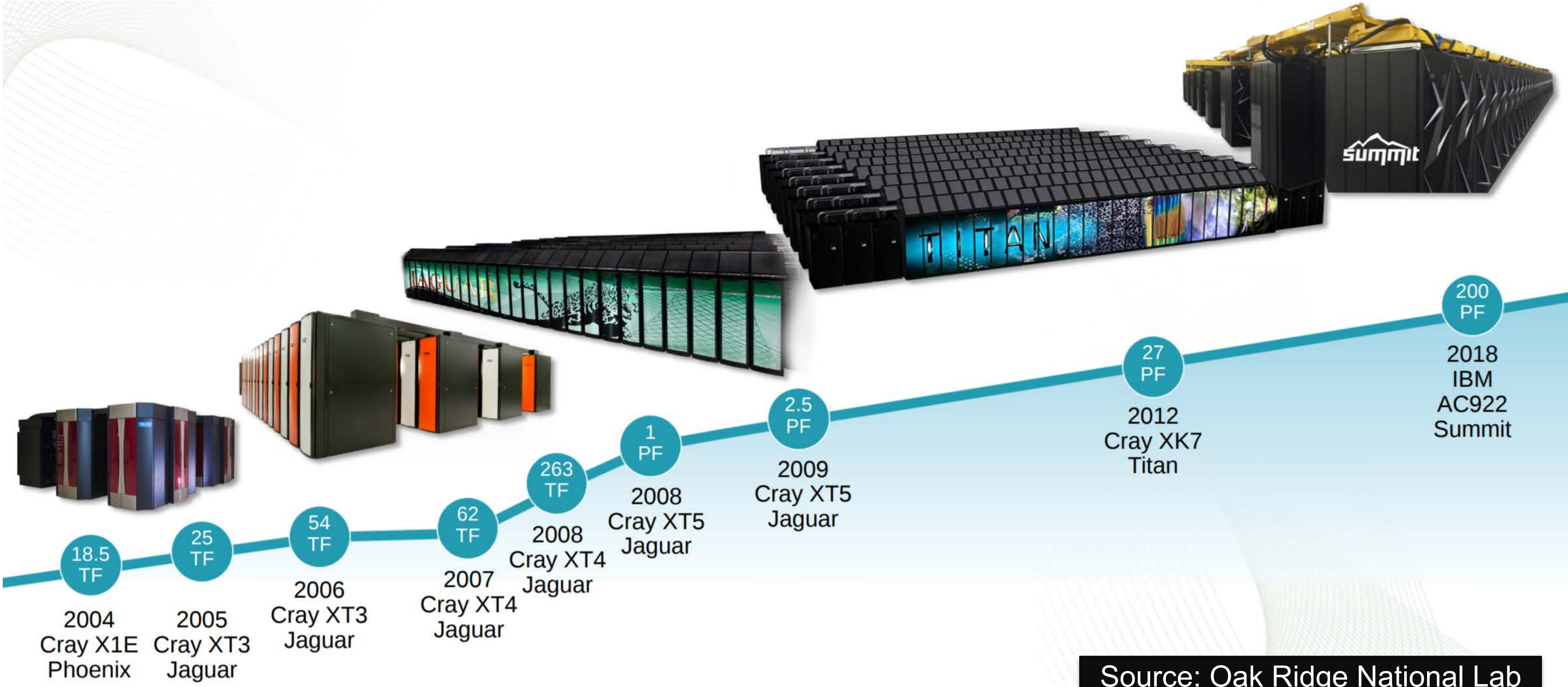
Georgia Tech
CREATING THE NEXT

Why Quantum Computers?

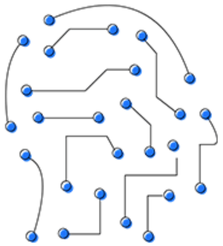


Source: Oak Ridge National Lab

Potential of Quantum Computers

Logistics

Machine Learning



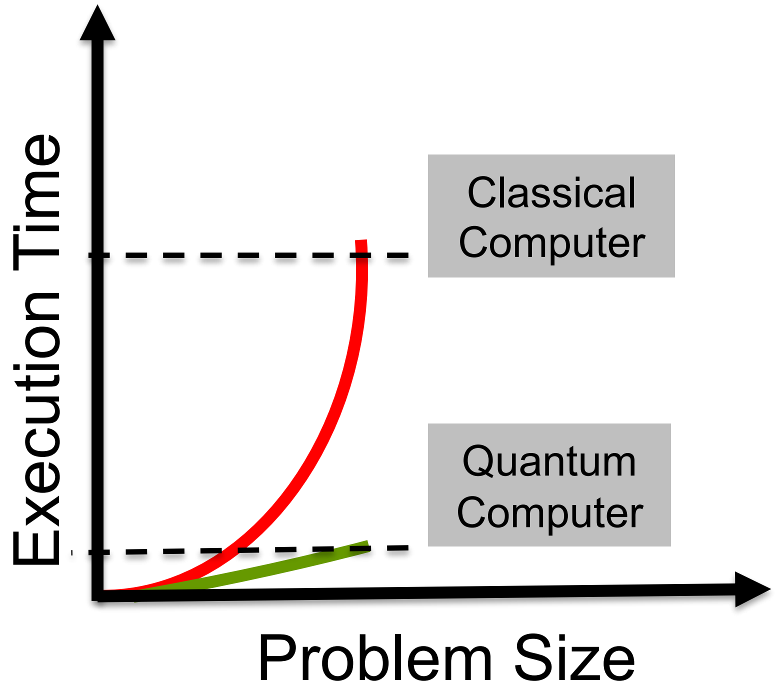
Drug Discovery

Energy

Optimization Problems

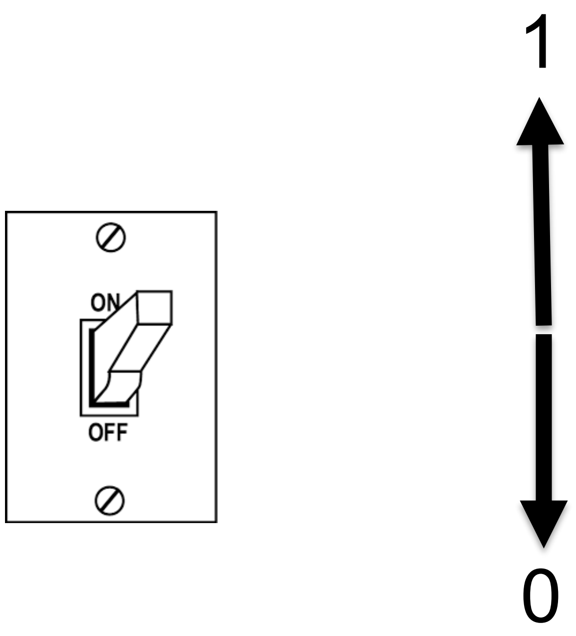
Quantum Simulations

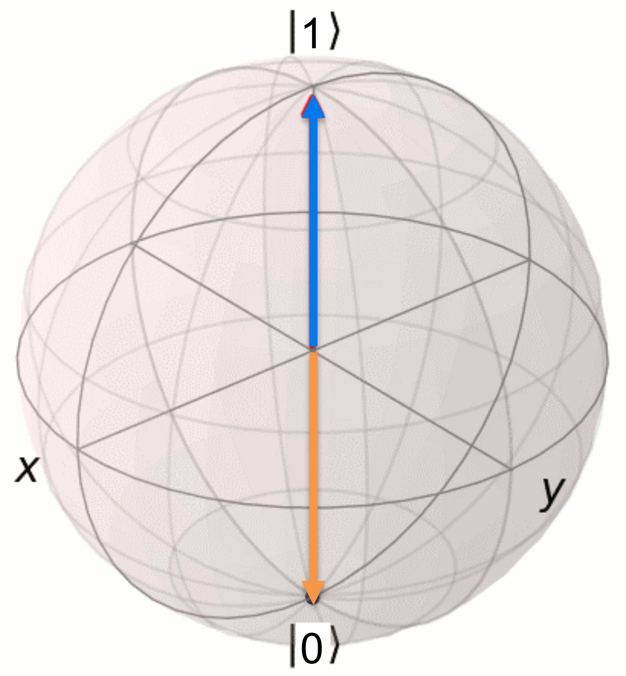
Algebraic Problems



Quantum Computers can enable solutions to important problems

Computing using Quantum Bits





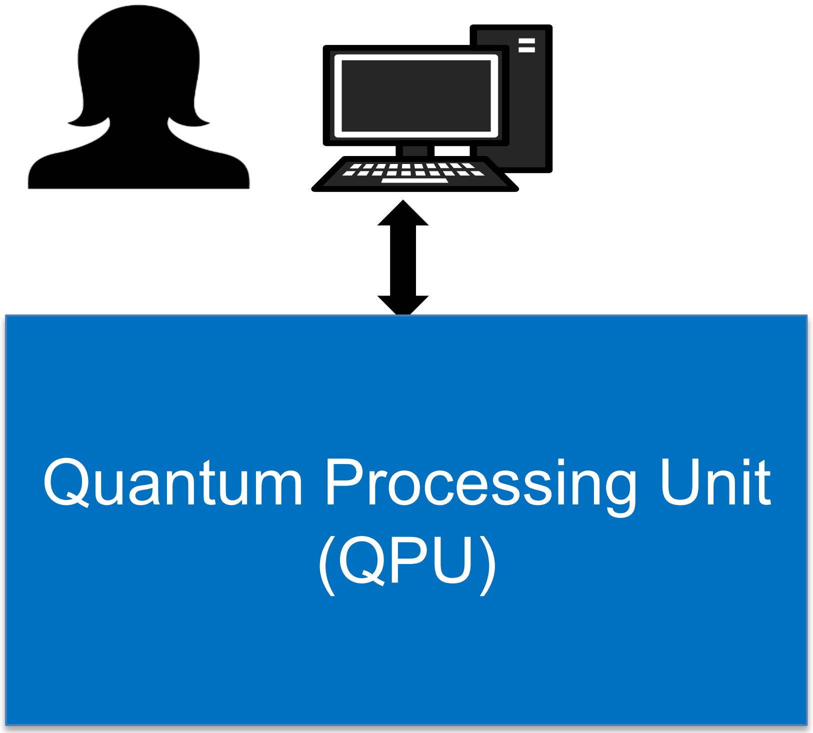
Classical Bit

State of a *Classical Bit*
→ 1 or 0 two points on sphere

Quantum Bit

State of a *Quantum Bit*
→ Any point on the sphere
(Vector in Complex Hilbert Space)

Quantum Computer is Domain Specific Accelerator



Quantum Machine	Number of Qubits Now
Google	53/72*
IBM	53
Intel	49
Rigetti	32
IonQ	11

* Fabricated but no data reported yet

Quantum Computers with 50+ qubits are here!

