A Case for Multi-Programming Quantum Computers

Poulami Das[*]
Swamit S. Tannu[*]
Prashant J. Nair[#]
Moinuddin Qureshi[*]

[*]Georgia Institute of Technology

[#]The University of British Columbia

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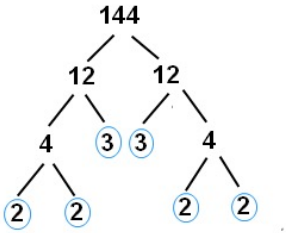

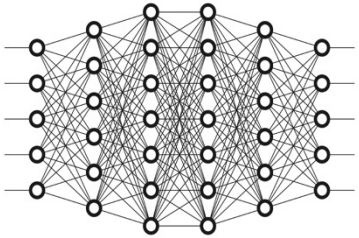

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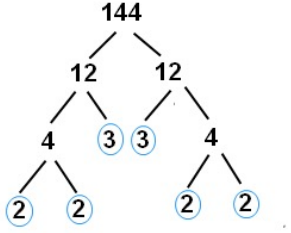

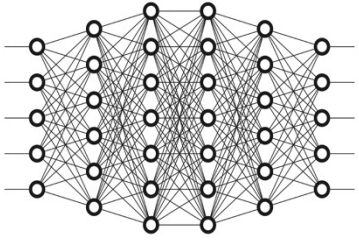

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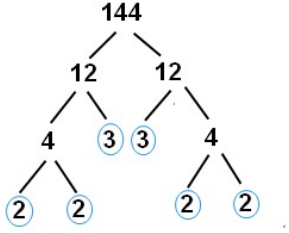

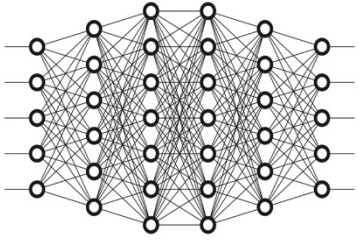

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	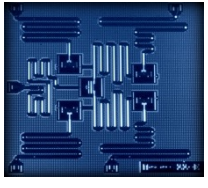	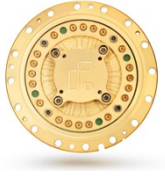	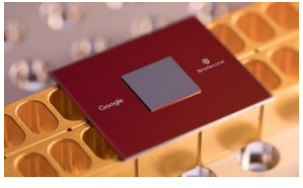	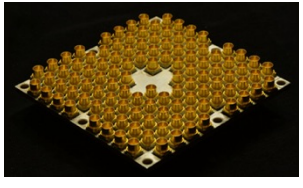
# Qubits	5, 16, 20, 53	19	53, 72	49

Noisy Intermediate Scale Quantum (NISQ) Computing

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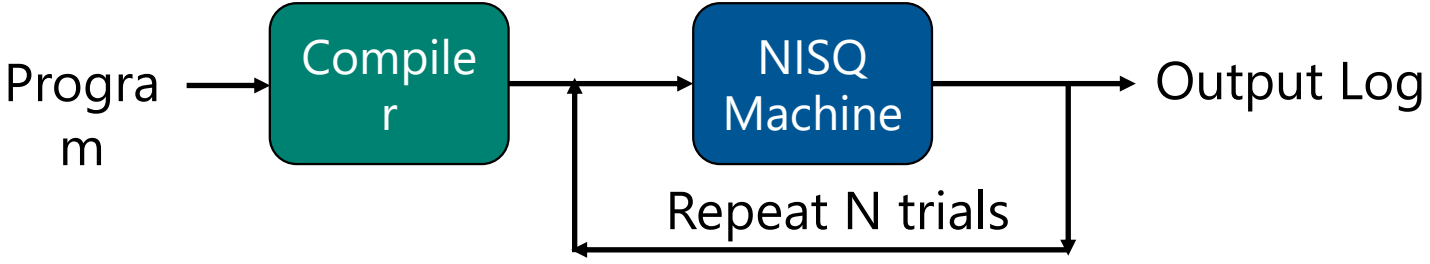

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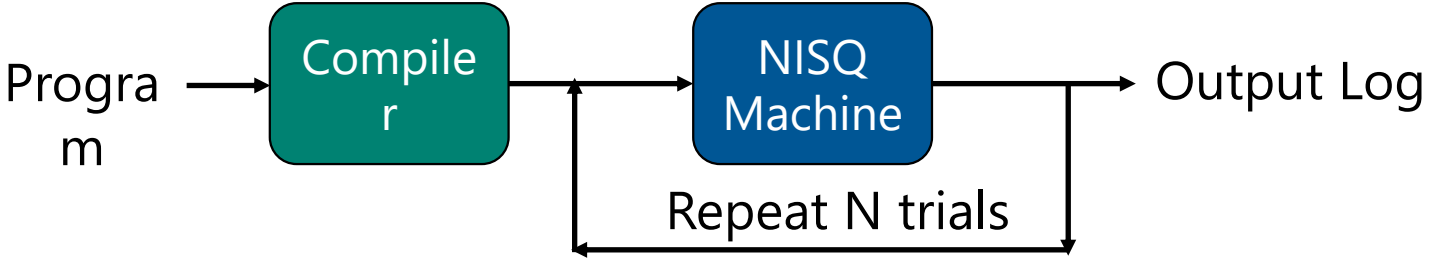

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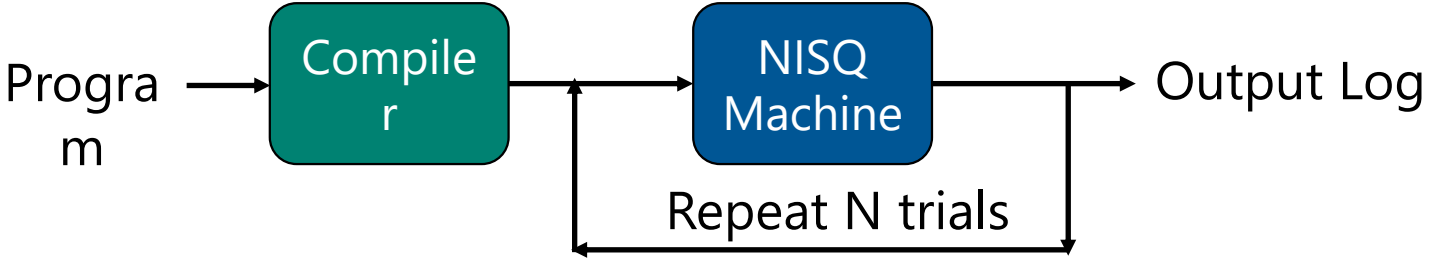

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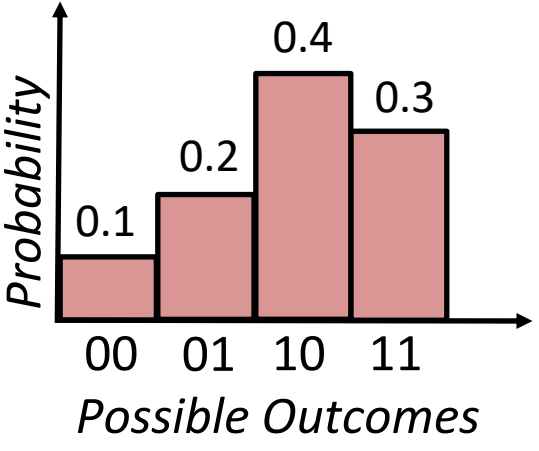

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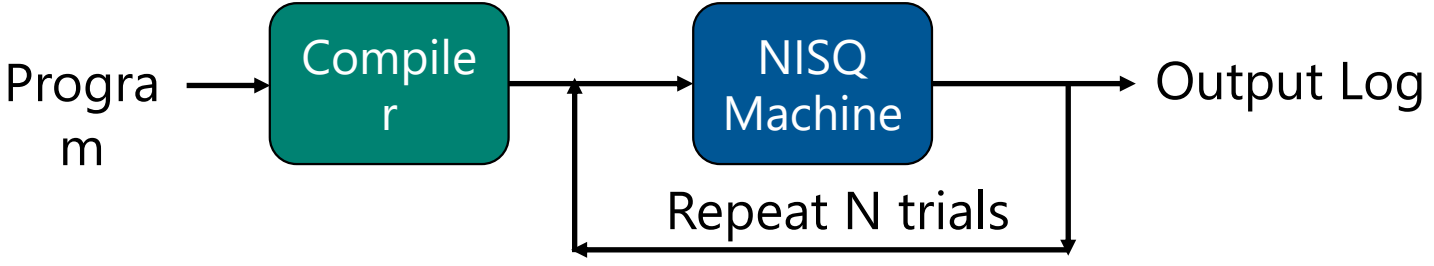

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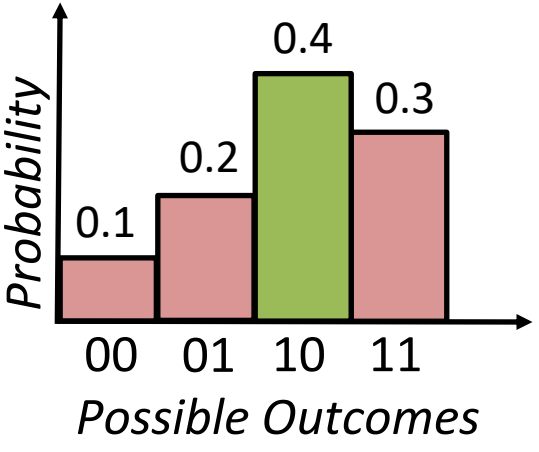

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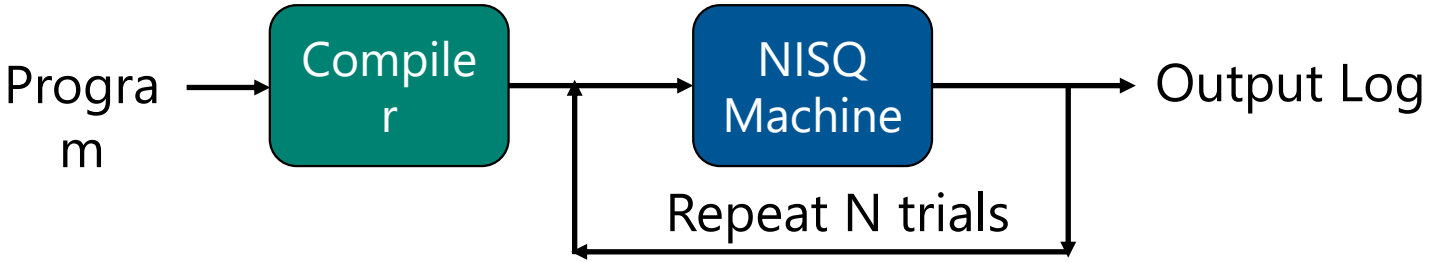

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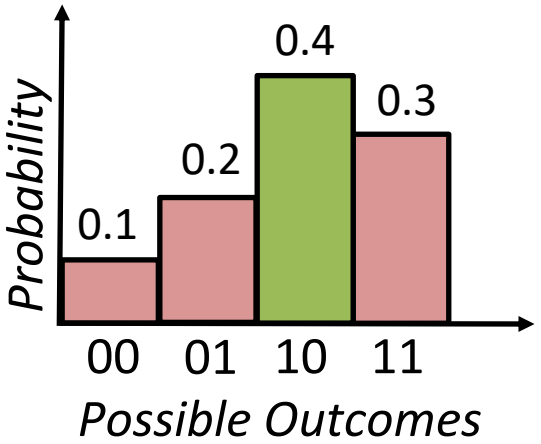

- Reliability measured using *Probability of Successful Trial (PST)*

NISQ computers will be operated in the presence of noise and reliability is measured using the PST from multiple trials

Underutilization in NISQ Computers

Error rates limit the number of reliable operations

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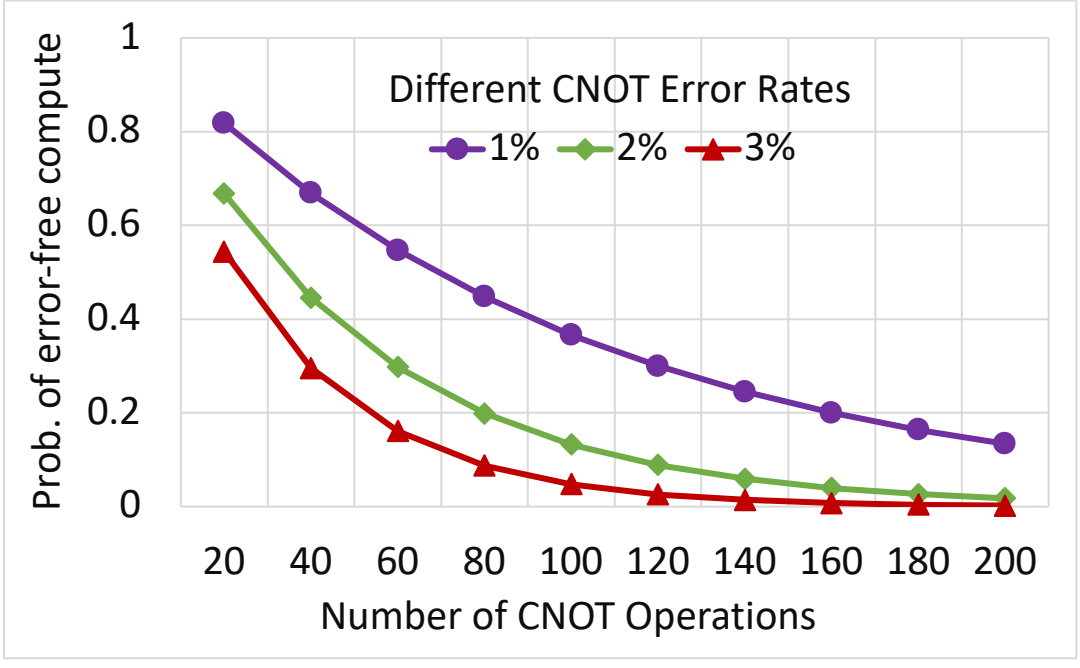

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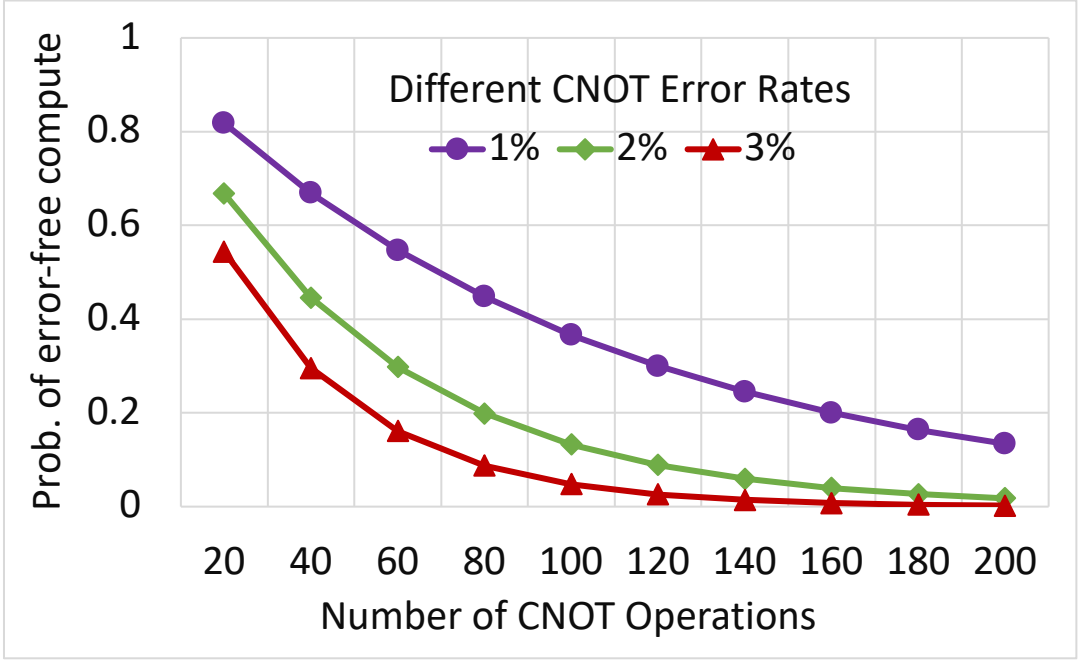

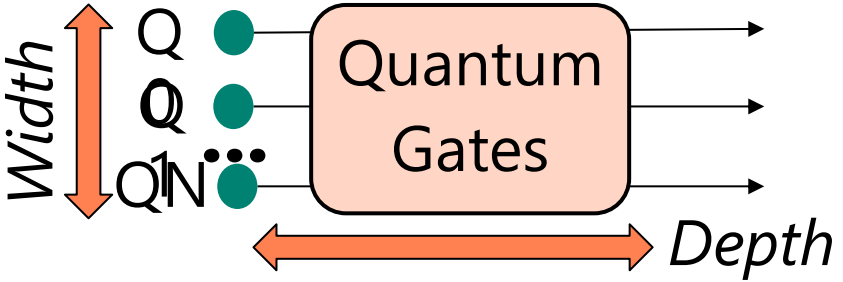

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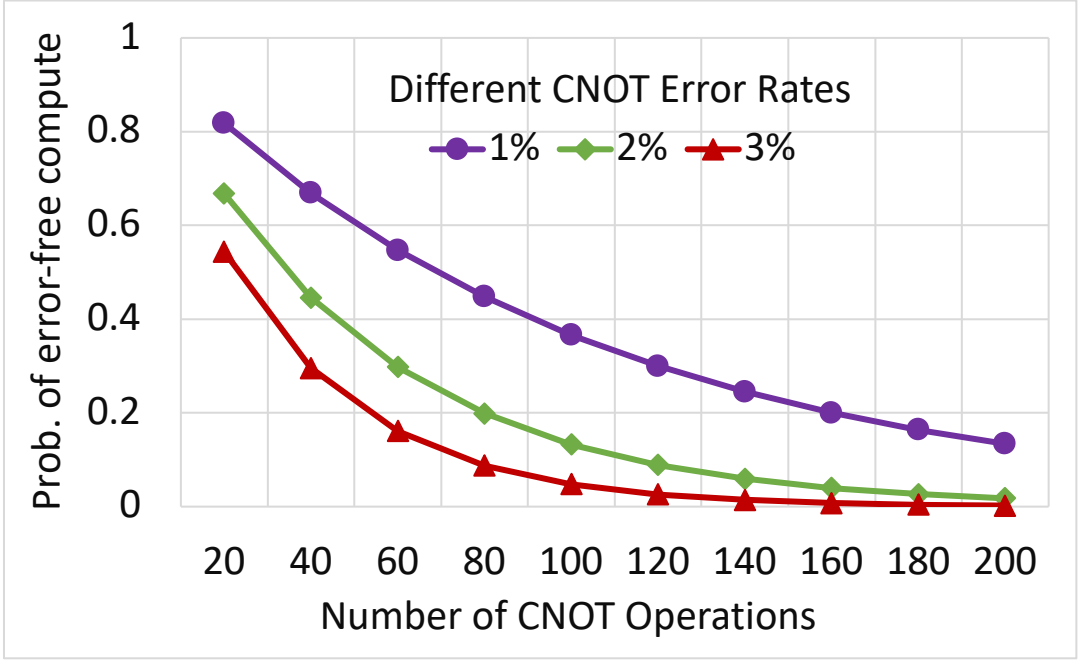

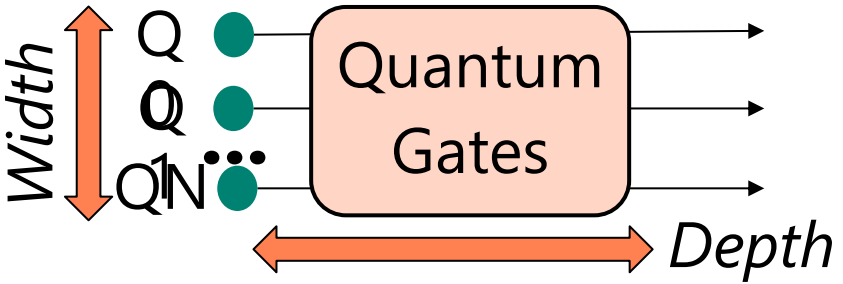

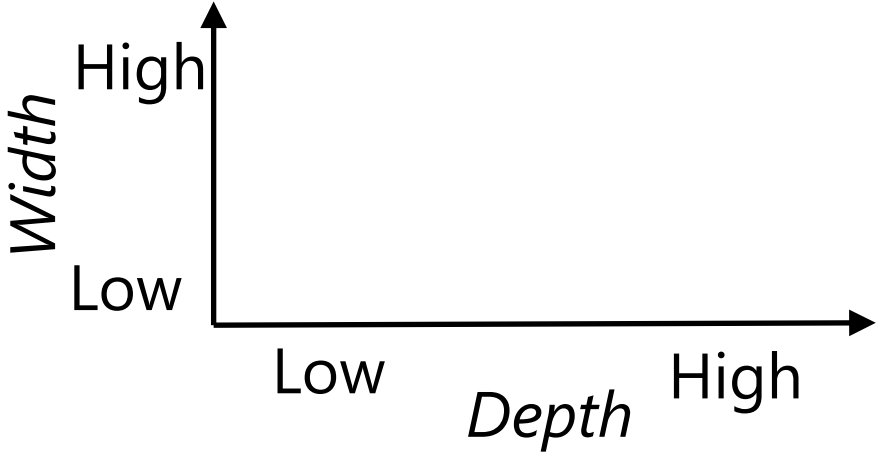

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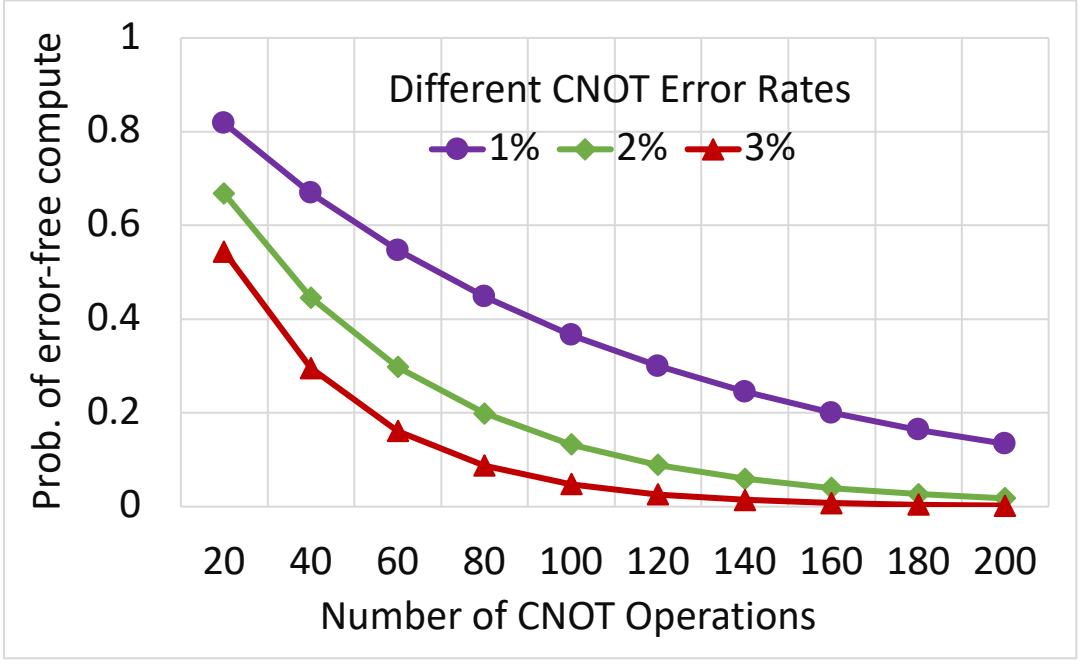

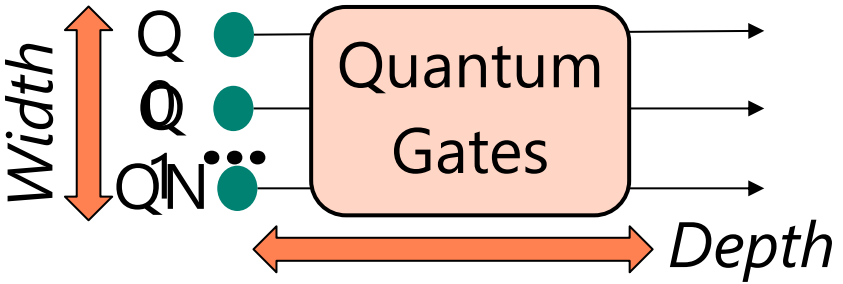

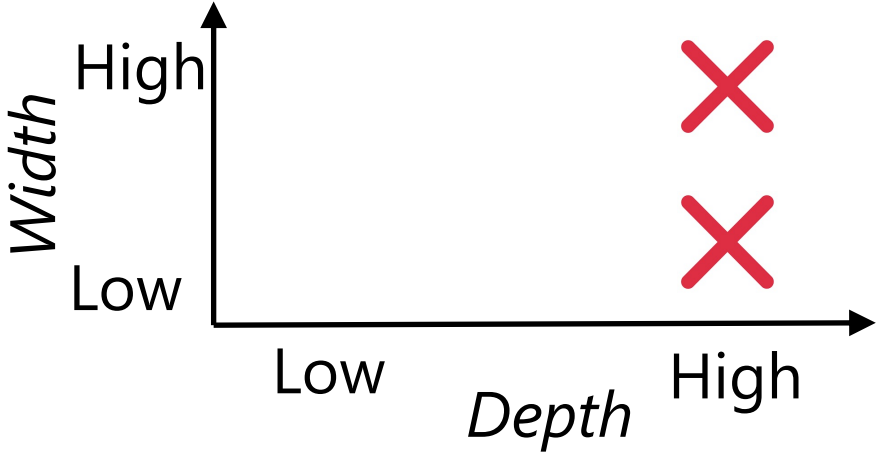

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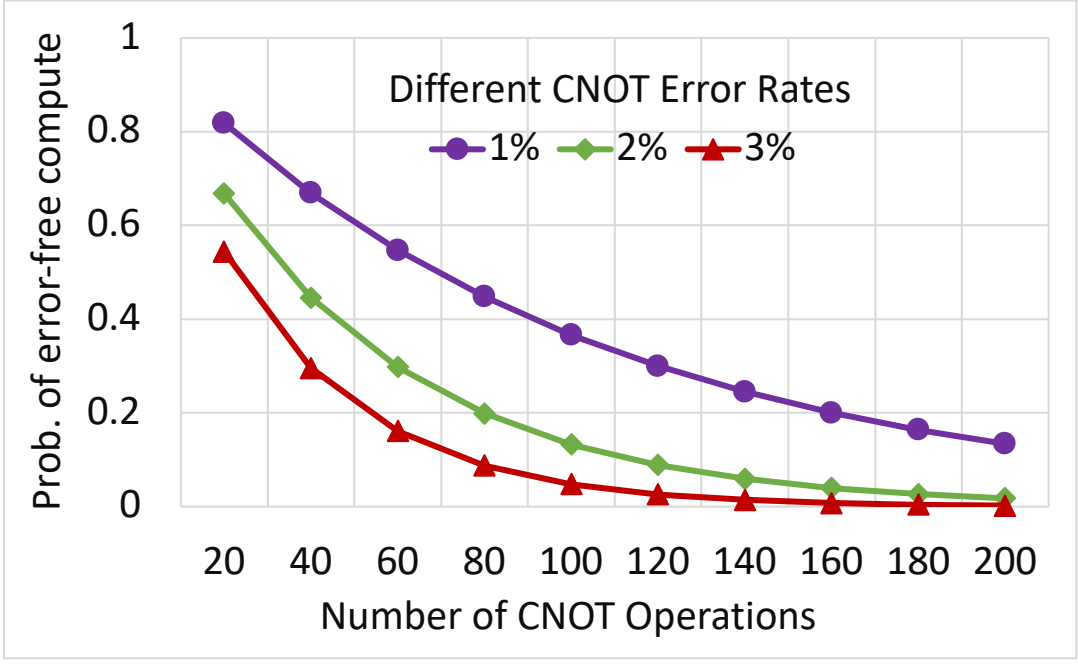

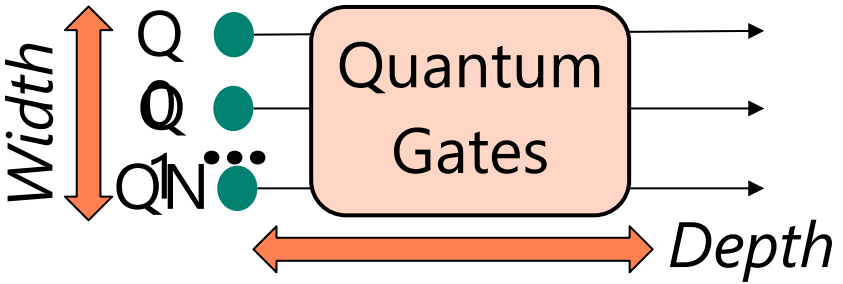

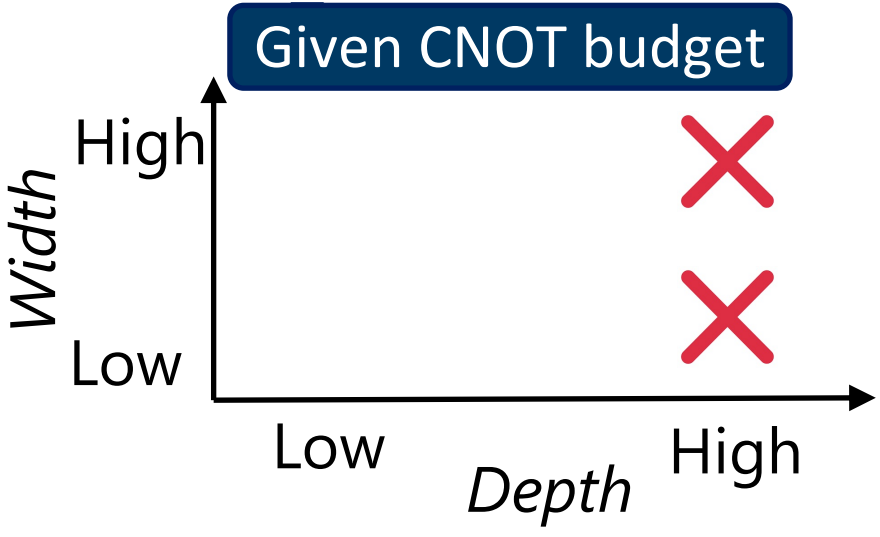

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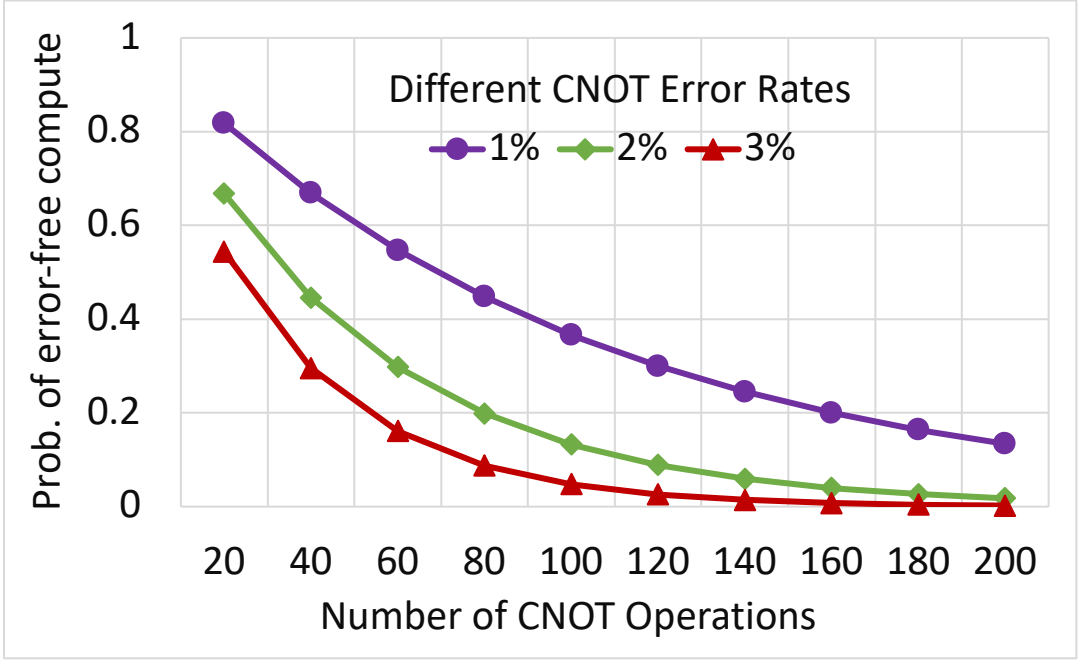