Quantum Computing is a Full Stack Problem

Problem
- Algorithms
- PL, Compilers
- Architecture
- Circuits
- Devices

Electrons
(Classical States)

Problem
- Q Algorithms
- Q-PL, Q-Compilers
- Q Architecture
- Q Interfaces
- Q Devices

Photons/Ions/Electrons
(Quantum States)

Quantum Compilers For Robustness

Tannu et. al (ASPLOS'19)
Tannu et. al (MICRO'19a)
Tannu et. al (MICRO'19b)
Das et. al (MICRO'19c)

Cryogenic Control Architecture

Tannu et. al (MICRO'17)
Tannu et. al (CF'19)
Tannu et. al (MEMSYS'17)

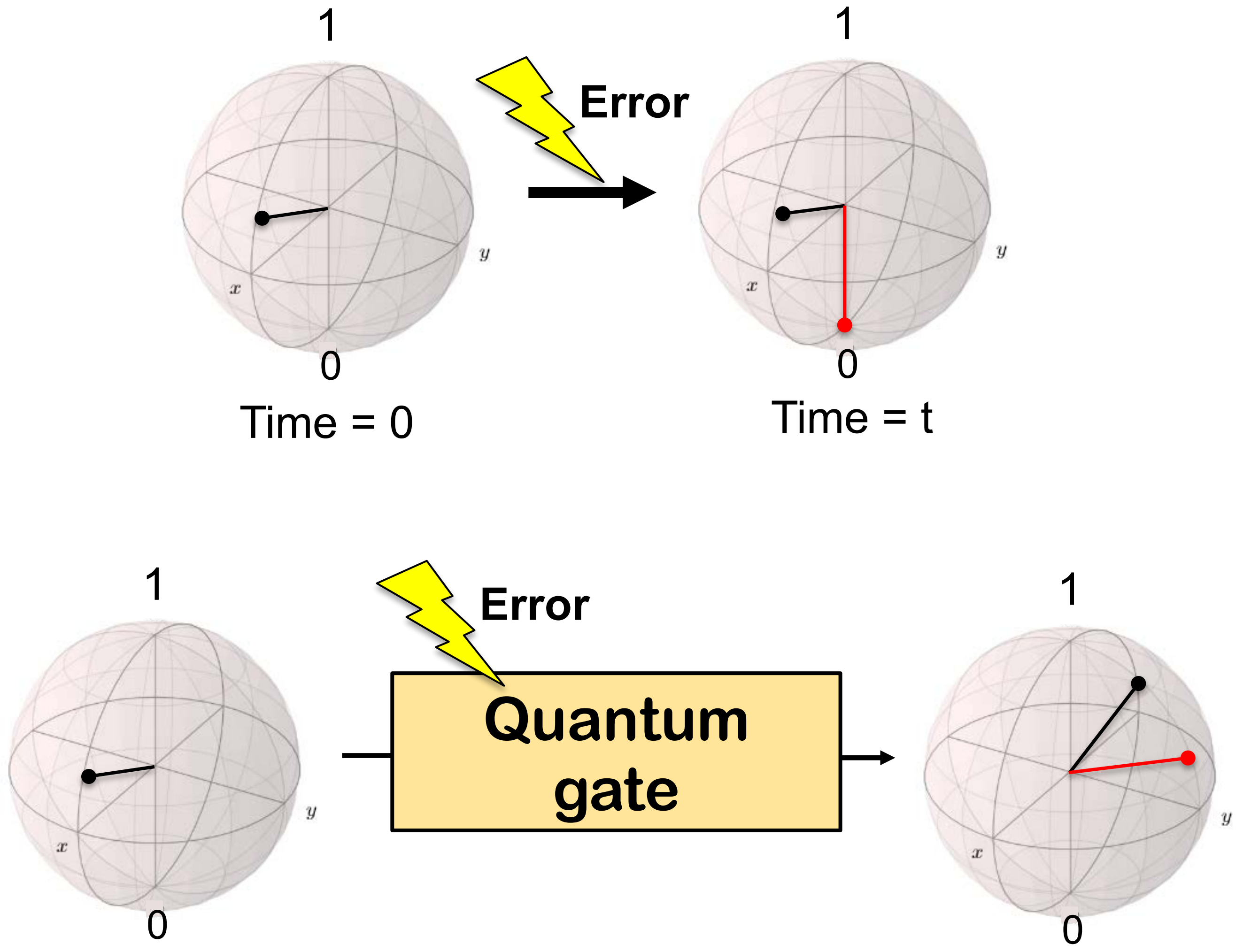
Outline

- Introduction
- **Background on Qubit Errors and NISQ**
- Exploiting Variability in Device Errors
- Guarding Against Correlated Errors
- Mitigating Bias in Measurement Errors
- Summary

Qubit State is Fickle and Vulnerable to Errors

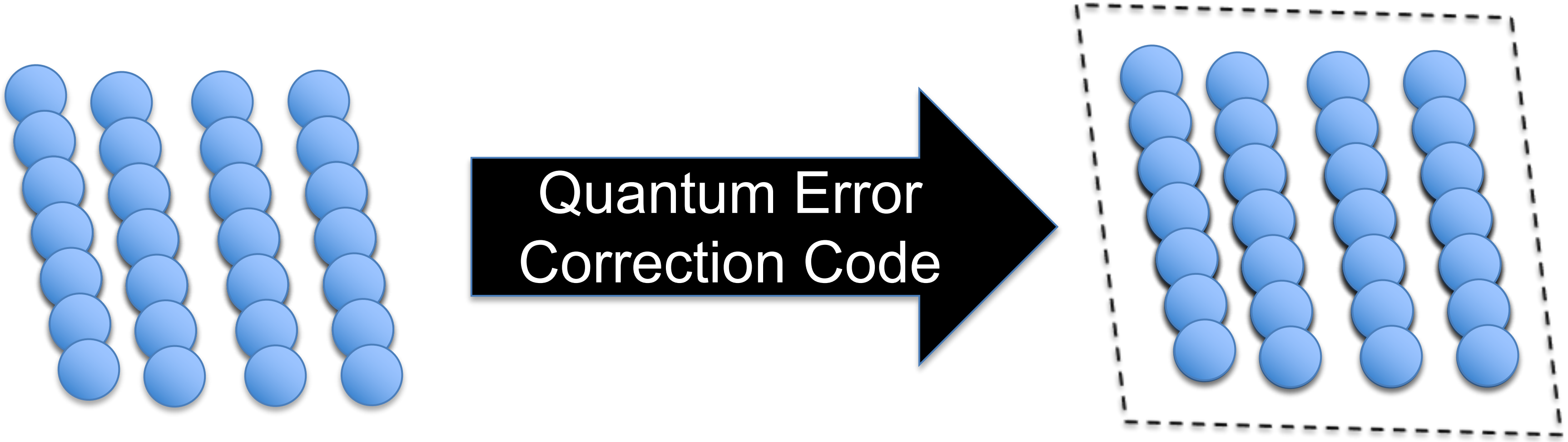
❖Qubits encounter errors and leak information

❖Quantum gate produces erroneous output (0.1% to 1% chance of error)



Qubit Errors is the biggest problem in Quantum Computing

Quantum Error Correction is Expensive



Collection of Noisy
Physical Qubit Devices

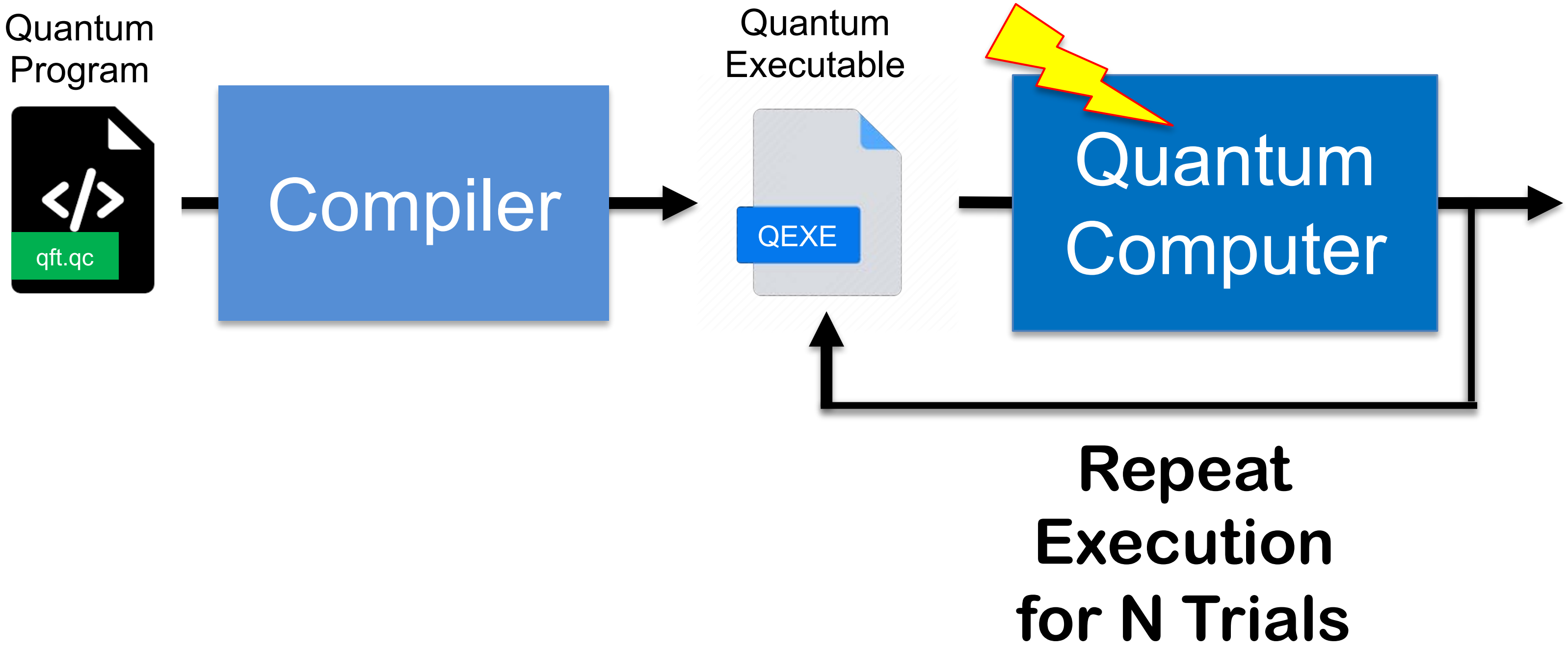
Fault-Tolerant
Logical Qubit

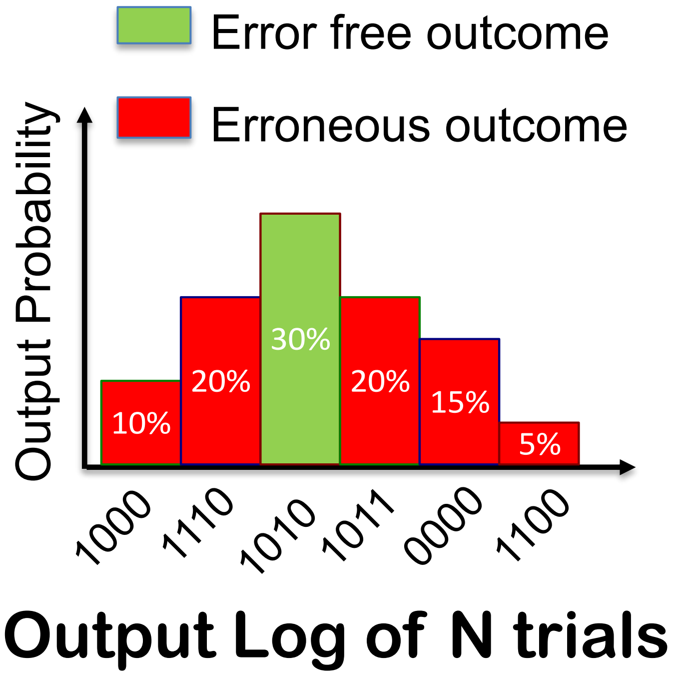
Quantum Error Correction: Vulnerable Individually, tolerant to errors collectively