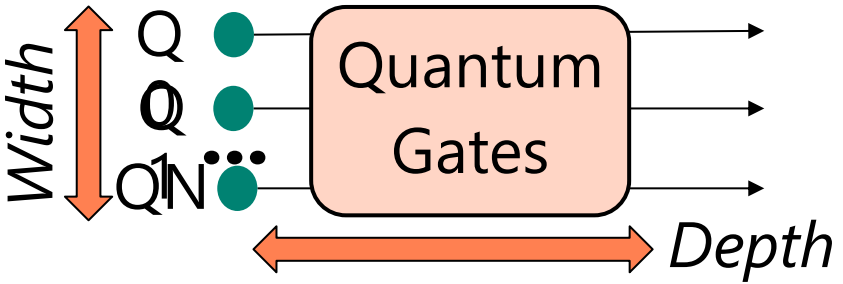

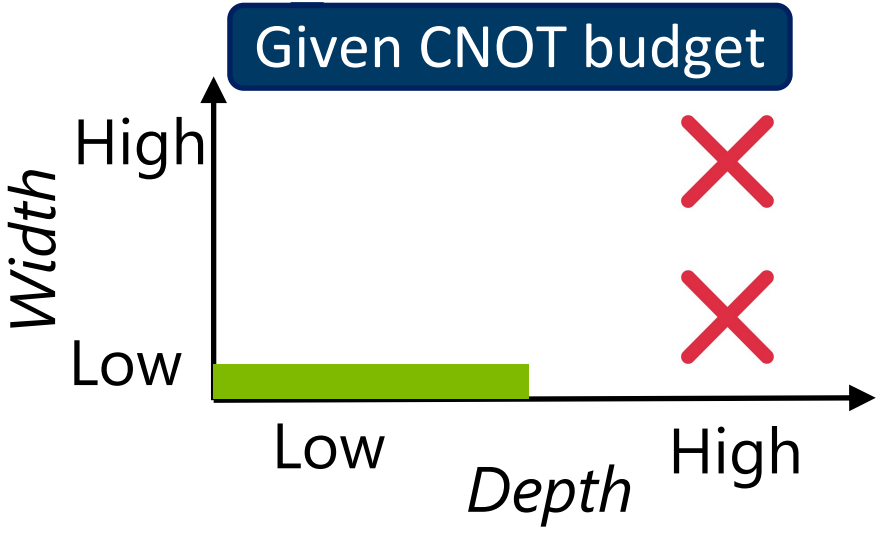

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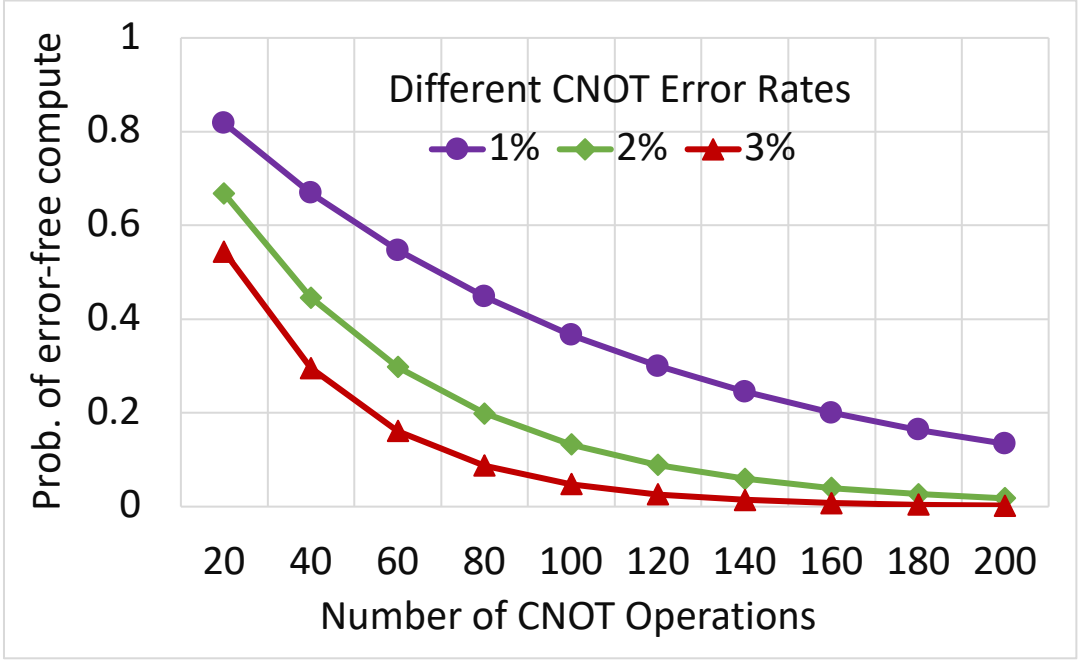

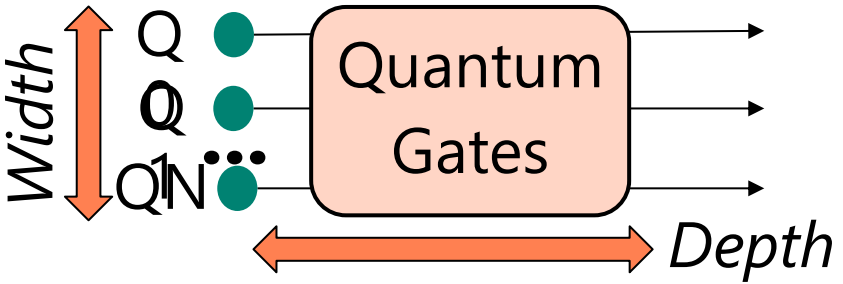

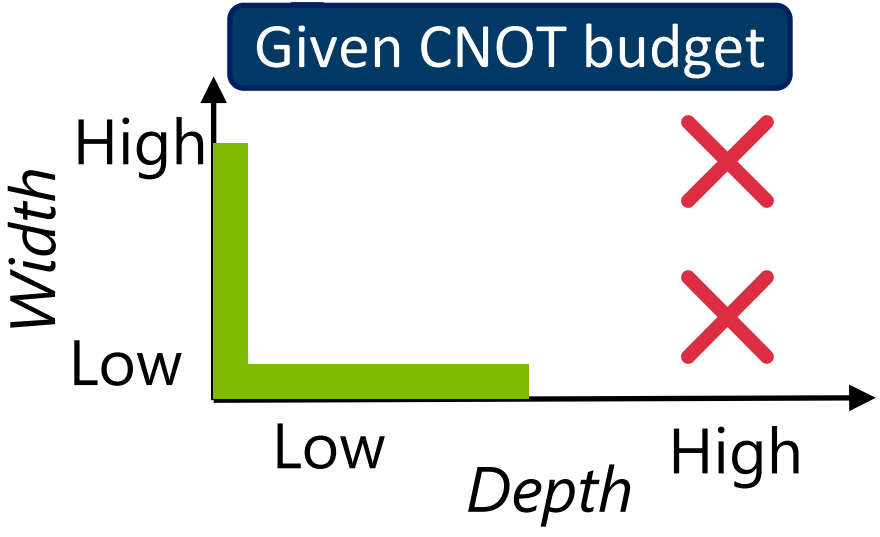

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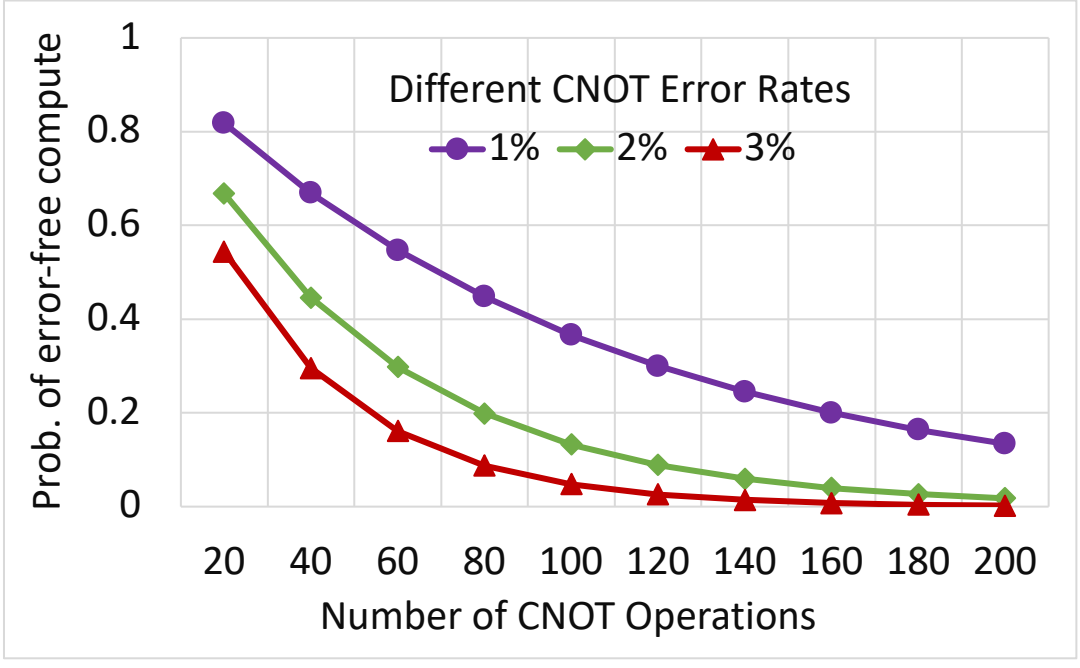

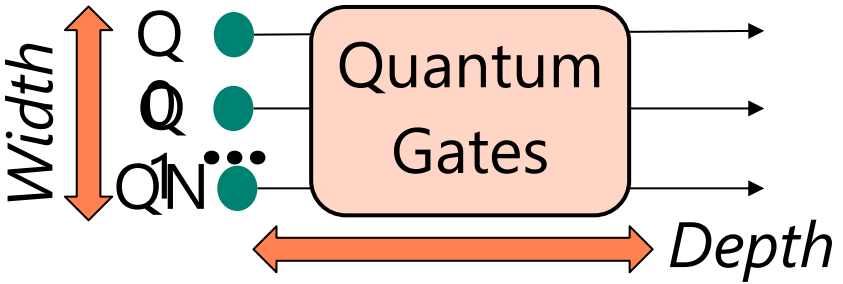

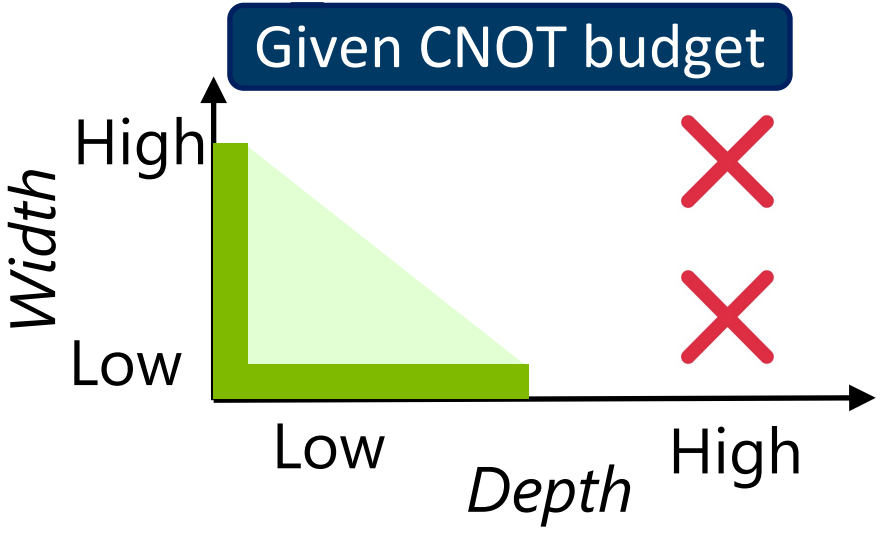

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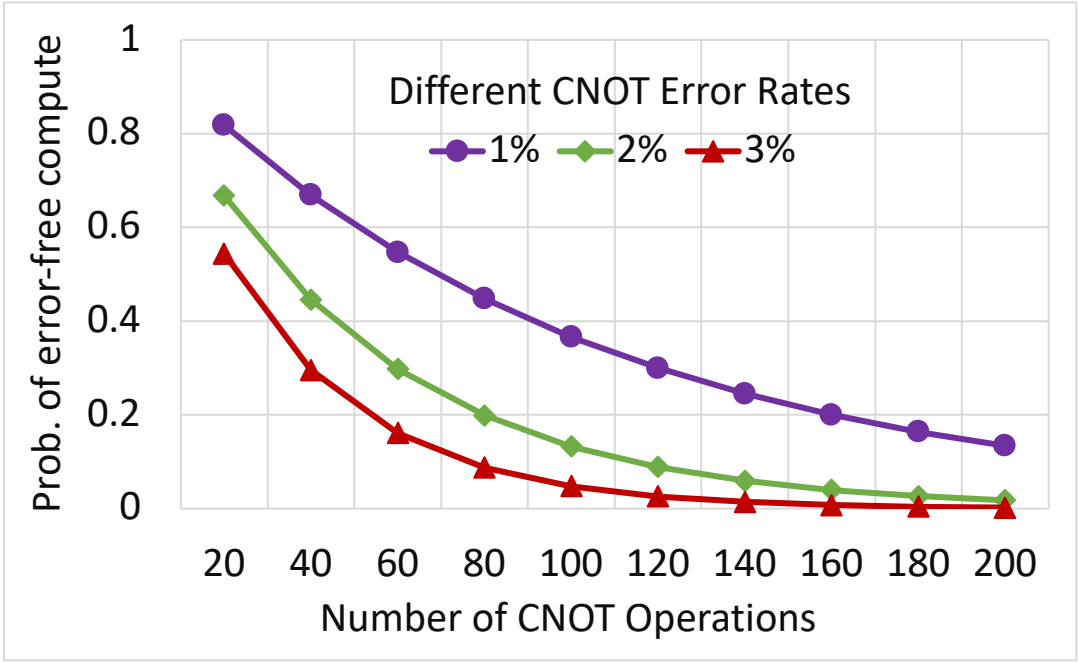
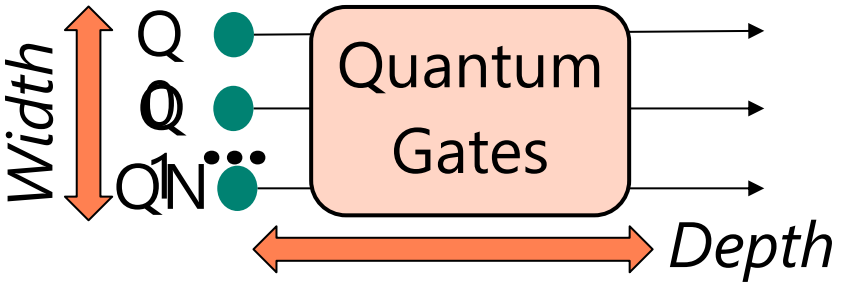
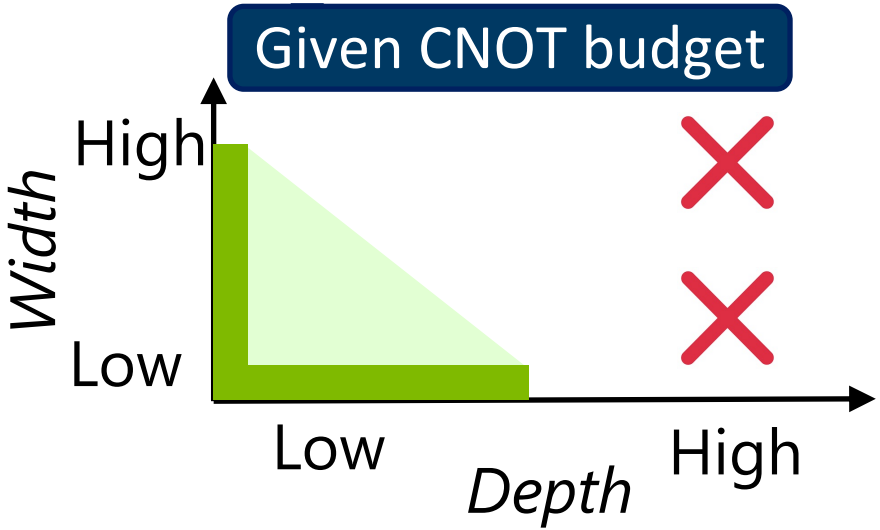
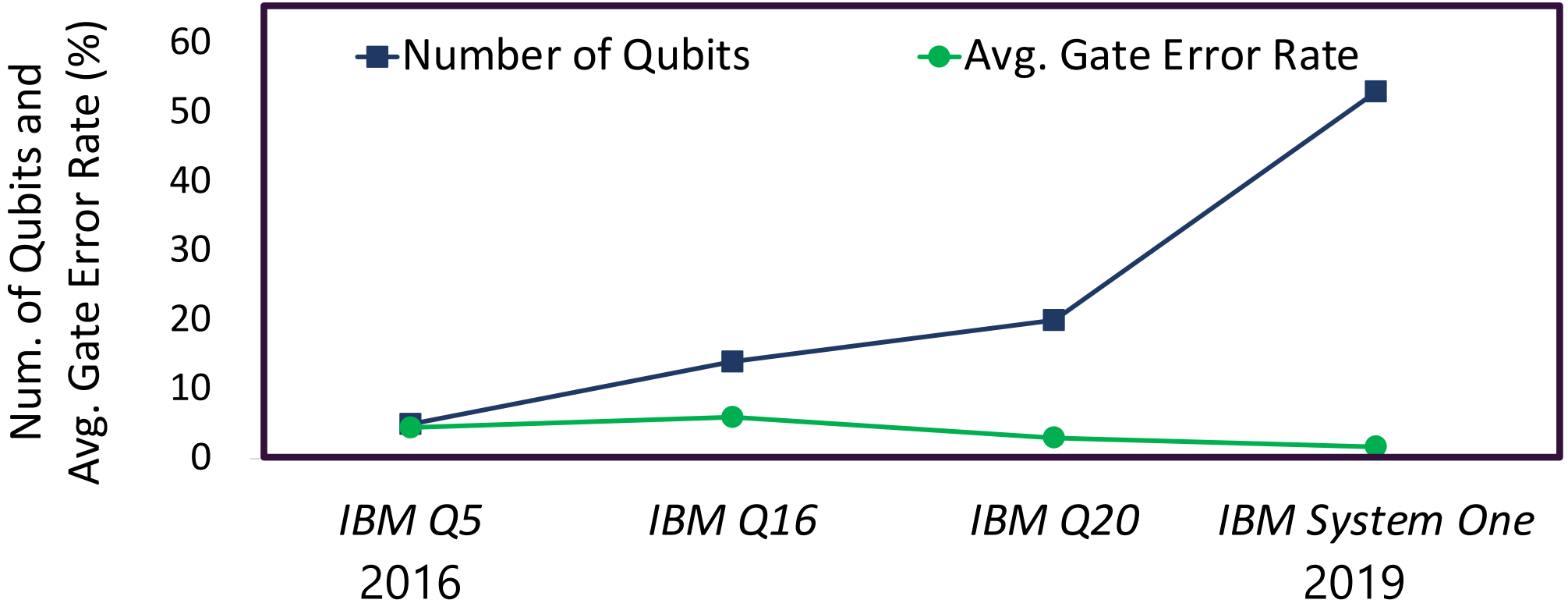