10 to 500 physical qubits to create one logical qubit

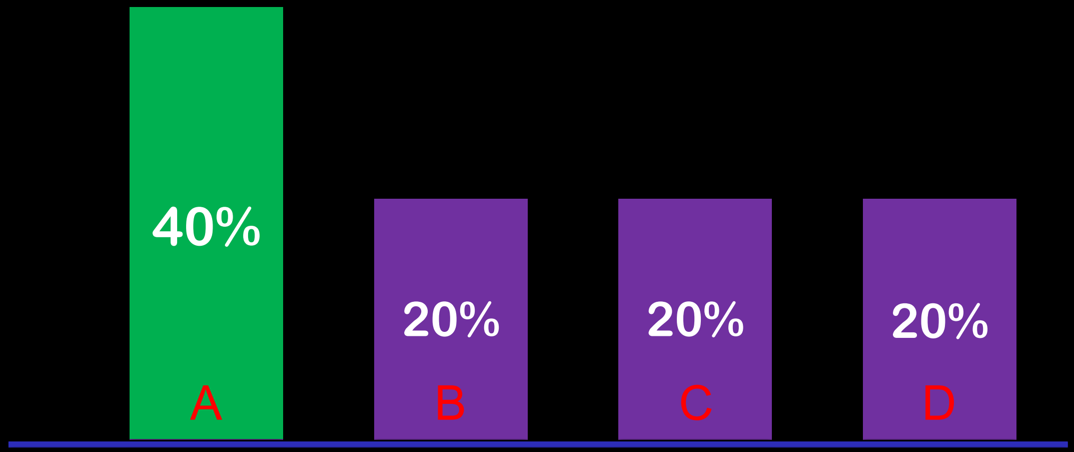
NISQ Model of Computing [Preskill'18]

Noisy Intermediate Scale Quantum Computers (NISQ)





Despite qubit errors, correct outcome can be inferred on NISQ Machines



Which of the following is a patented color by an American professional sports team?

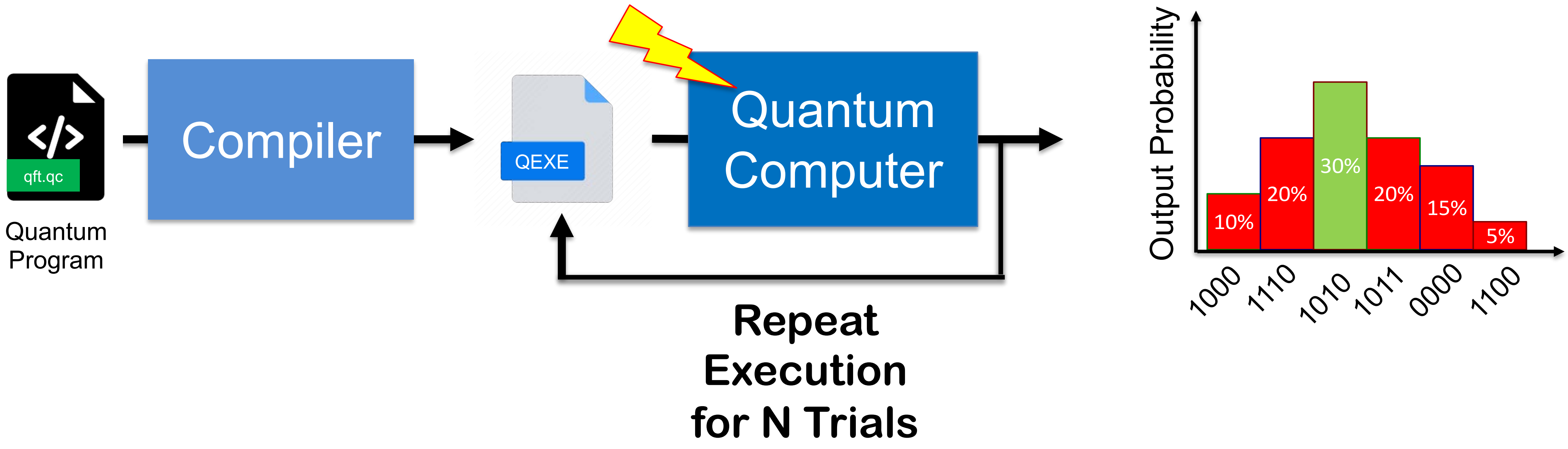
A. Fenway Green

B. Magic Magenta

C. Burnt Orange

D. Georgian Blue

NISQ Model of Computing



Goal: Develop software transformations to reduce the impact of hardware errors on Quantum Computer

Outline

- Introduction
- Background on Qubit Errors and NISQ Paradigm
- **Exploiting Variability in Device Errors**

Session: Quantum Computing ASPLOS'19, April 13–17, 2019, Providence, RI, USA

Not All Qubits Are Created Equal

A Case for Variability-Aware Policies for NISQ-Era Quantum Computers

Swamit S. Tannu Moinuddin K. Qureshi

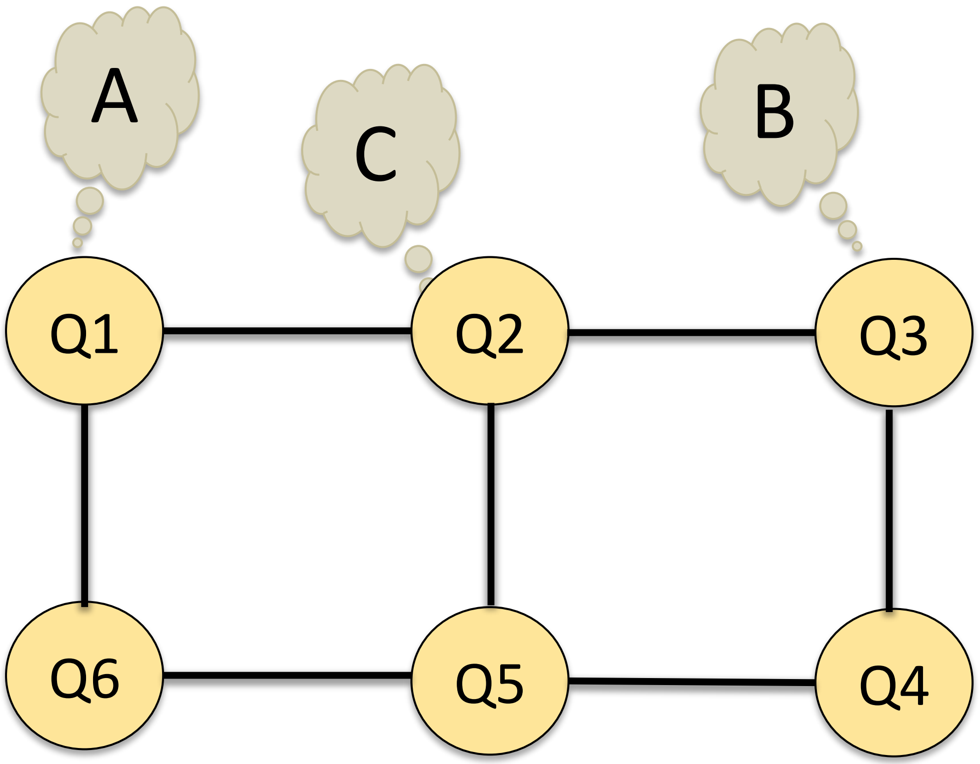
Problem: Limited Connectivity and SWAPs

`CNOT A,B` ✗ **Not Possible no link between A and B**

↓

`SWAP B,C`

`CNOT A,B` ✓ **link between A and B, CNOT can be performed**



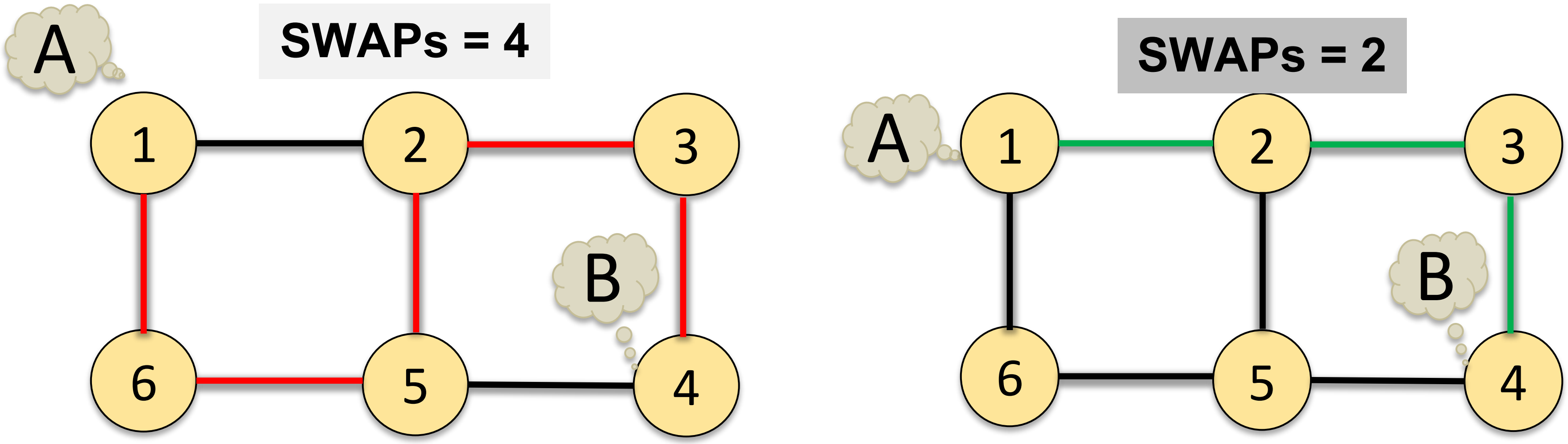
SWAP facilitate data movement

Compiler insert SWAPs → SWAPs are extra instructions which can also fail

NISQ Compiler Policies

[1] Zulehner+, (DATE'18)
[2] Siraichi+, (CGO'18)
[3] Li+, (ASPLOS'19)