Programs may not use all the qubits leaving unused resources

Quantity vs. Quality Gap



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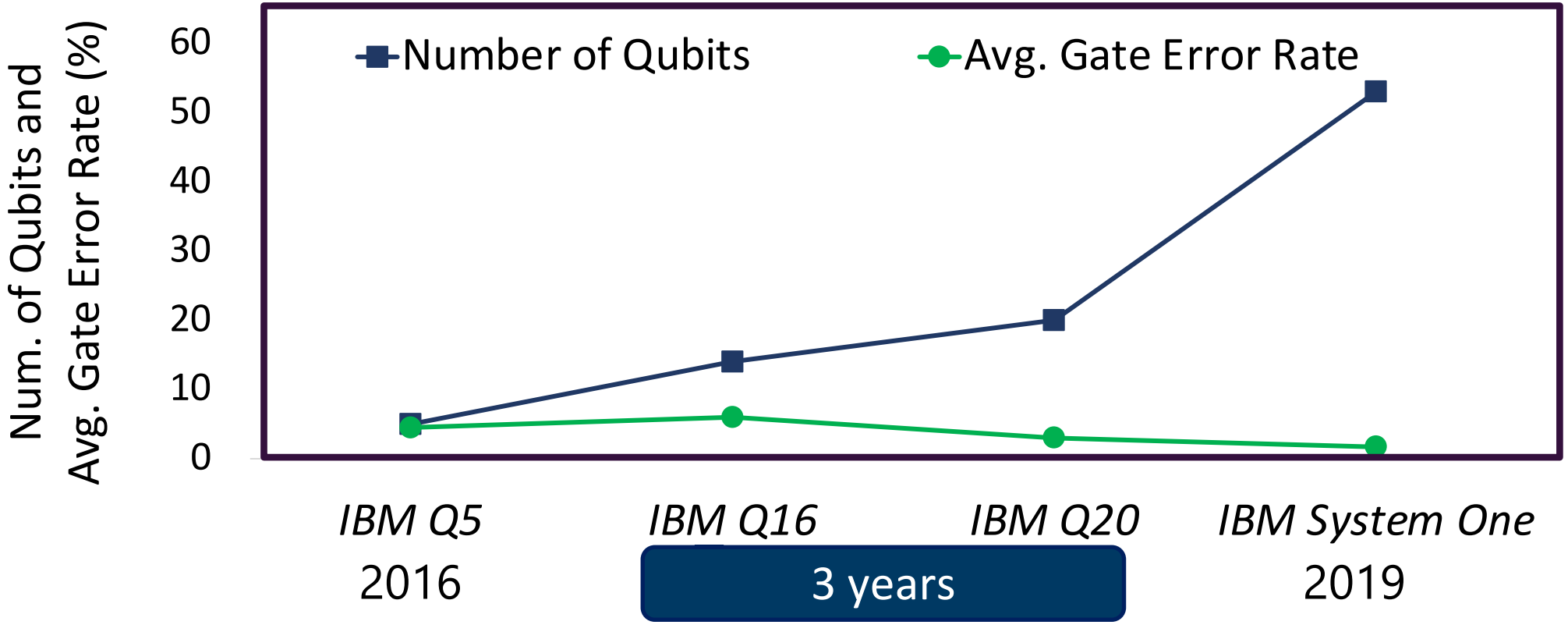

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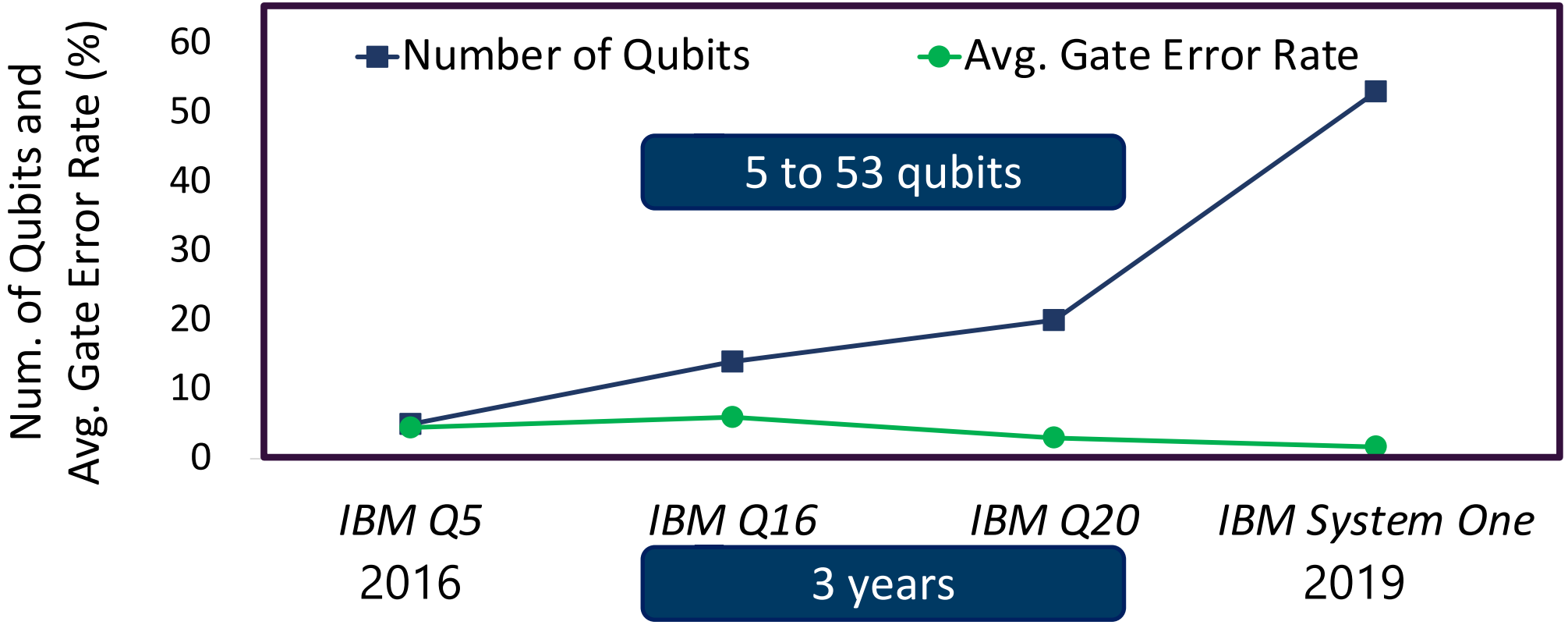

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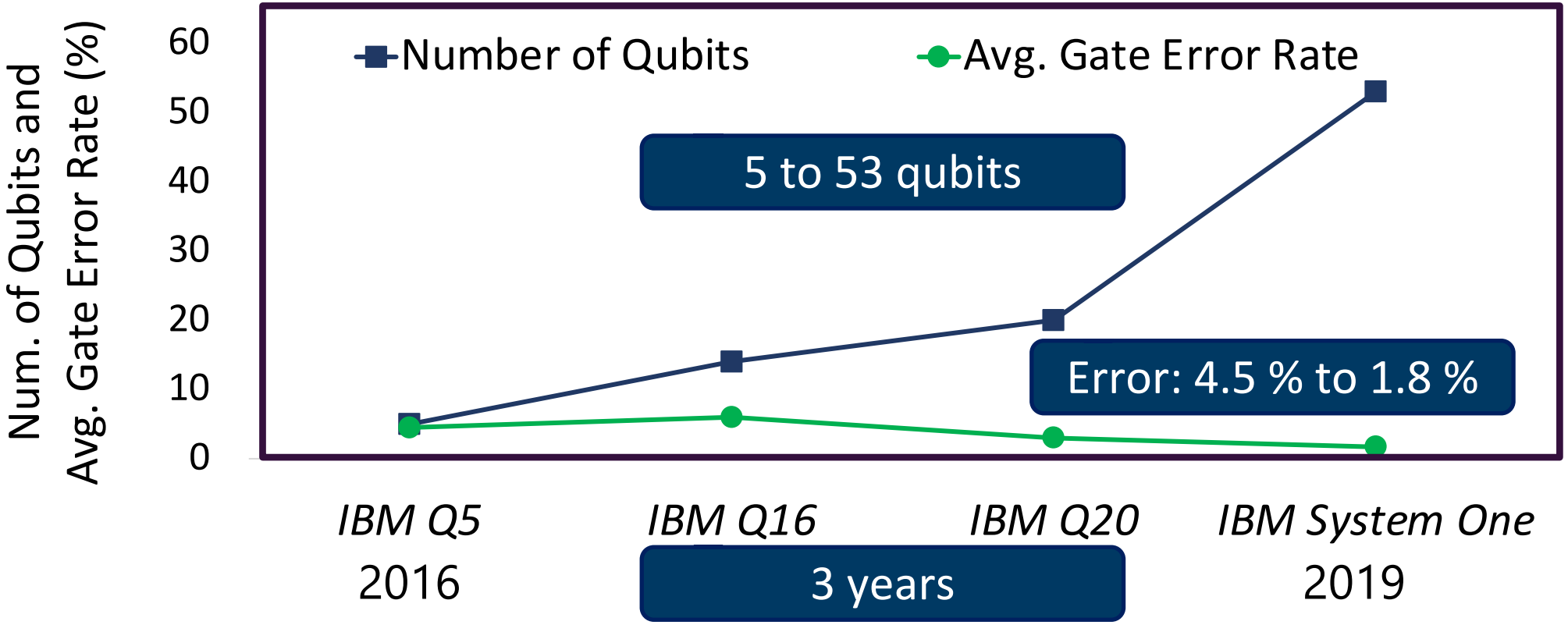

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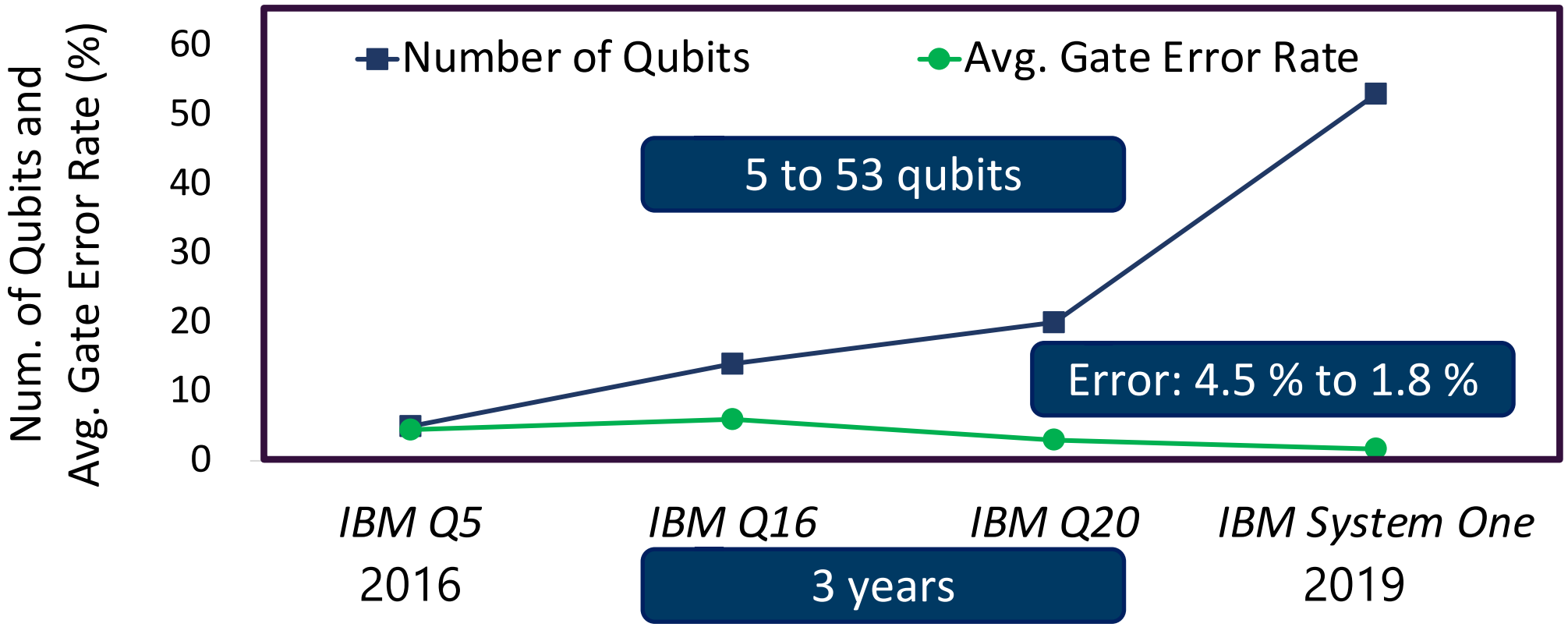

With current scaling of error rates, it is difficult to use all the qubits

Demand for Limited NISQ Resources

High
Demand

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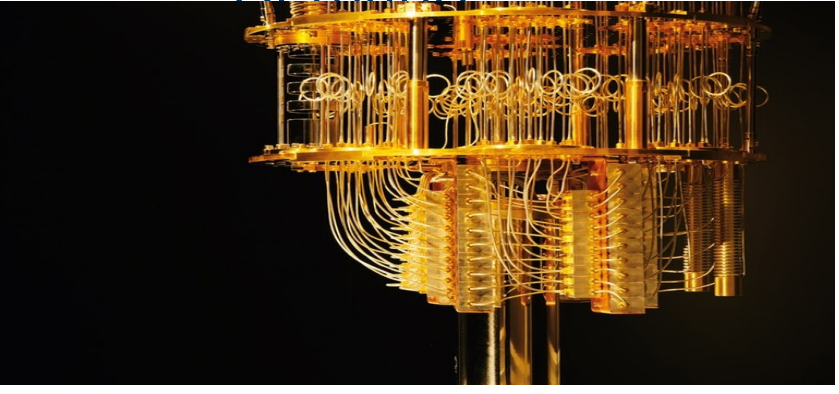
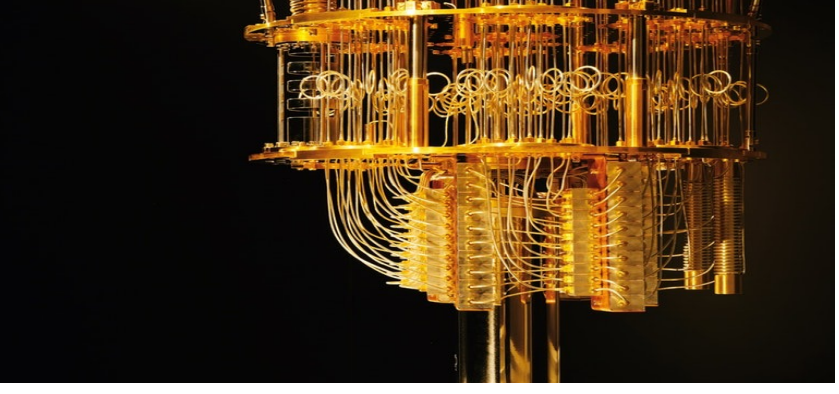


Expensive and Limited

Demand for Limited NISQ Resources

High Demand

Increasing Gap



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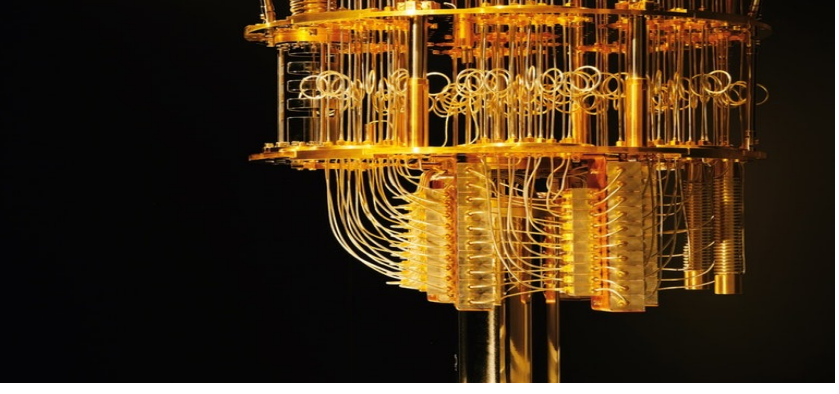

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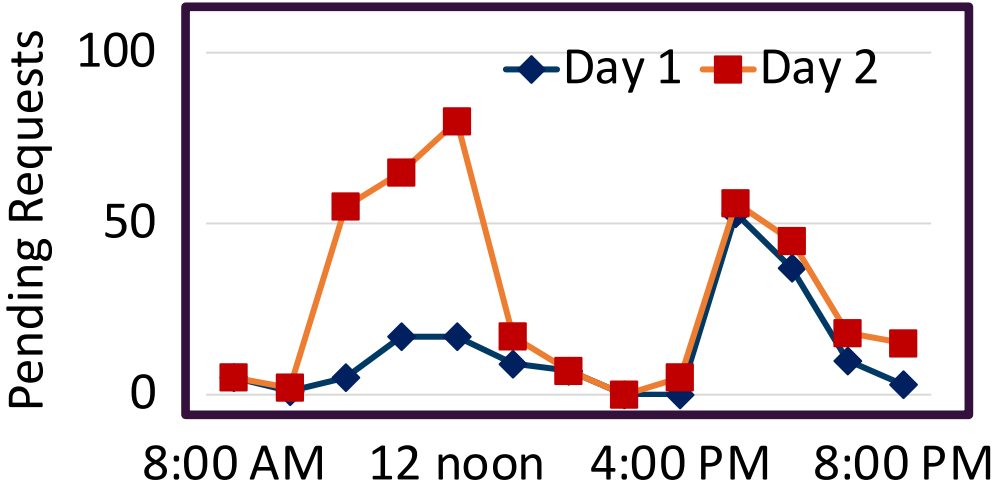

Pending Requests for access to IBM Q16 on different days

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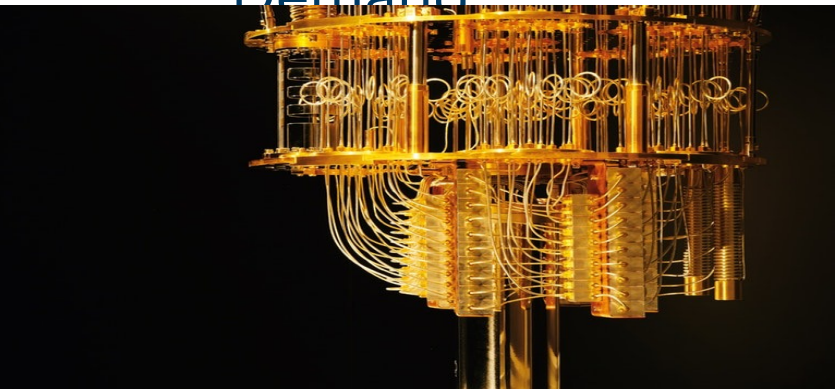

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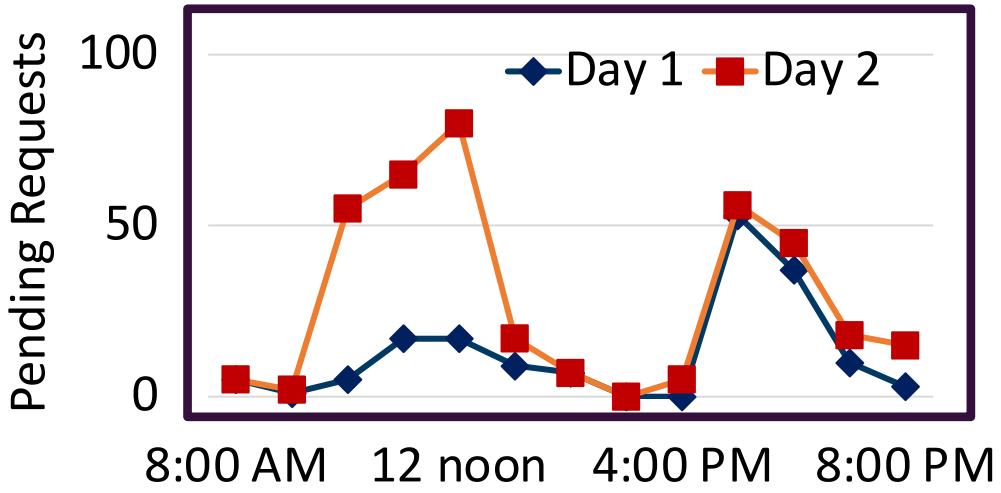

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Limited NISQ resources must scale to a large number of users

Our Proposal: Multi-Program Quantum Computers

Multi-programming can improve throughput and utilization

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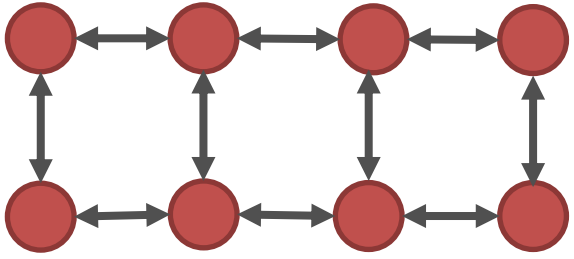

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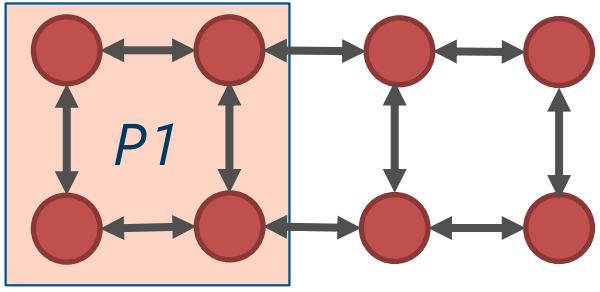

Current Approach

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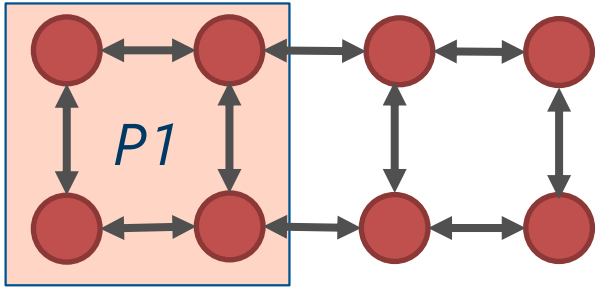
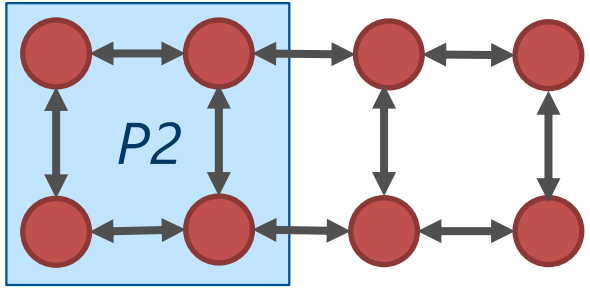


time = T2



Current Approach

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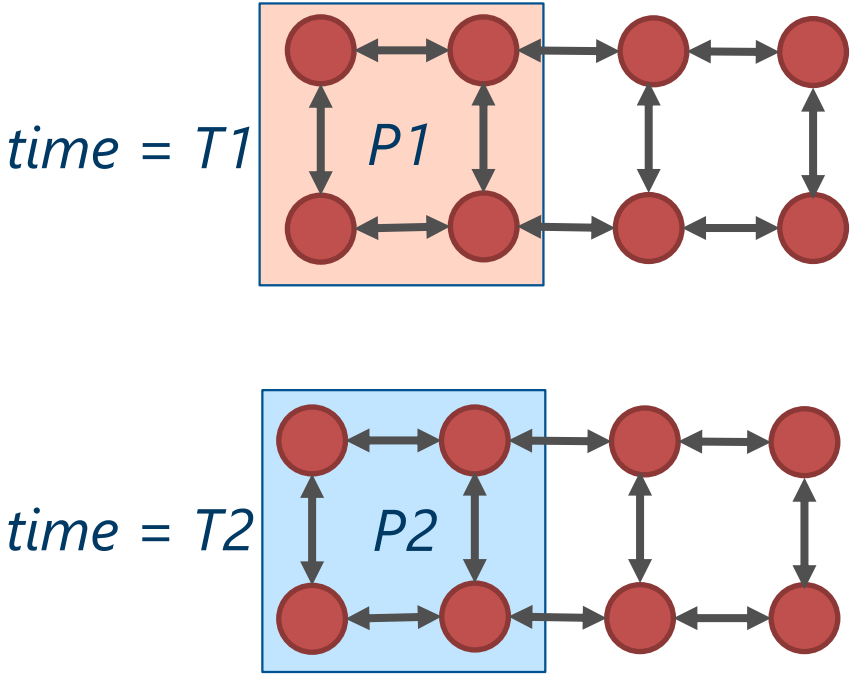

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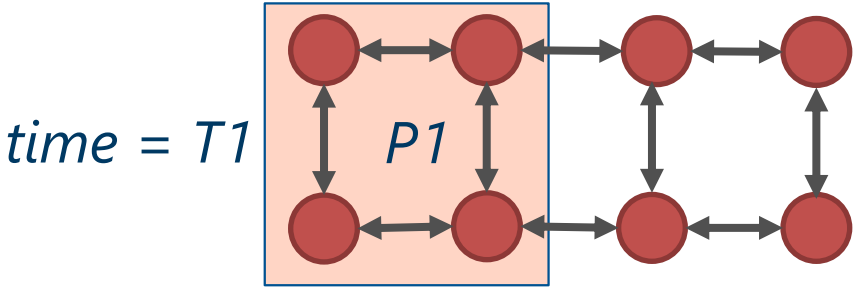

Proposed Approach

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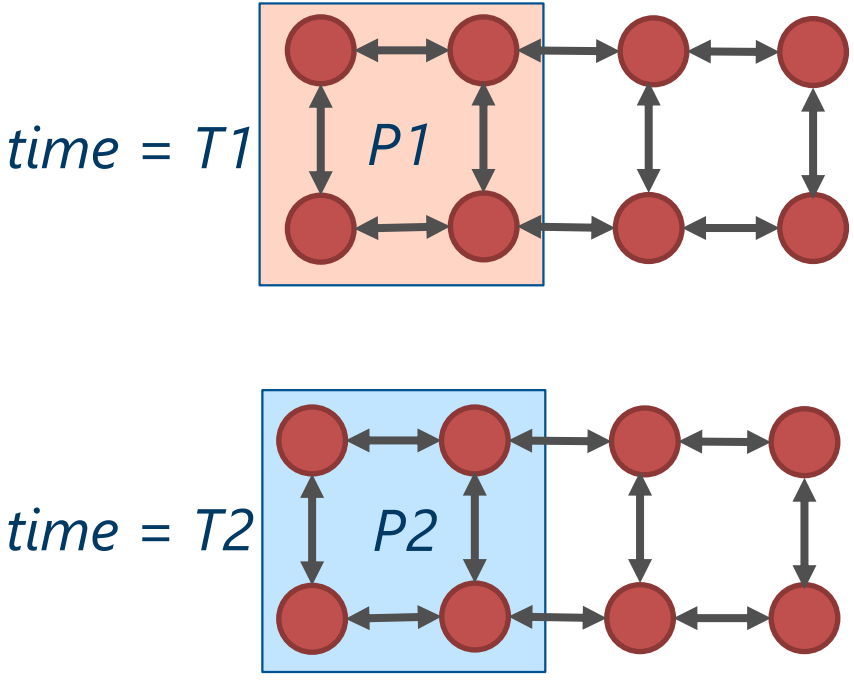

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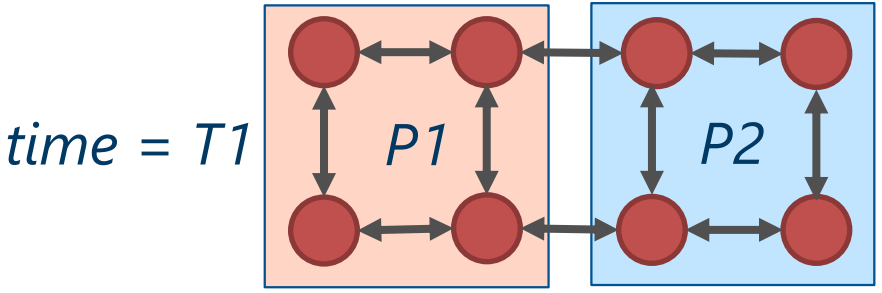
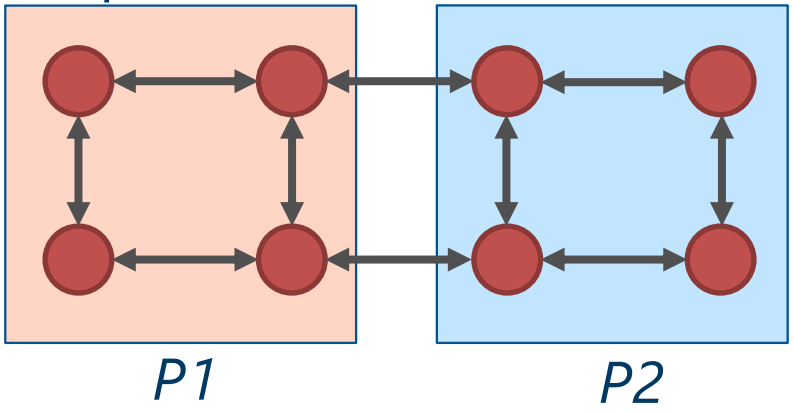