Compiler responsible for qubit allocation and movement



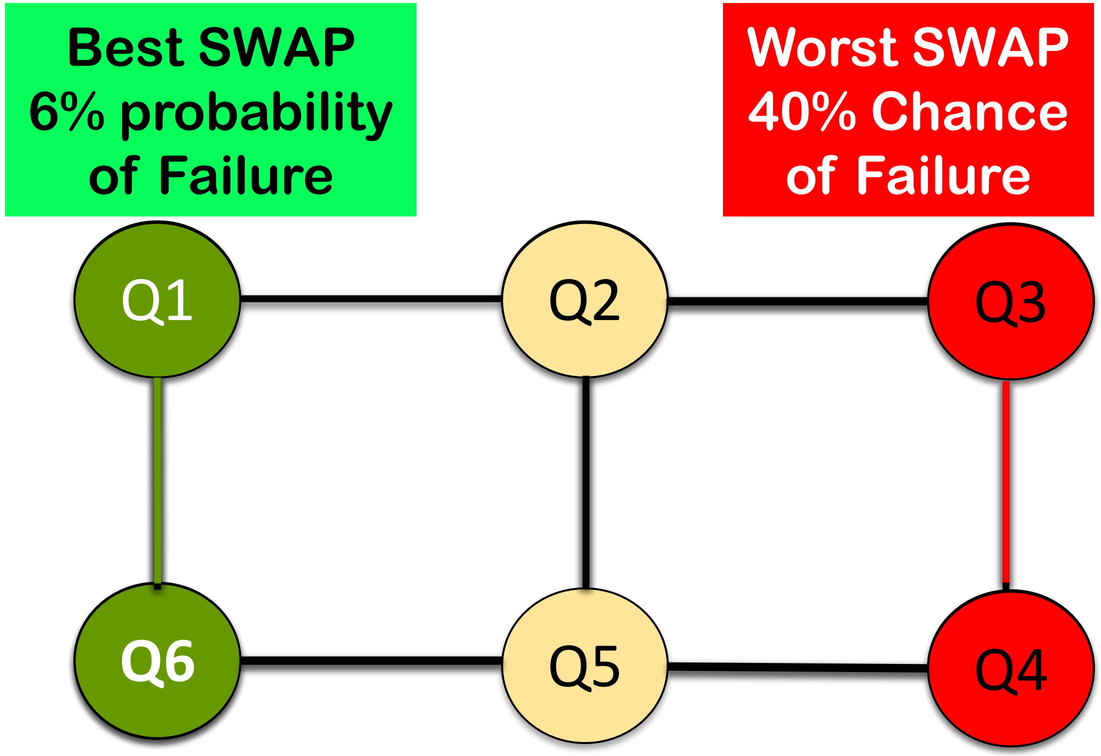
Qubit movement policy minimizing SWAPs

Existing compiler policies solely focus on minimizing SWAPs

Not All Qubits Are Created Equal

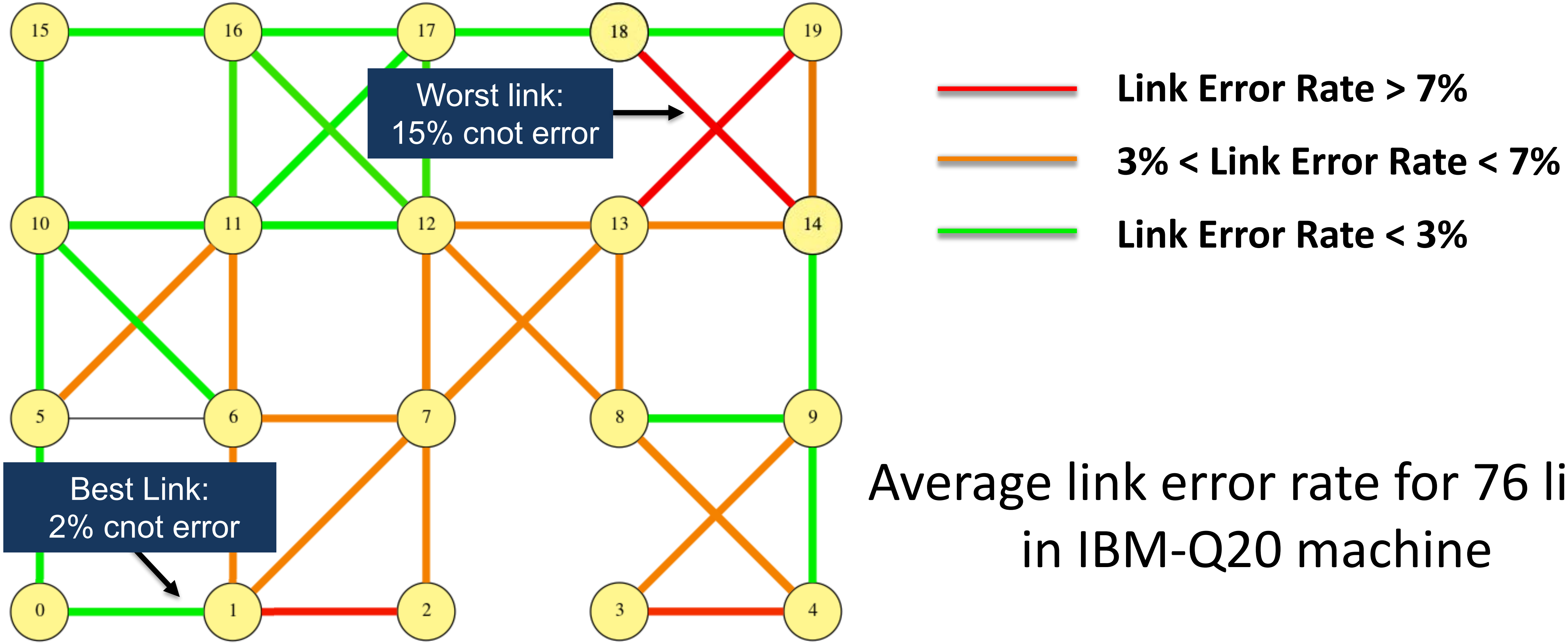
- **Variability:** Some qubits and links fail with higher probability than others

- Avoiding certain links can improve reliability significantly



Goal: Exploit variation in error rates to improve reliability (assign more operations on reliable qubits/links)

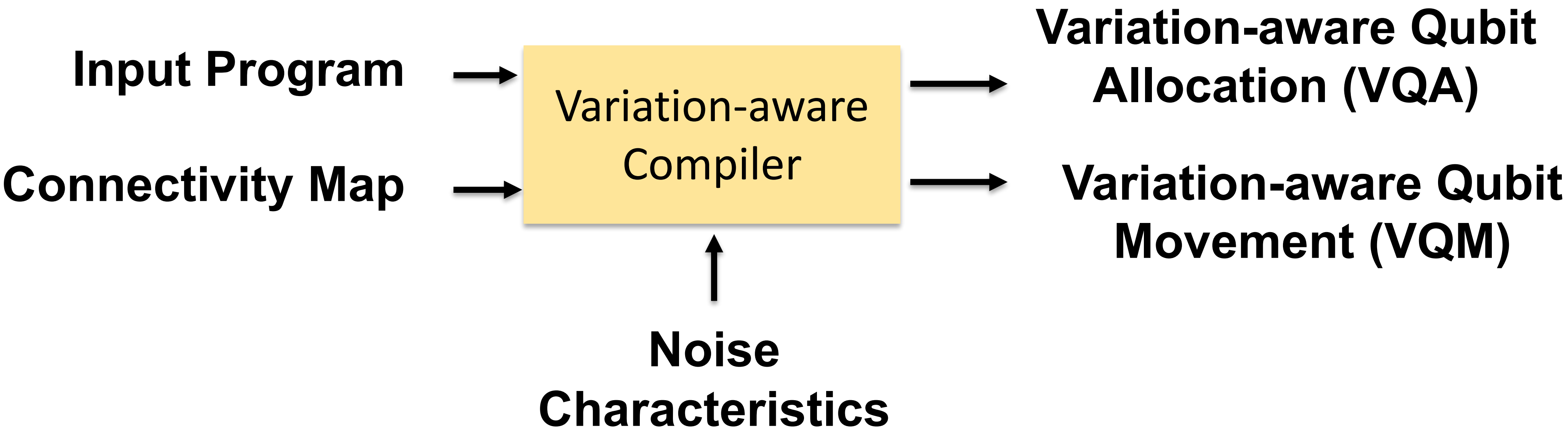
Spatial Variation in Link Error Rates



Average link error rate for 76 links in IBM-Q20 machine

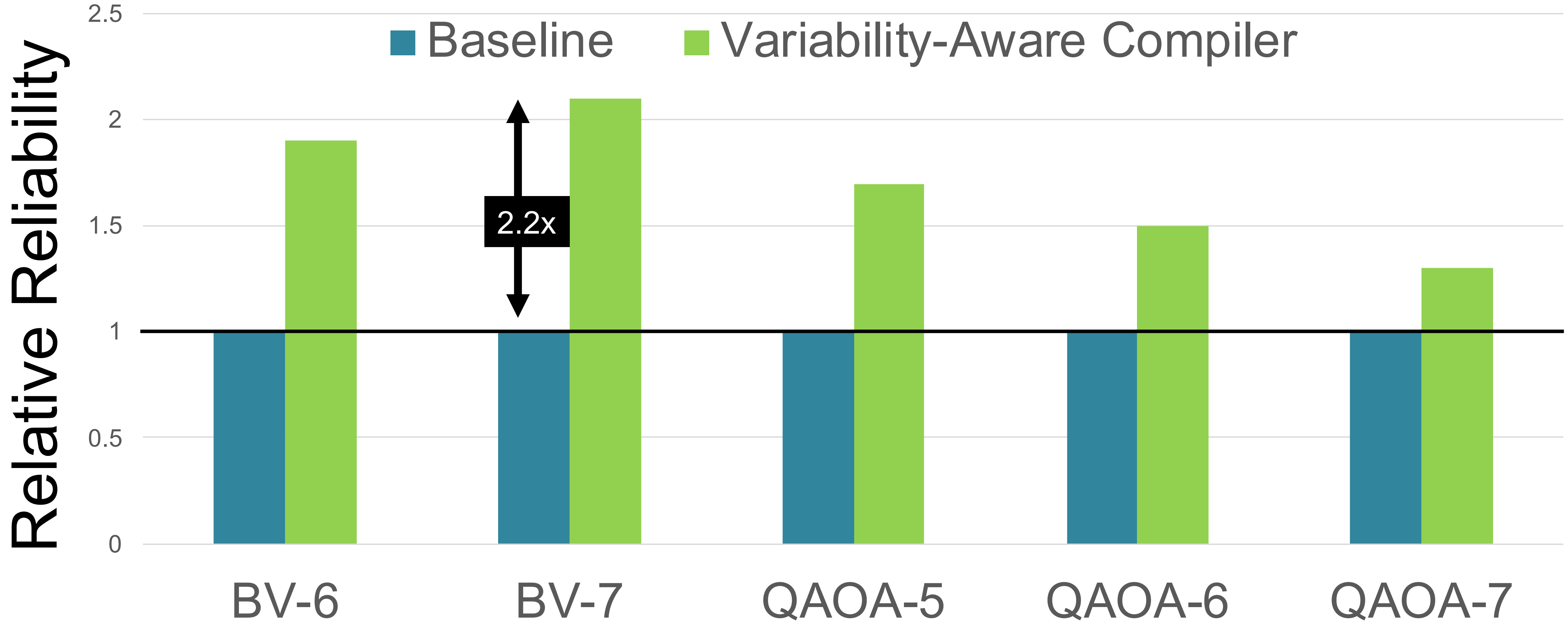
Some links are consistently more error prone than others