Proposed Approach

Challenges in Multi-Programming NISQ Computers



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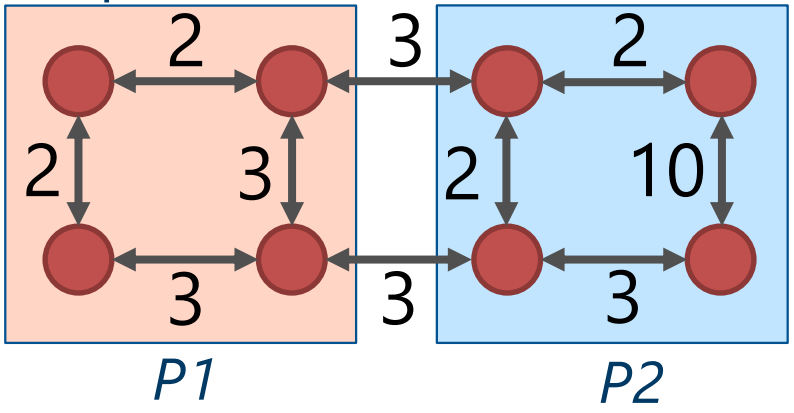

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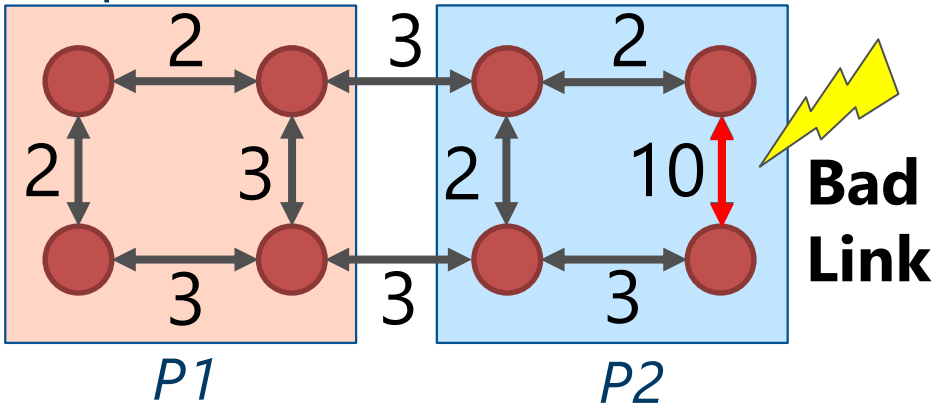

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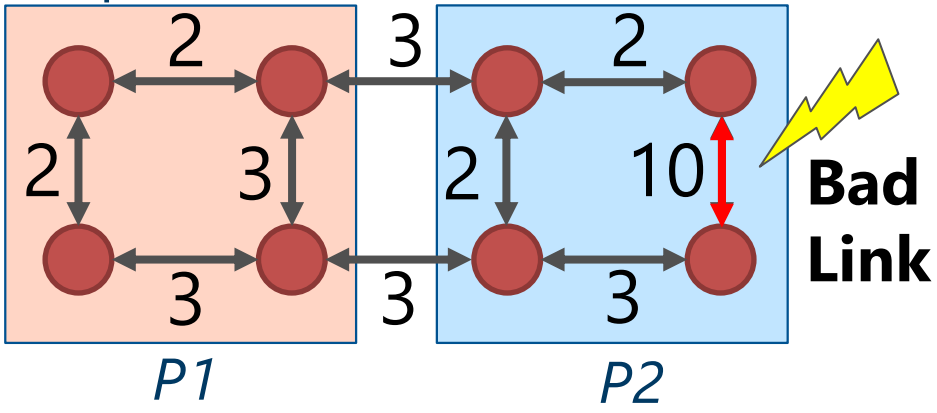
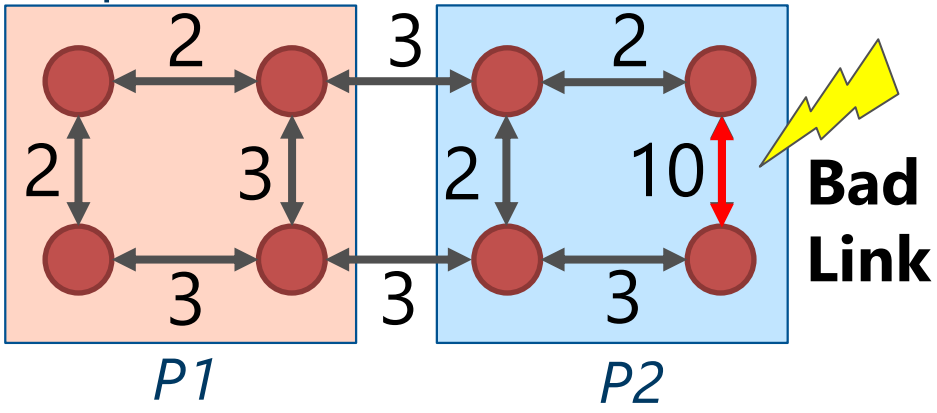


Correctness and Reliability Issue!

Challenges in Multi-Programming NISQ Computers



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- Fairness in resource allocation

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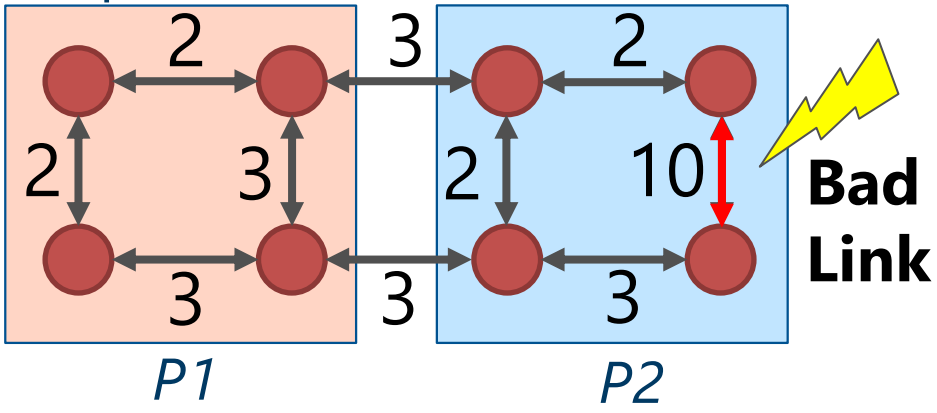

Correctness and Reliability Issue!

- Fairness in resource allocation
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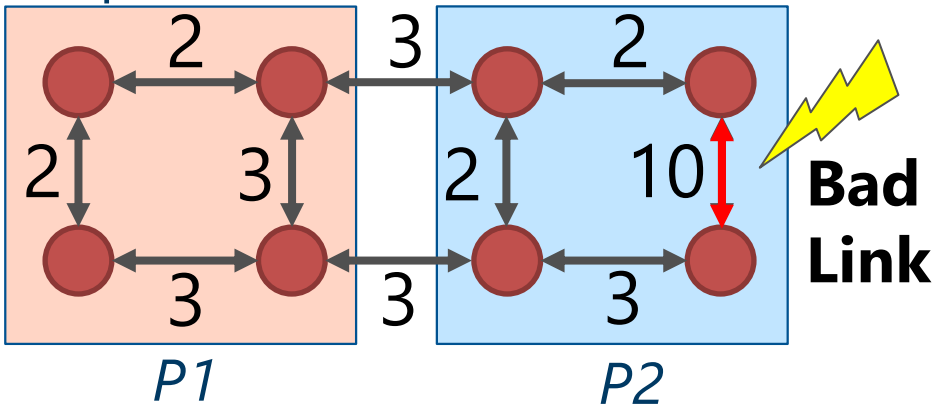

Correctness and Reliability Issue!

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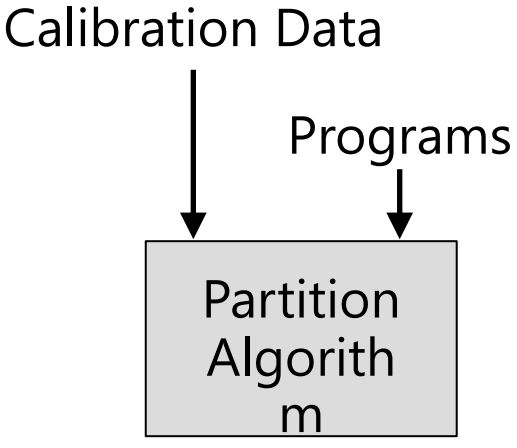
Our goal is to enable multi-programming to improve the throughput and utilization of quantum computers while minimizing the impact on reliability

Outline

- Introduction
- Background and Motivation
- Policies for Multi-Programming
- Evaluation Methodology
- Adaptive Multi-Programming Design
- Results and Conclusion

Overview Of Our Proposals



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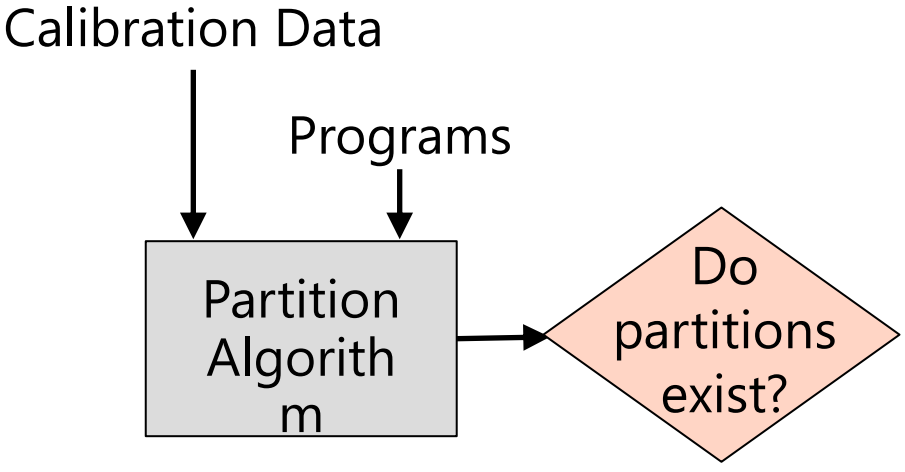

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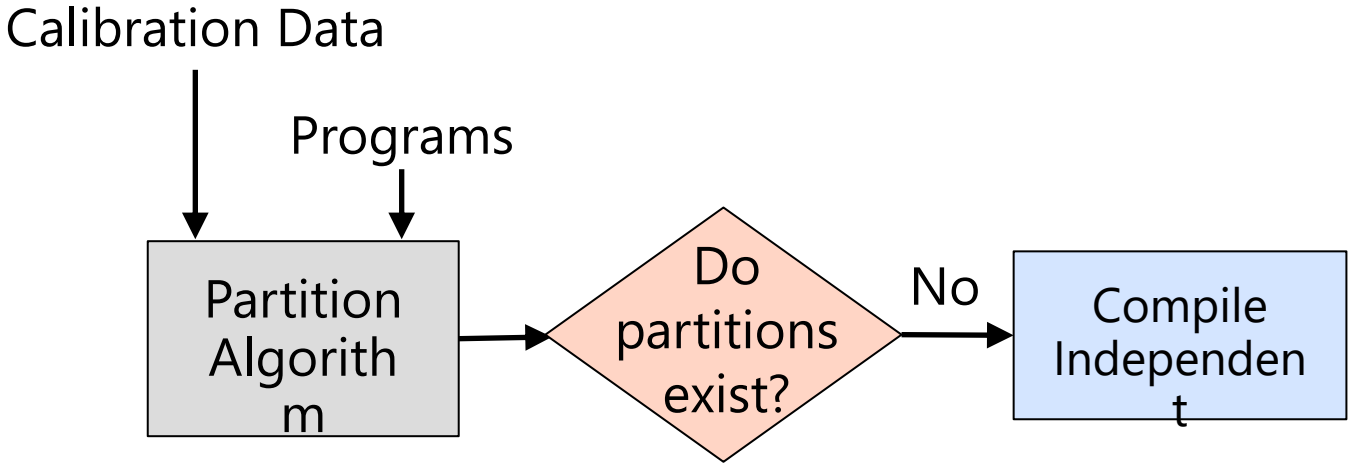

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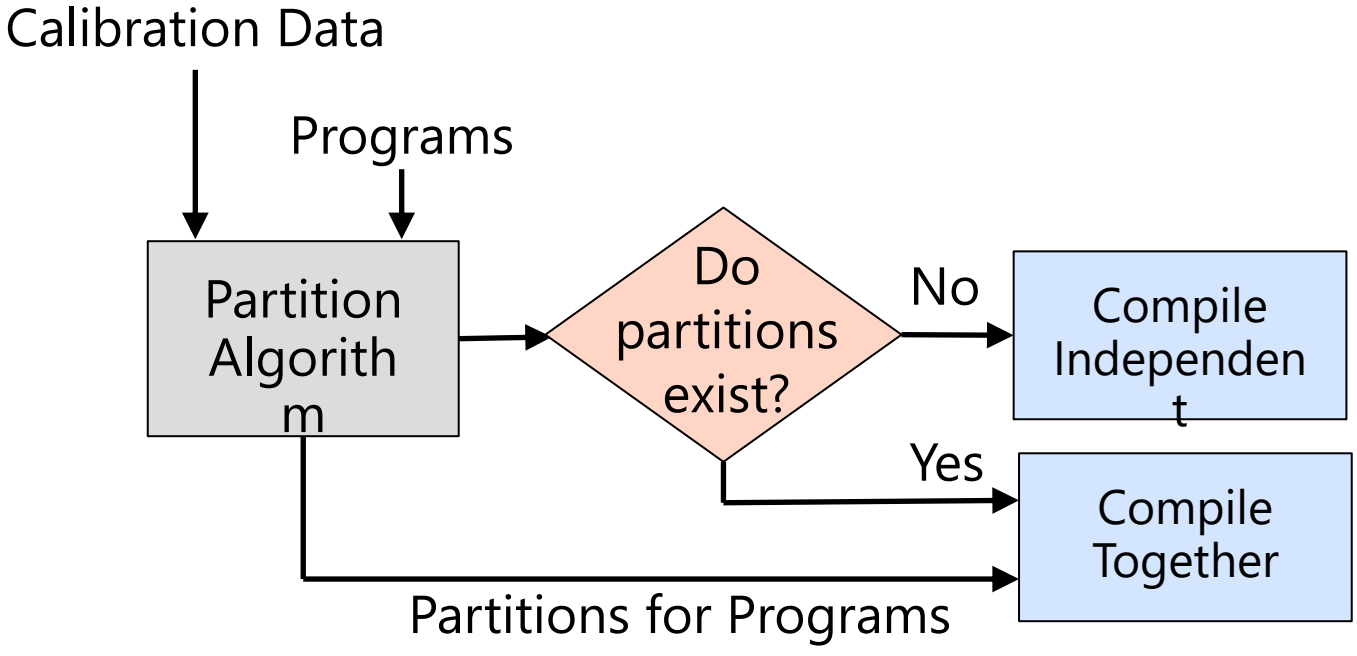

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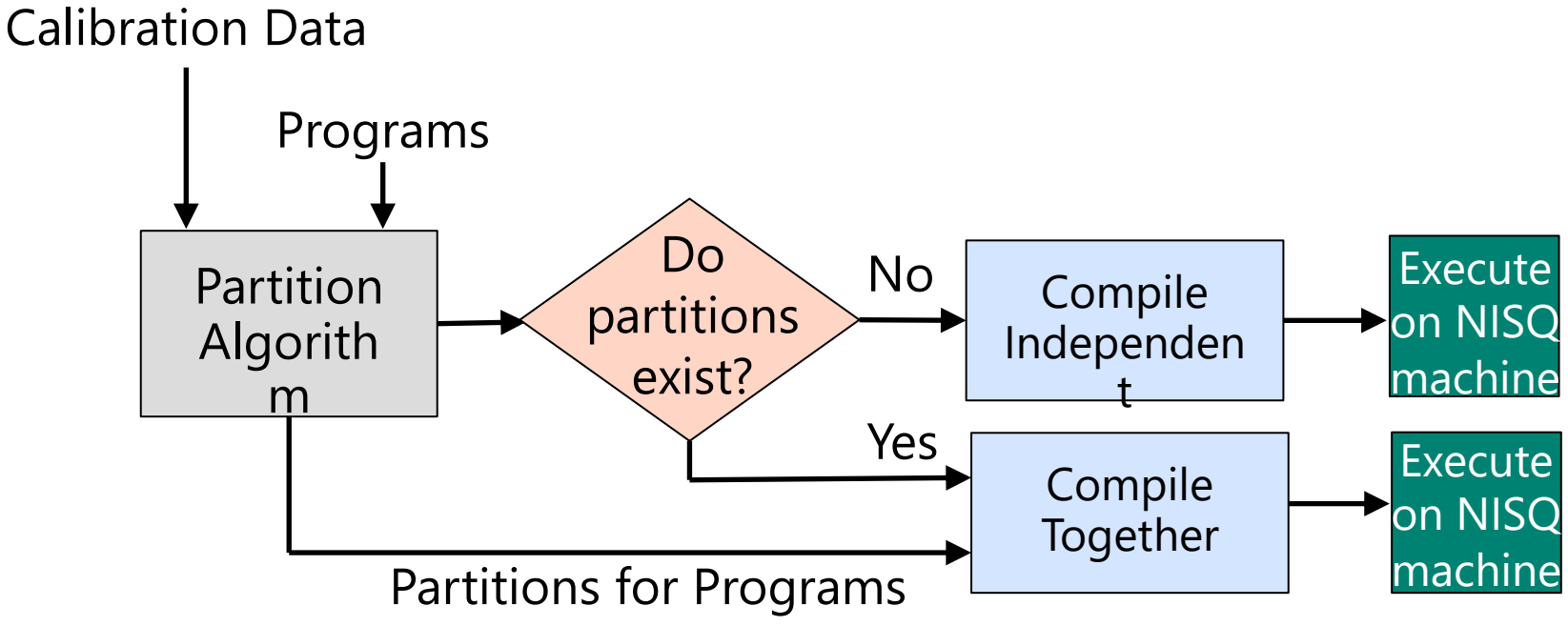

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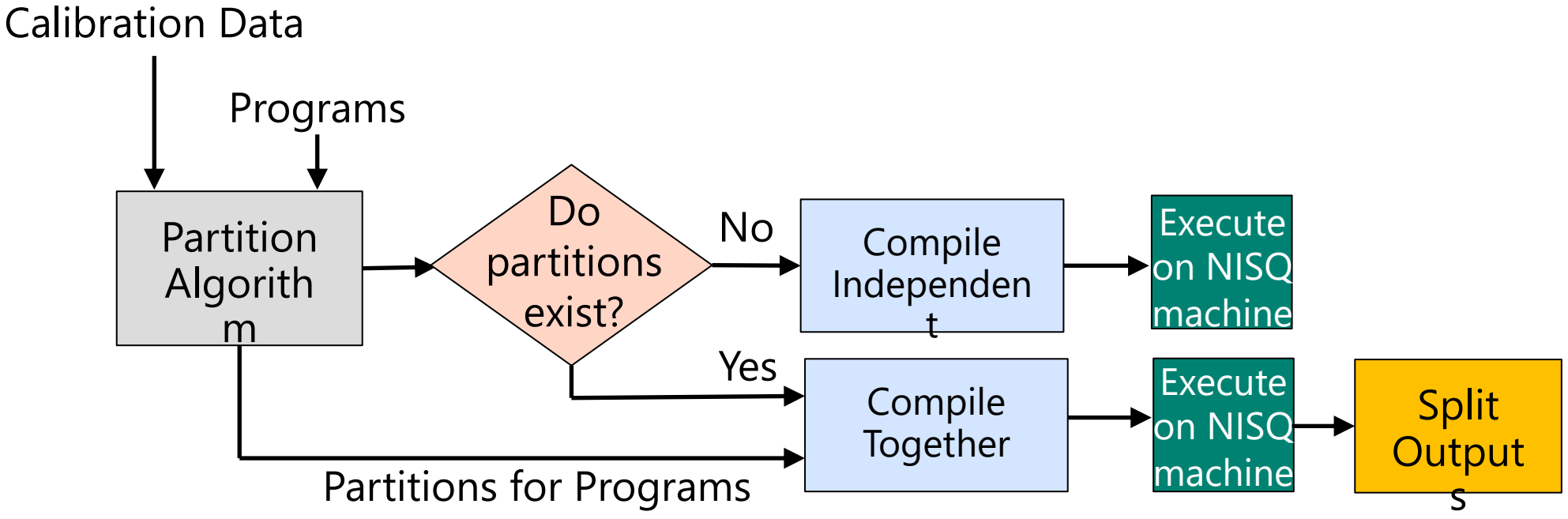

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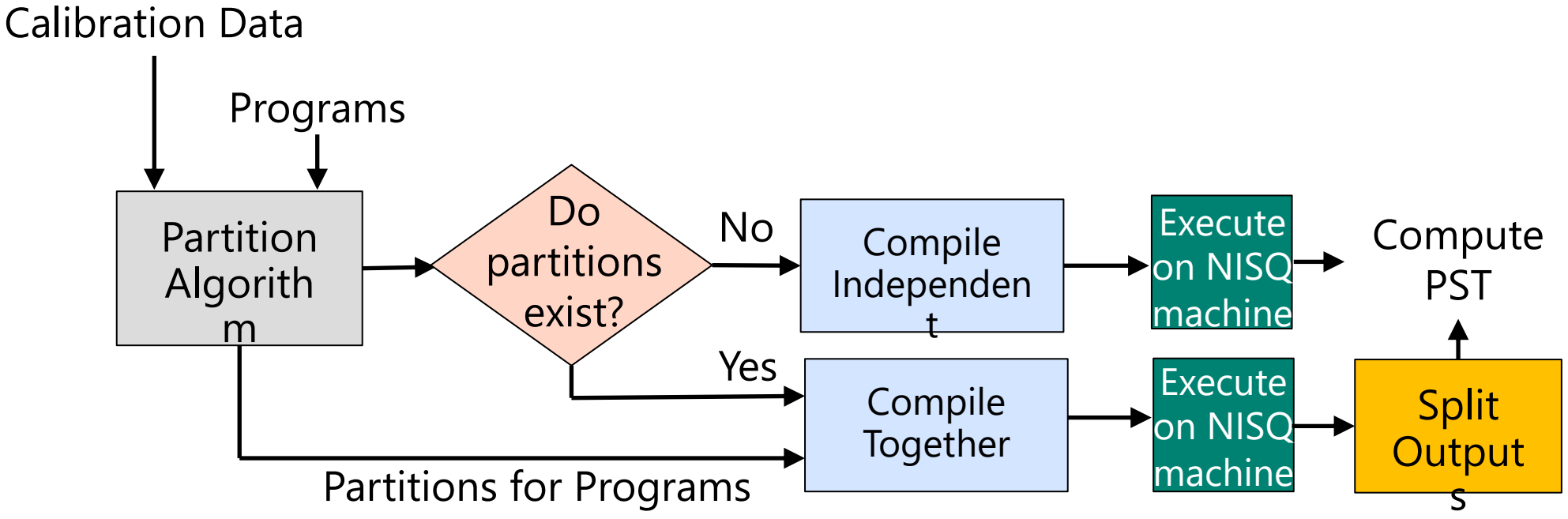

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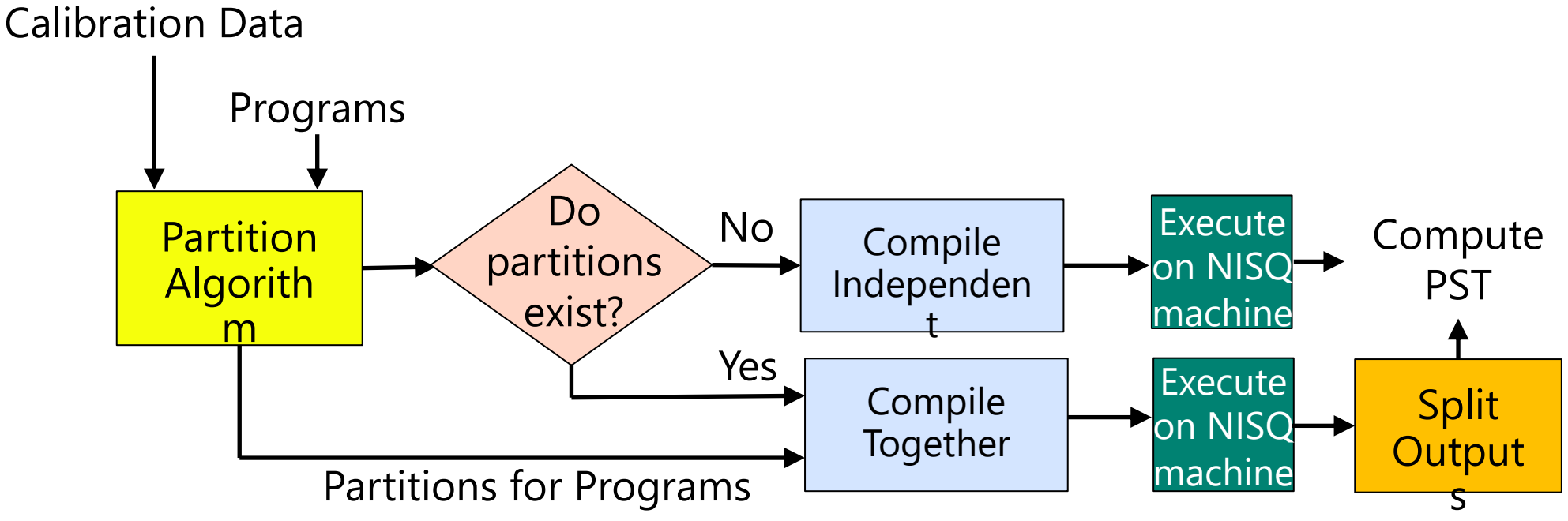

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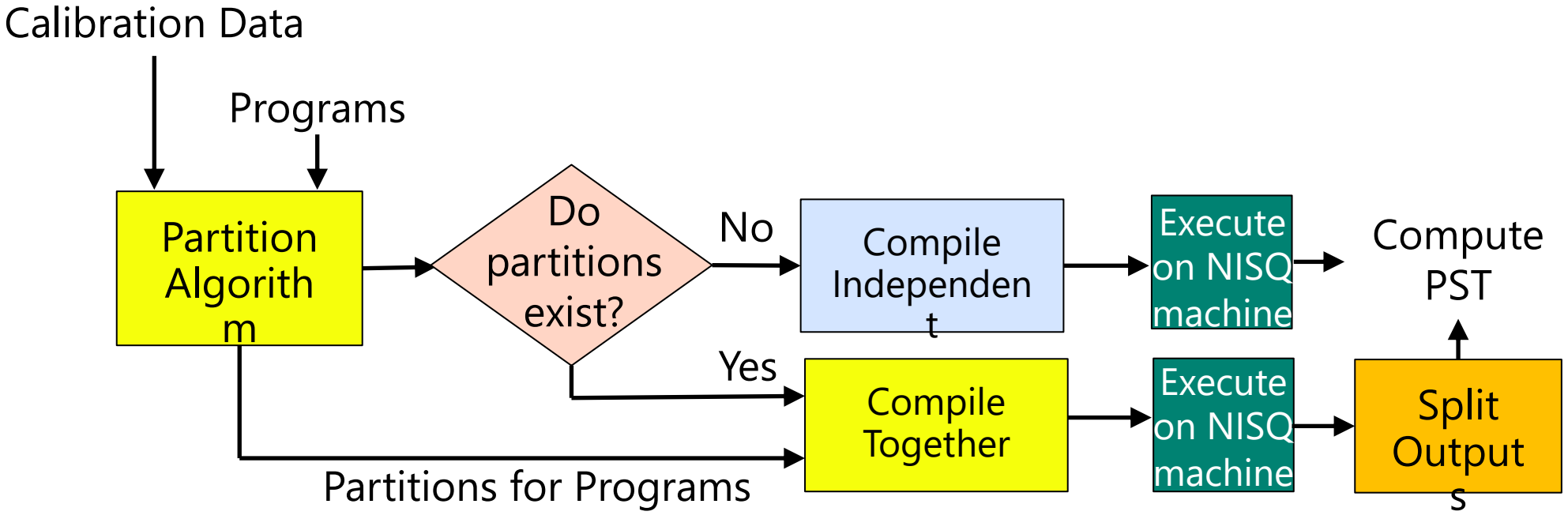
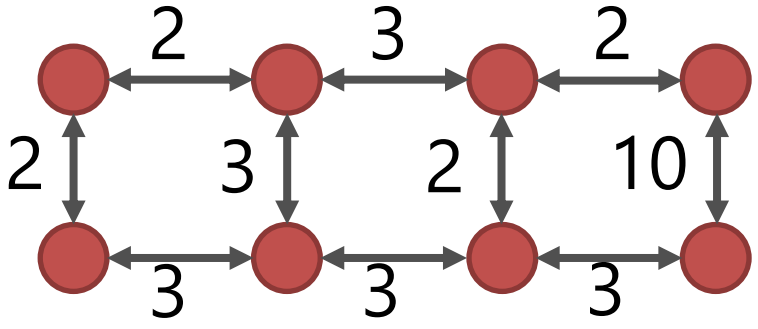


Fair And Reliable Partitioning *(FRP)* Algorithm



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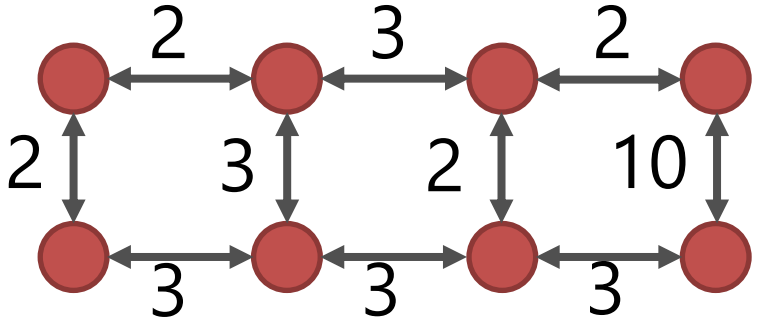

$$Utility = \frac{Number\ of\ links}{\sum Link\ error\ rates}$$

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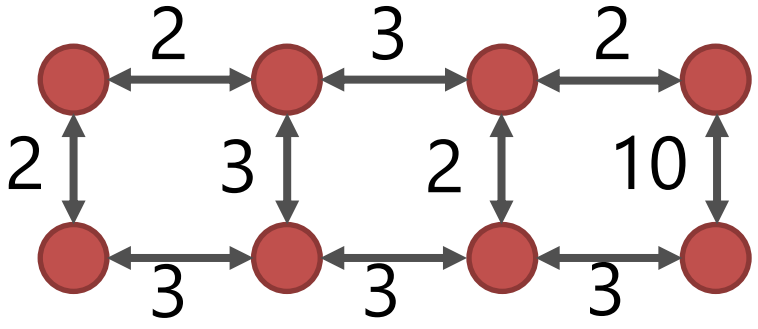