Variation-Aware Policy



We propose variation-aware policy , to generate initial assignment and operation schedule that maximize the reliability, not just SWAP count

Evaluations on Real System: IBM-Q14



Up to 2.2 times improvement in Program Reliability

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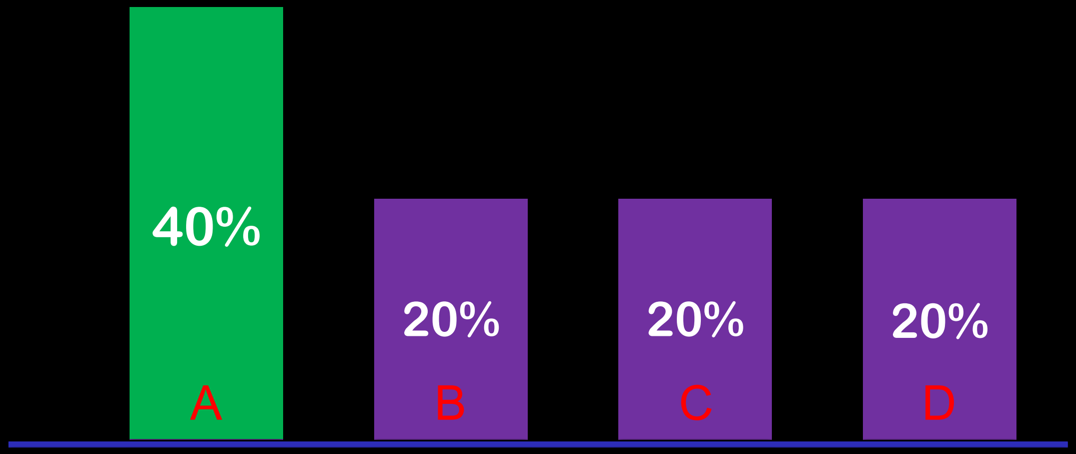
- ❖ Introduction
- ❖ Background on Qubit Errors and NISQ Paradigm
- ❖ Exploiting Variability in Device Errors
- ❖ **Guarding Against Correlated Errors**

Ensemble of Diverse Mappings:
Improving Reliability of Quantum Computers by Orchestrating Dissimilar Mistakes

Swamit S. Tannu Moinuddin Qureshi



Which of the following is a patented color by an American professional sports team?

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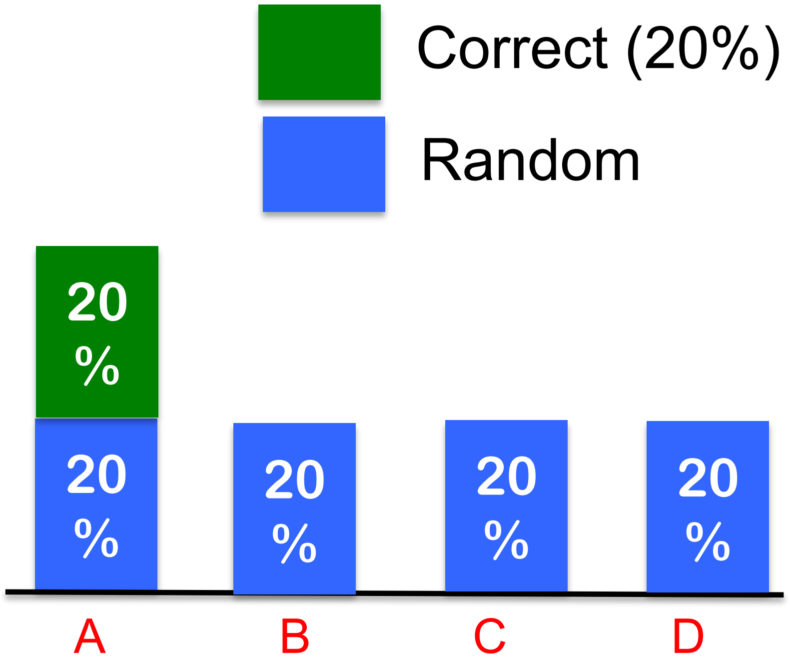
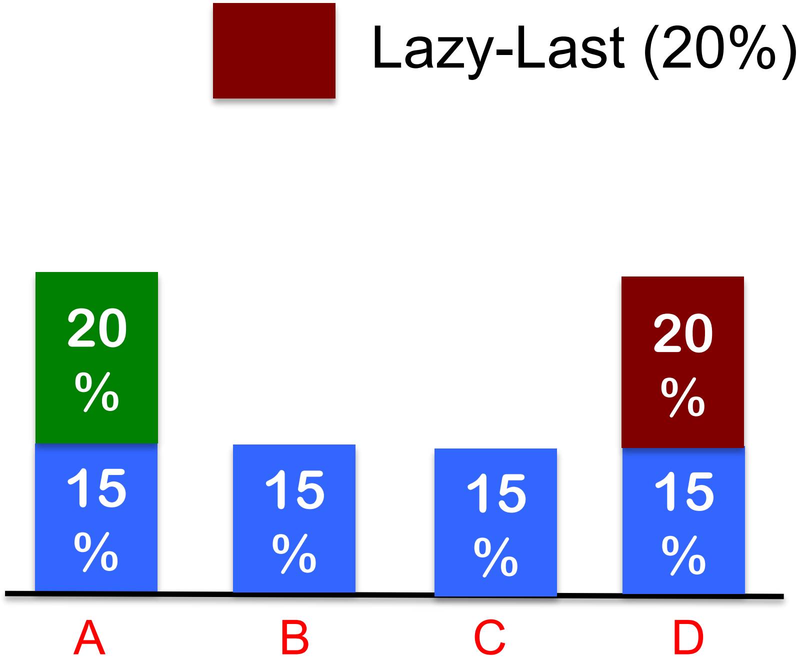
Impact of Correlated Mistakes on Voting



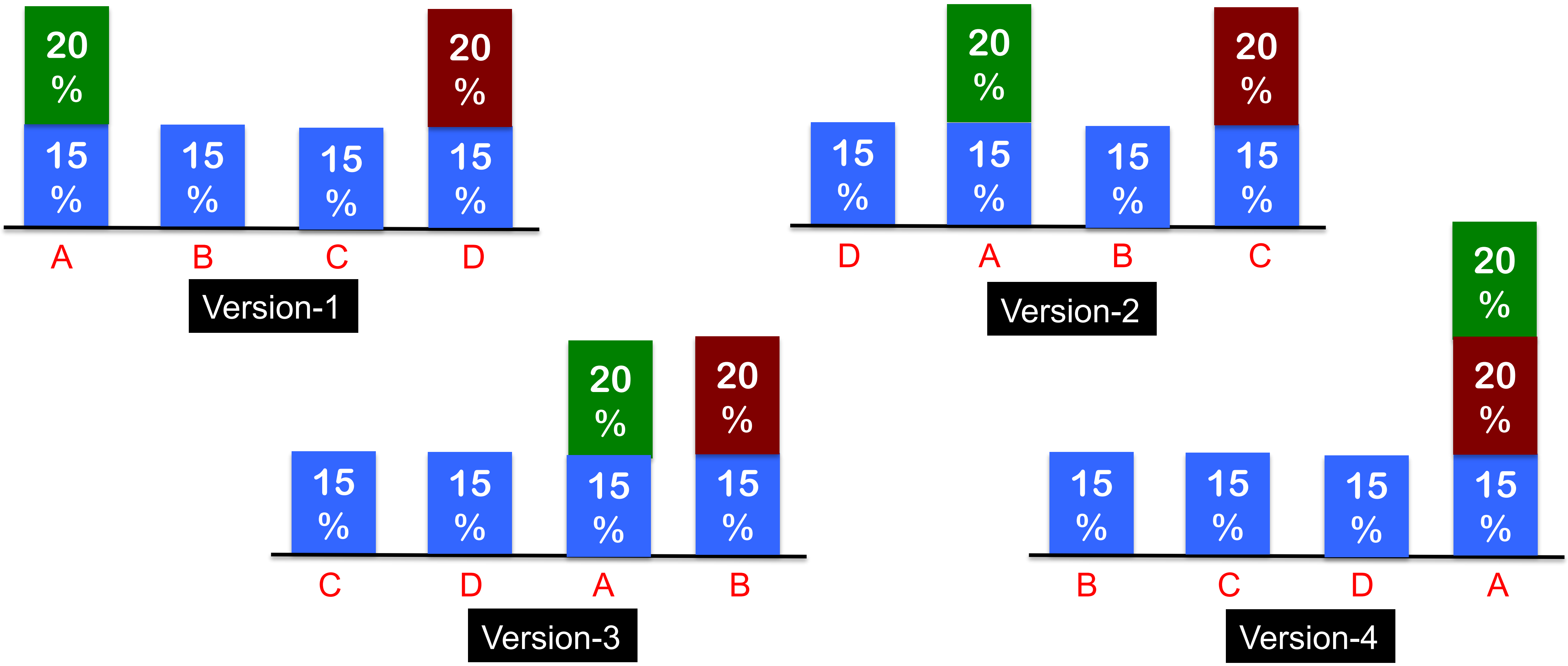
Wrong answers randomly distributed



20% of audience lazy ➔ Always selects last option

Correlated errors limit the ability to infer the correct answer

Idea: Use Diversity to Break Correlated Errors



Have different versions, each with diverse option subjected to error

Suppressing Incorrect Answer with Diversity

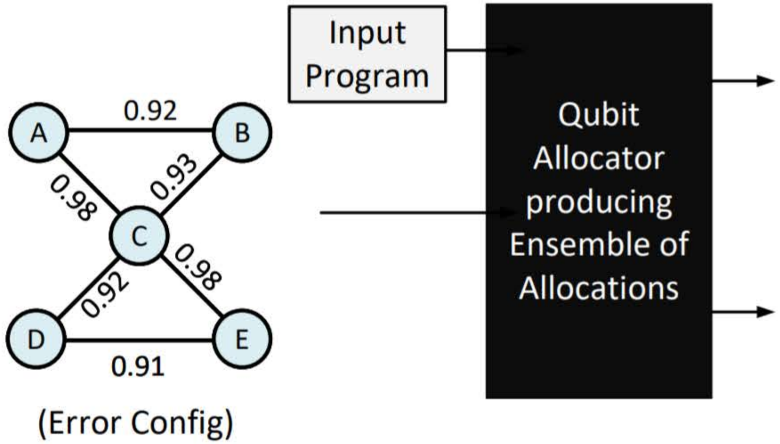
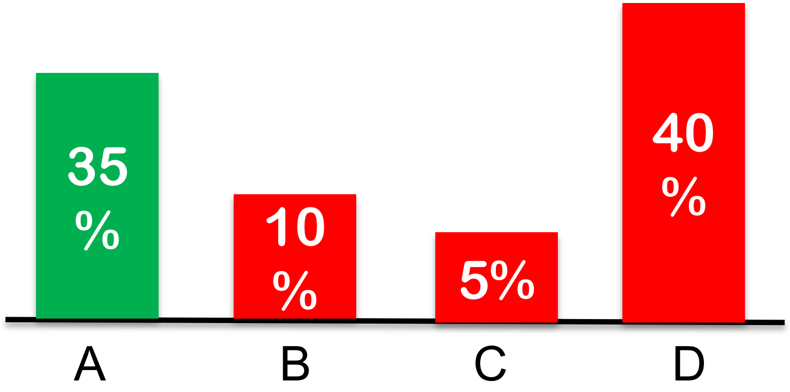


Figure of Merit: Inference Strength (IST)

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

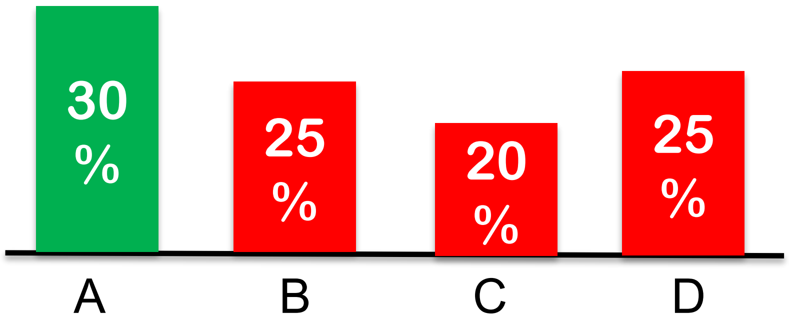
Inference Strength = $\frac{0.35}{0.40}$ = 0.87

Incorrect Inference



Inference Strength = $\frac{0.3}{0.25}$ = 1.25

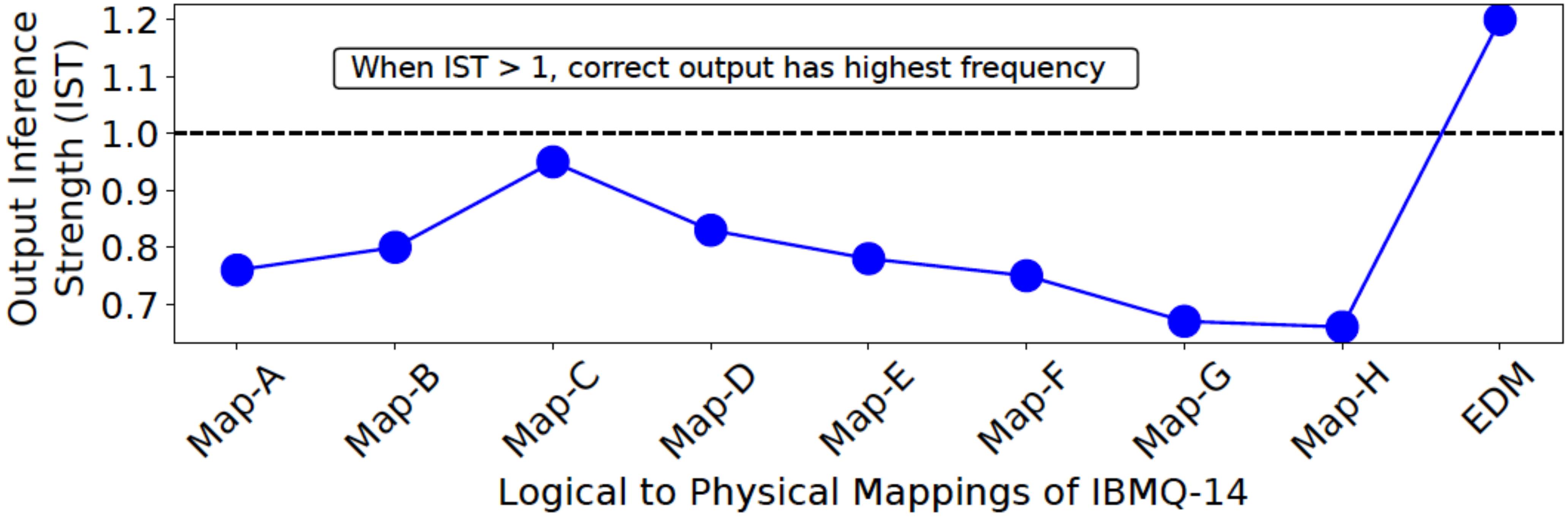
Correct Inference



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

Ensemble of Diverse Mappings

EDM creates four copies of the program using mappings A, B, C, and D



With diverse set of mappings we can orchestrate dissimilar mistakes

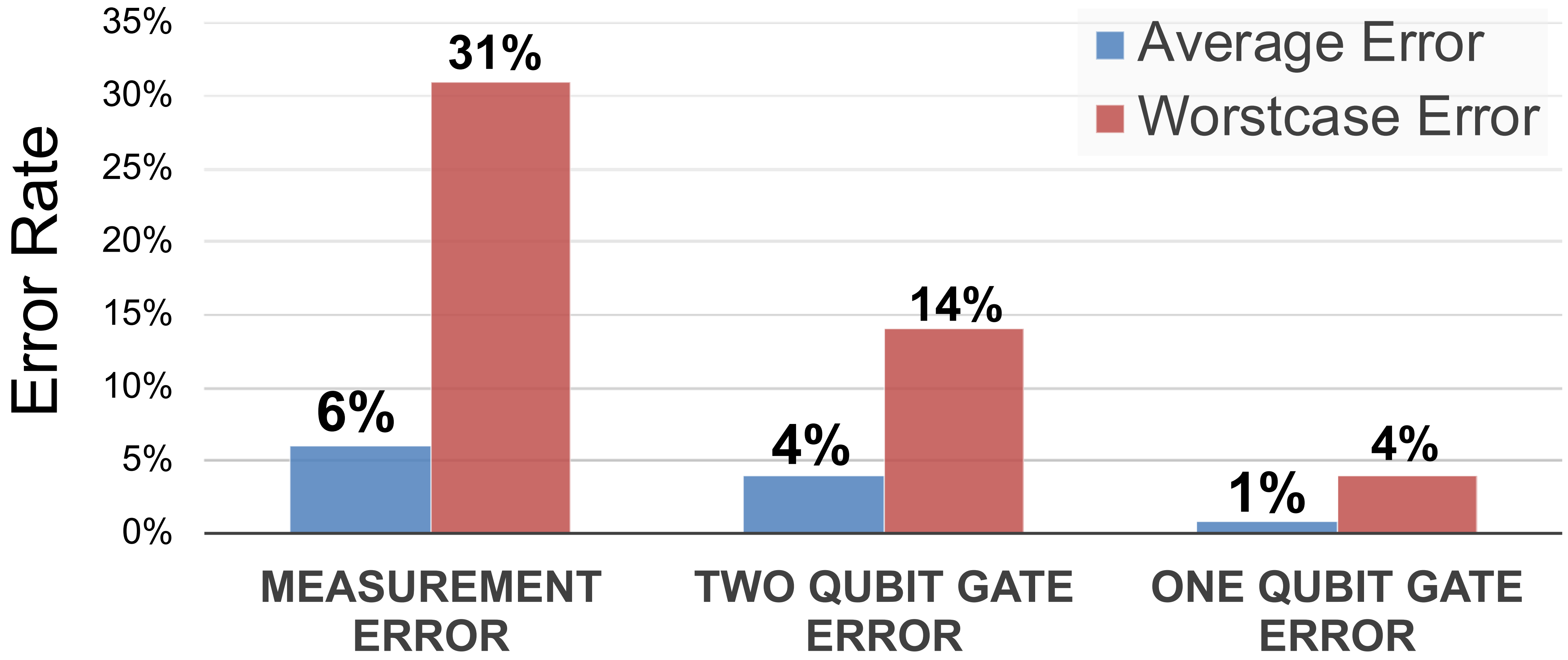
Outline

- ❖ Background on Qubit Errors and NISQ
- ❖ Exploiting Variability in Device Errors
- ❖ Guarding Against Correlated Errors
- ❖ **Mitigating Bias in Measurement Errors**

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

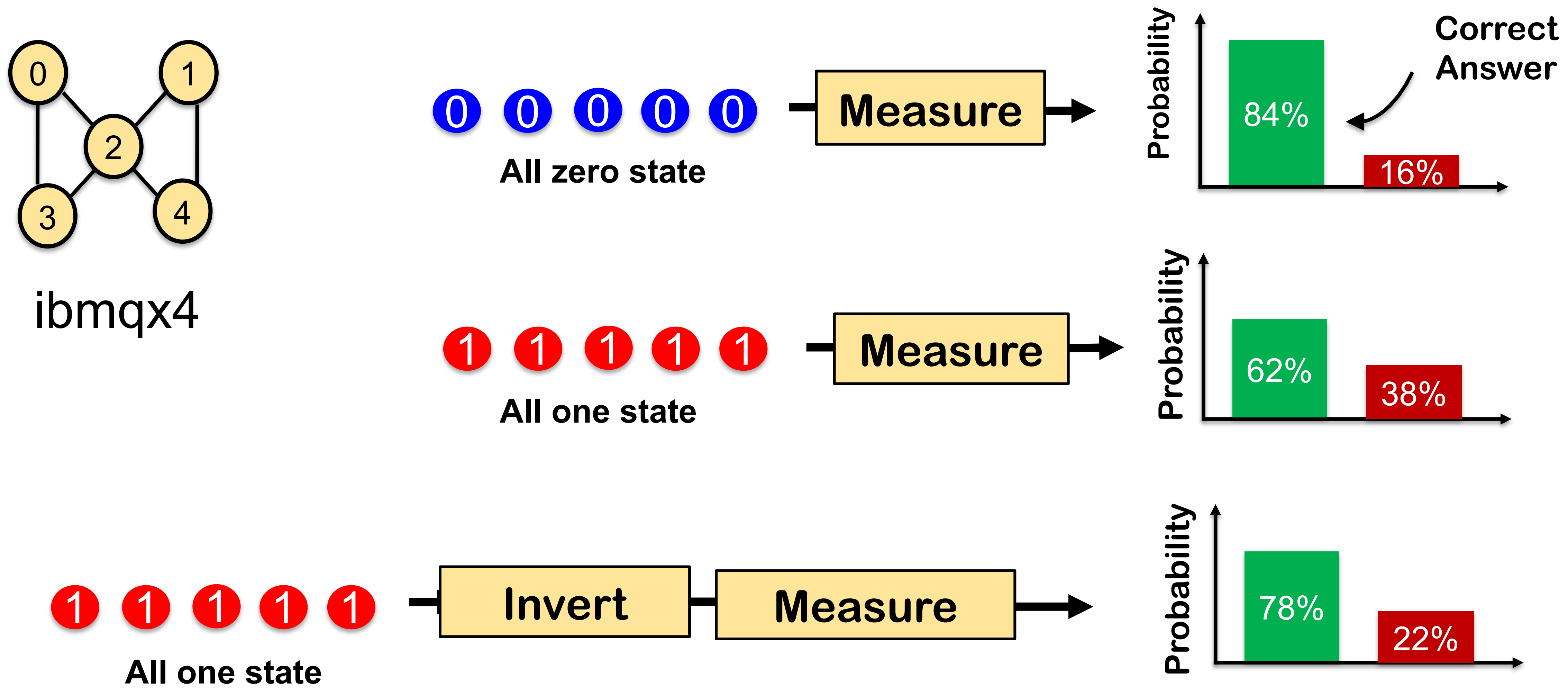
Swamit S. Tannu   Moinuddin K. Qureshi

Error on IBMQ14 Quantum Computer



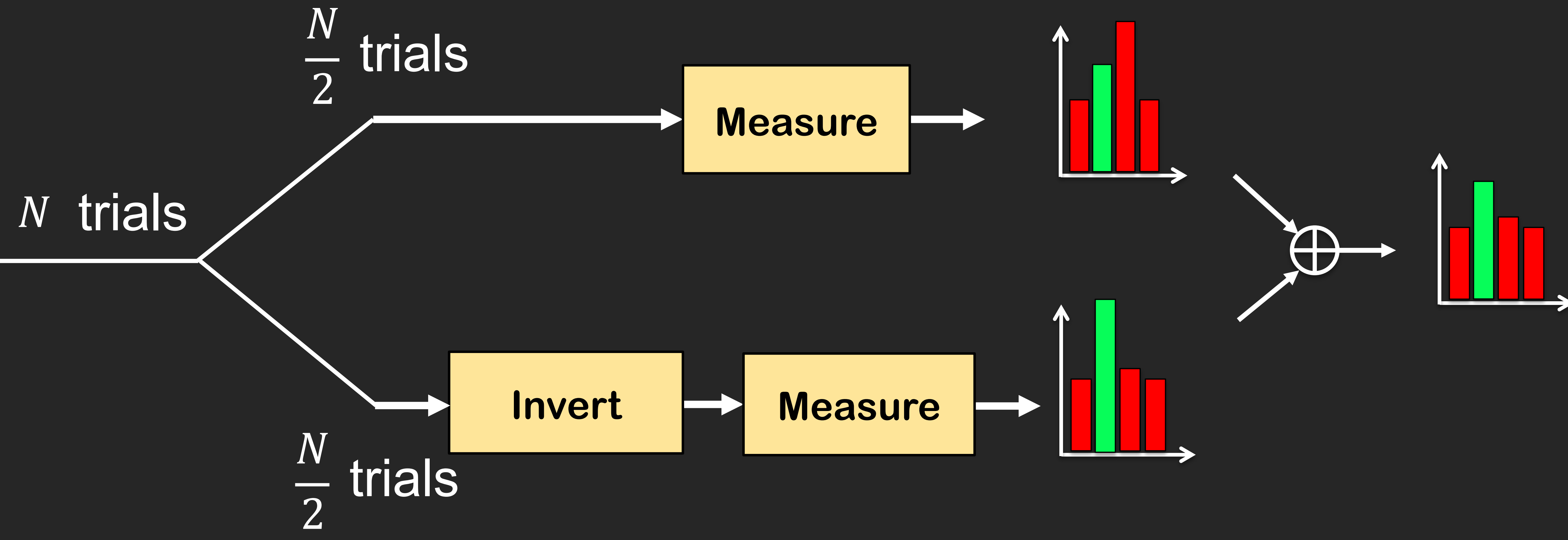
Qubit measurement error → dominant error

Experiments on IBM Quantum Computer



Measurement errors have directional bias

Static Invert and Measure (SIM)



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

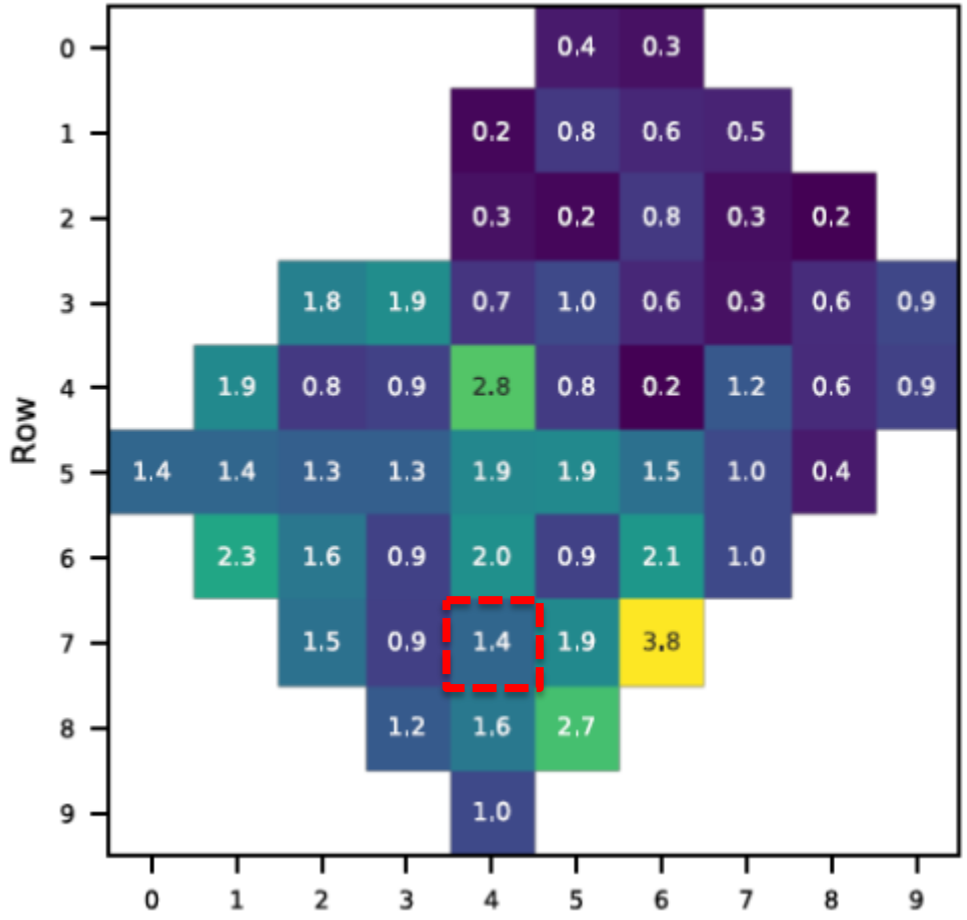
Evaluations: Improvement in Inference Strength

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

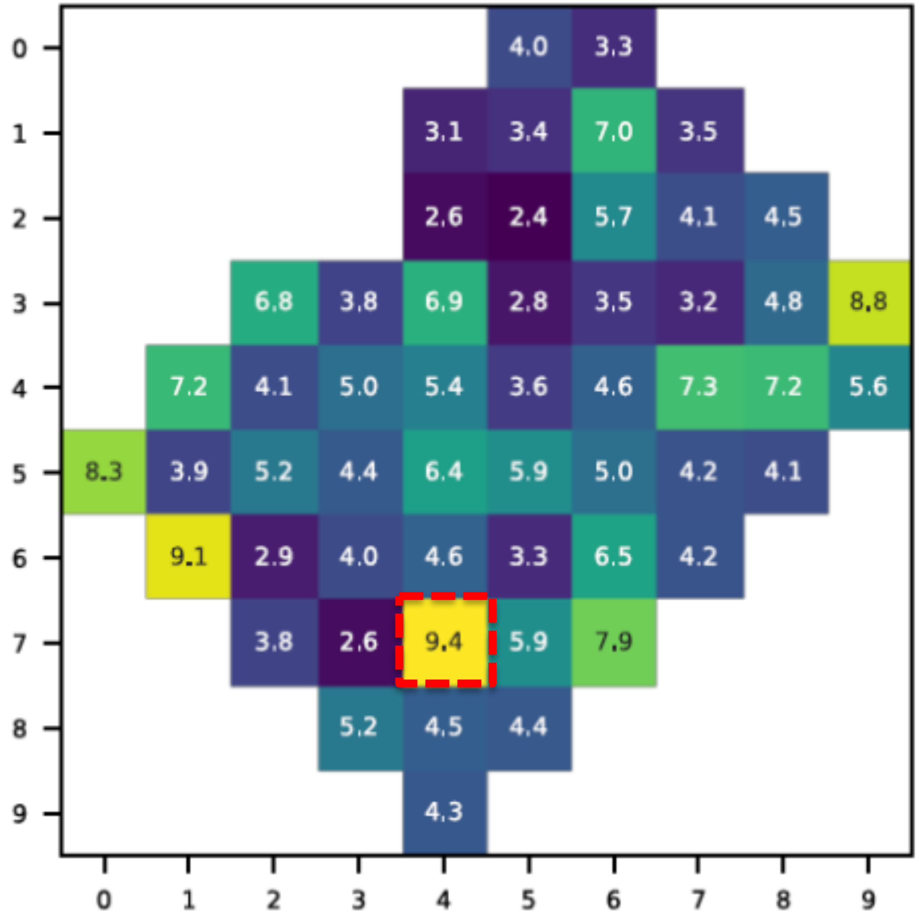
Inference Strength (IST) captures quality of inference. IST > 1 ensures correct answer is most likely

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"

Want to Win the Formula 1 Race?

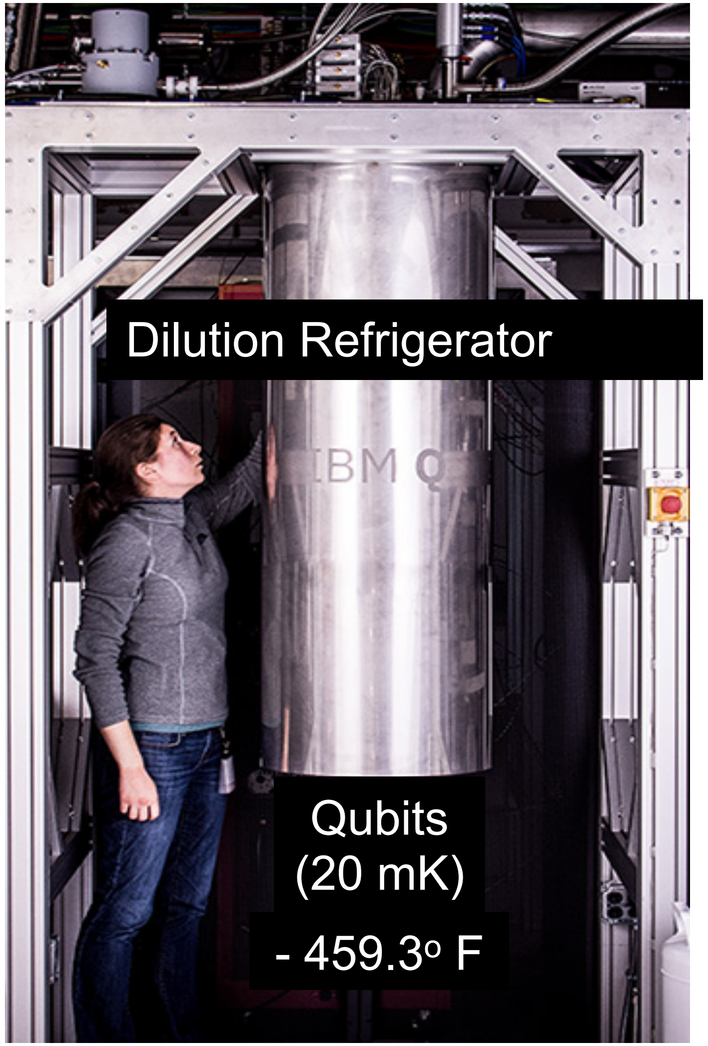
Having the best hardware is not enough, need to run the “right” software to win

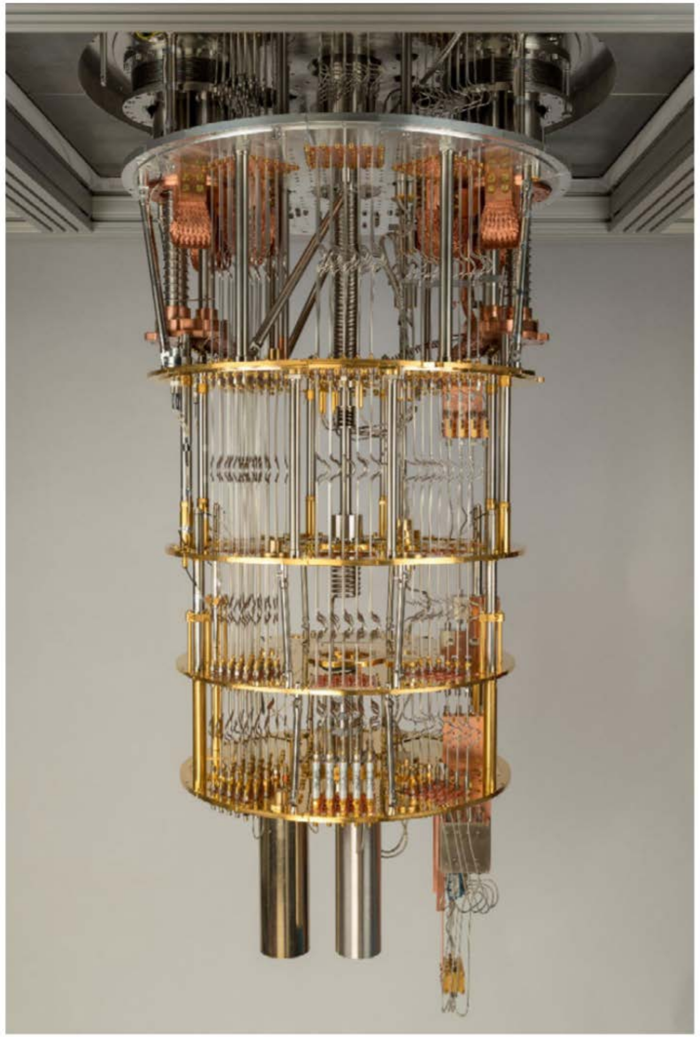
Takeaway

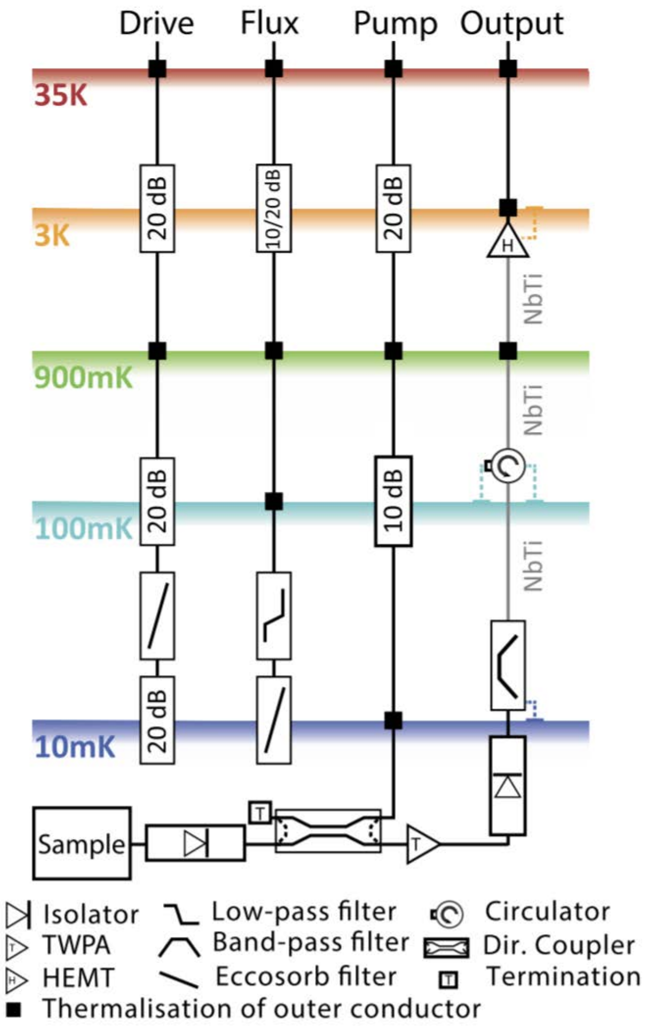
- Quantum Computers can solve important and intractable problems
- The top-three problem in QC: Errors, Errors, and Errors
- Program Transformation for Improving Reliability of NISQ Computers
  - **Variability Aware Mapping Policies [ASPLOS 2019]**
  - **Ensemble of Diverse Mappings [MICRO 2019]**
  - **Exploiting State-Dependent Bias in Measurement [MICRO 2019]**
- Other System-Level Work on Quantum (not discussed)
  - **A Case for Multi-Programming Quantum Computers [MICRO 2019]**
  - **Cryogenic Control Processor for Large-Scale Quantum Computers [MICRO 2017]**
  - **Cryogenic DRAM for Large-Scale Quantum Computers [MEMSYS 2017]**

This is exciting time to be working on Quantum Computing in ECE/CS

Quantum Bits Require Cryogenic Temperature

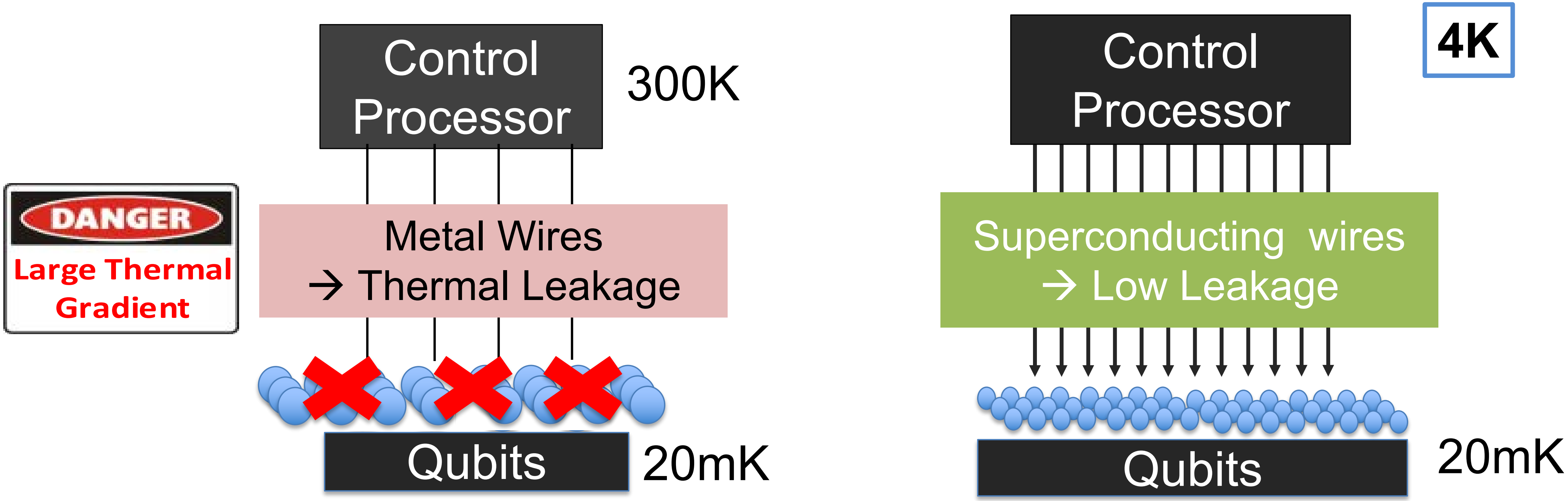






Source: Krinner et. al (ETH)

Cryogenic Control Processor



Cryogenic Control Processor is essential for scalable Quantum Computer

Towards Cryogenic Computing