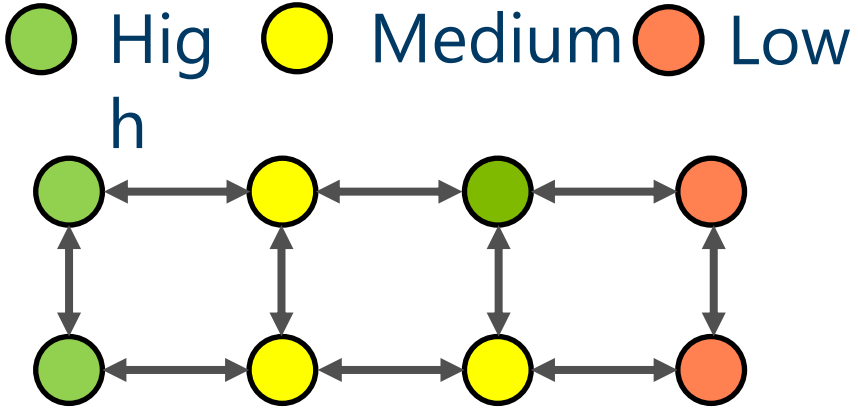

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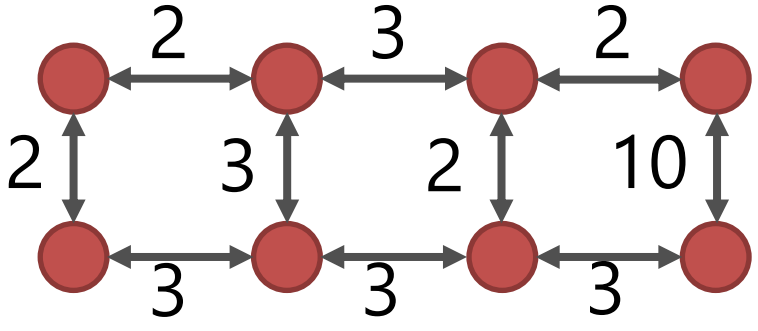

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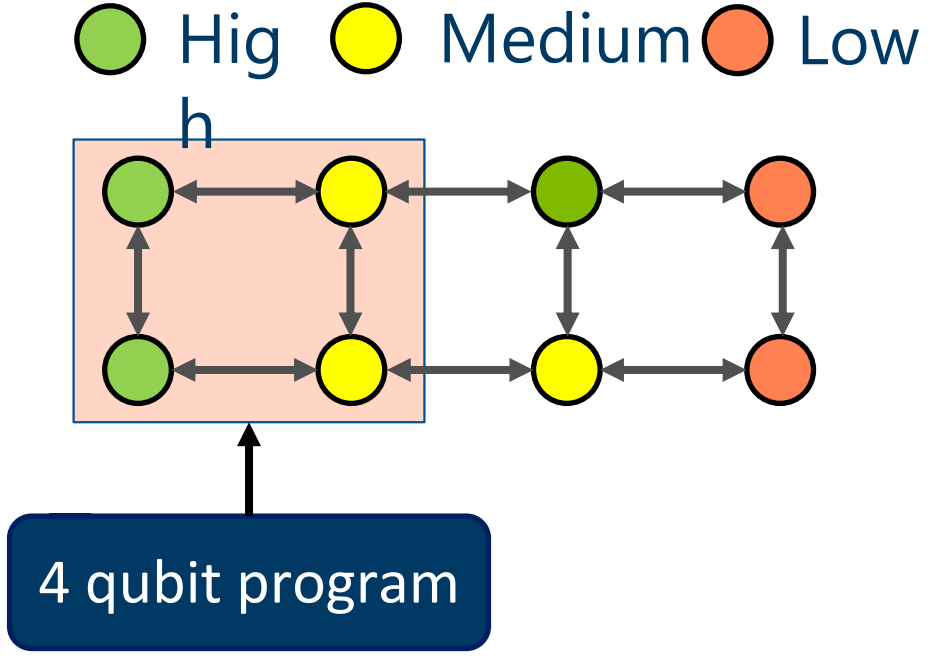

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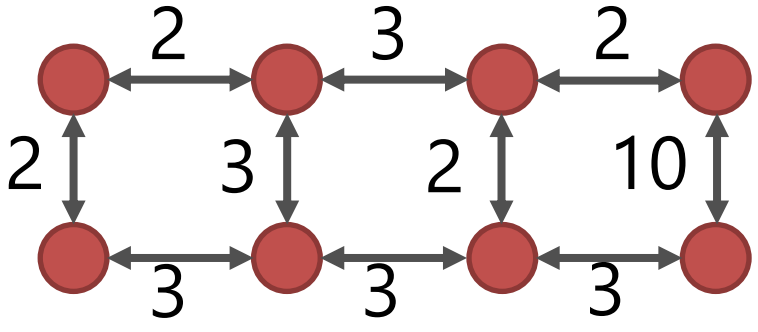

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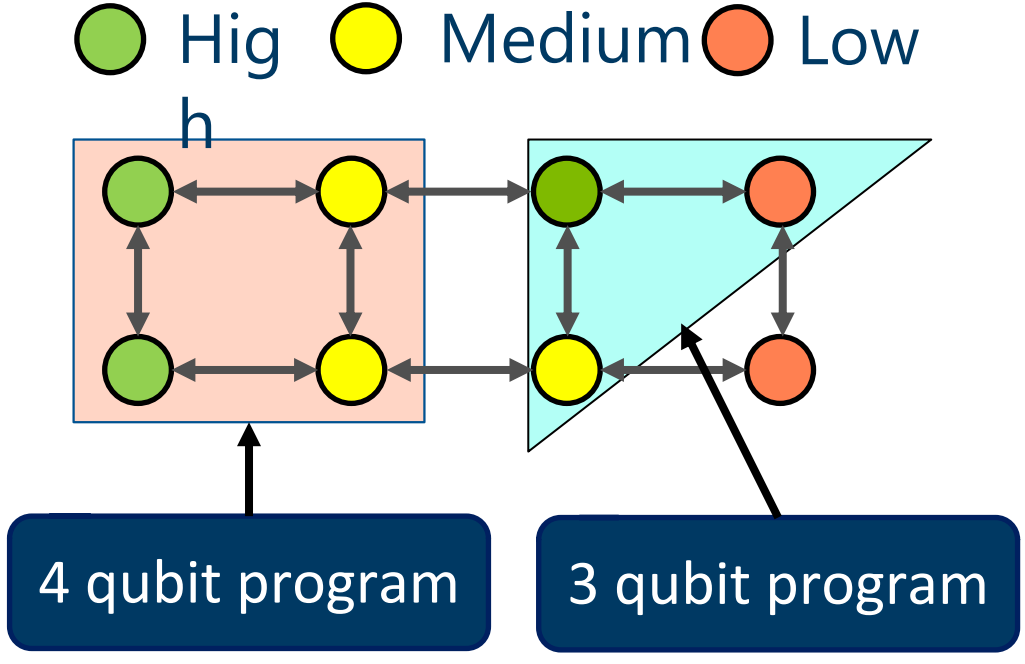

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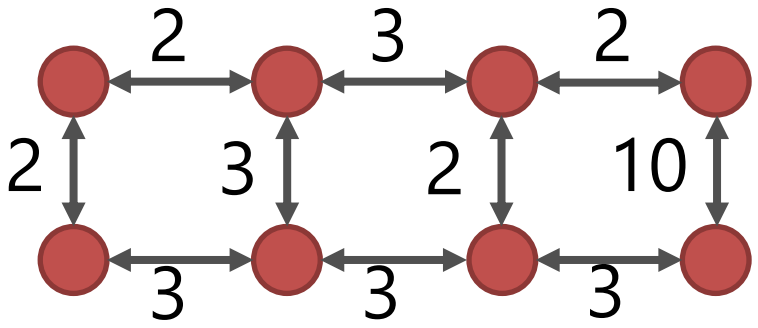

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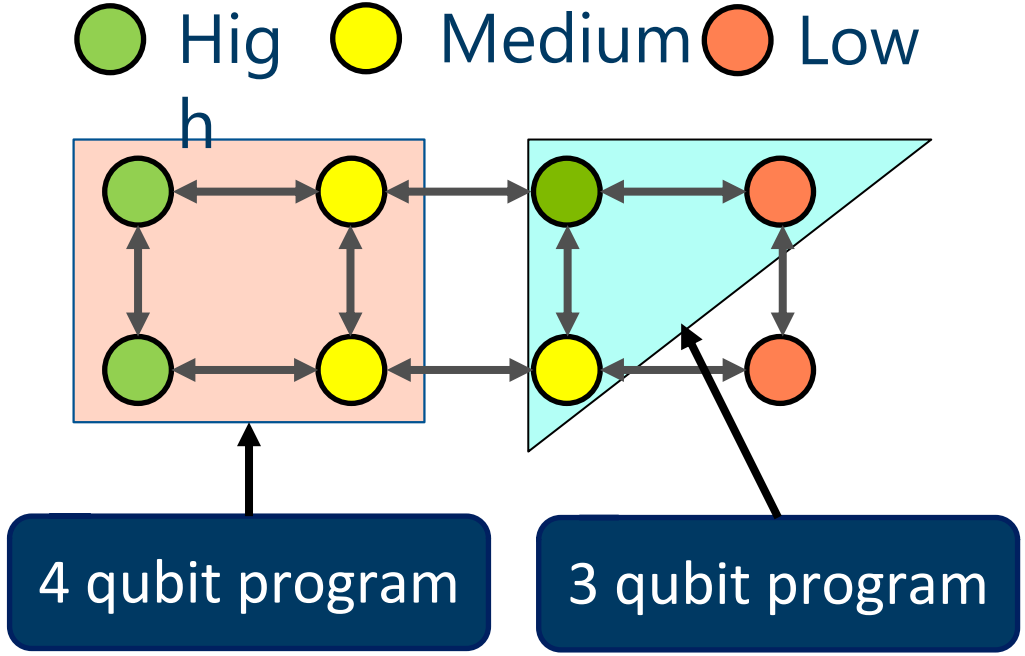

Algorithm ensures each program is allocated reliable qubits

Fair And Reliable Partitioning *(FRP)* Algorithm

Is a program's resource allocation in shared environment fair?

Fair And Reliable Partitioning *(FRP)* Algorithm

Is a program's resource allocation in shared environment fair?

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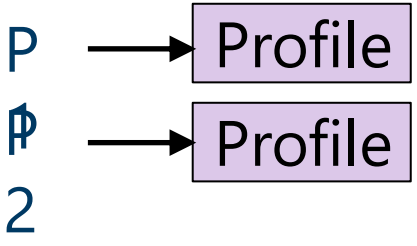

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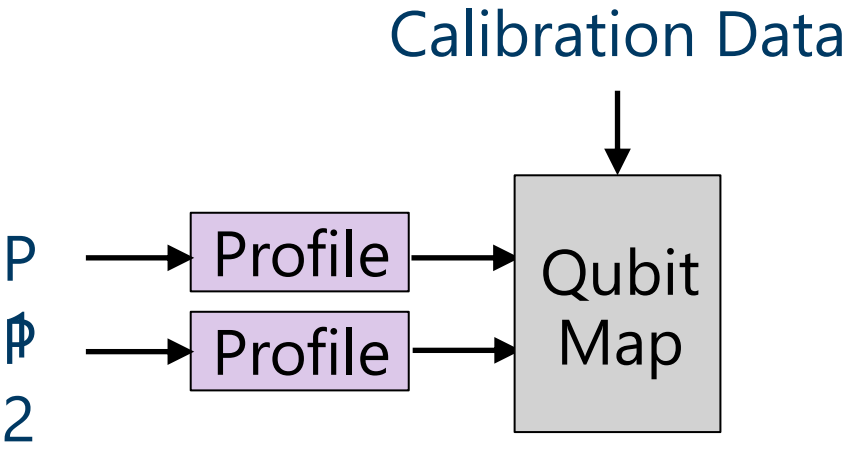

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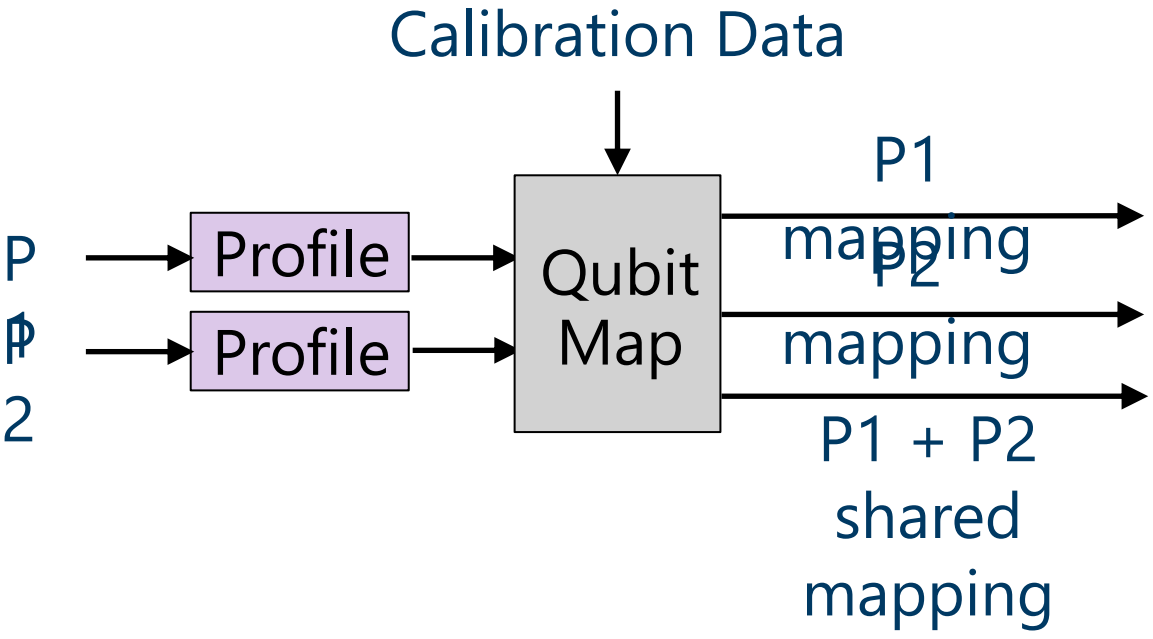

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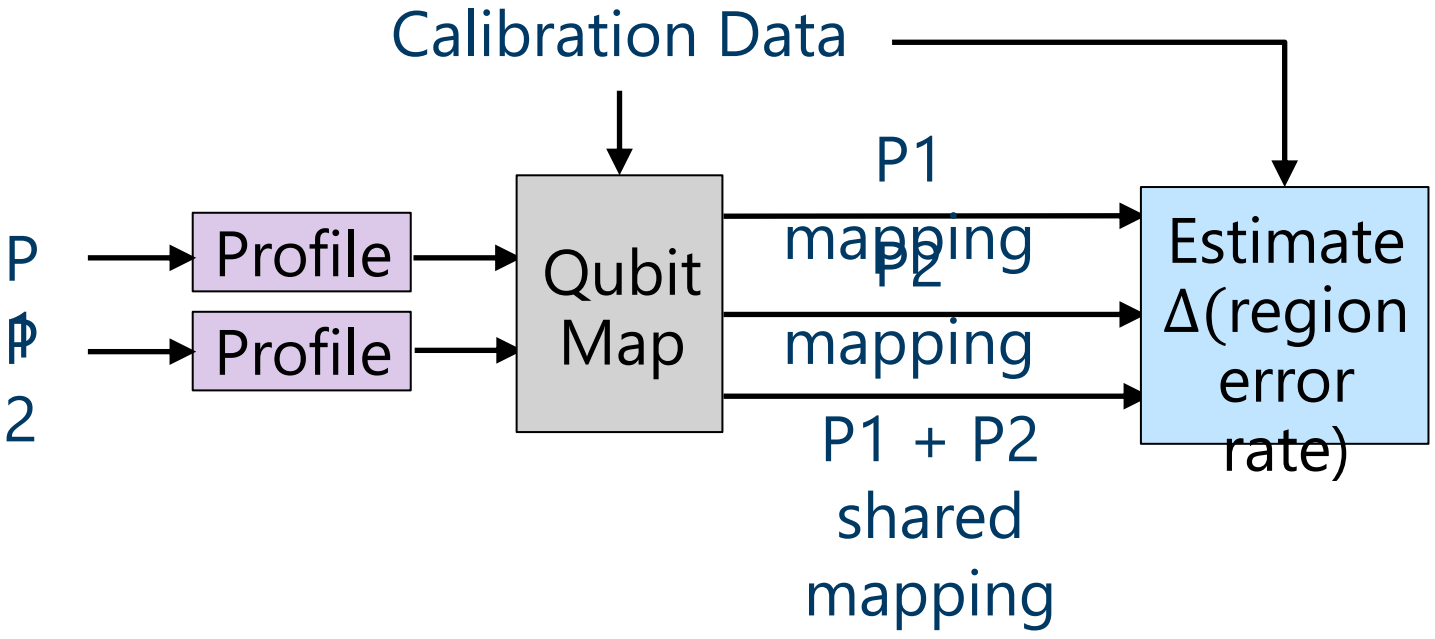

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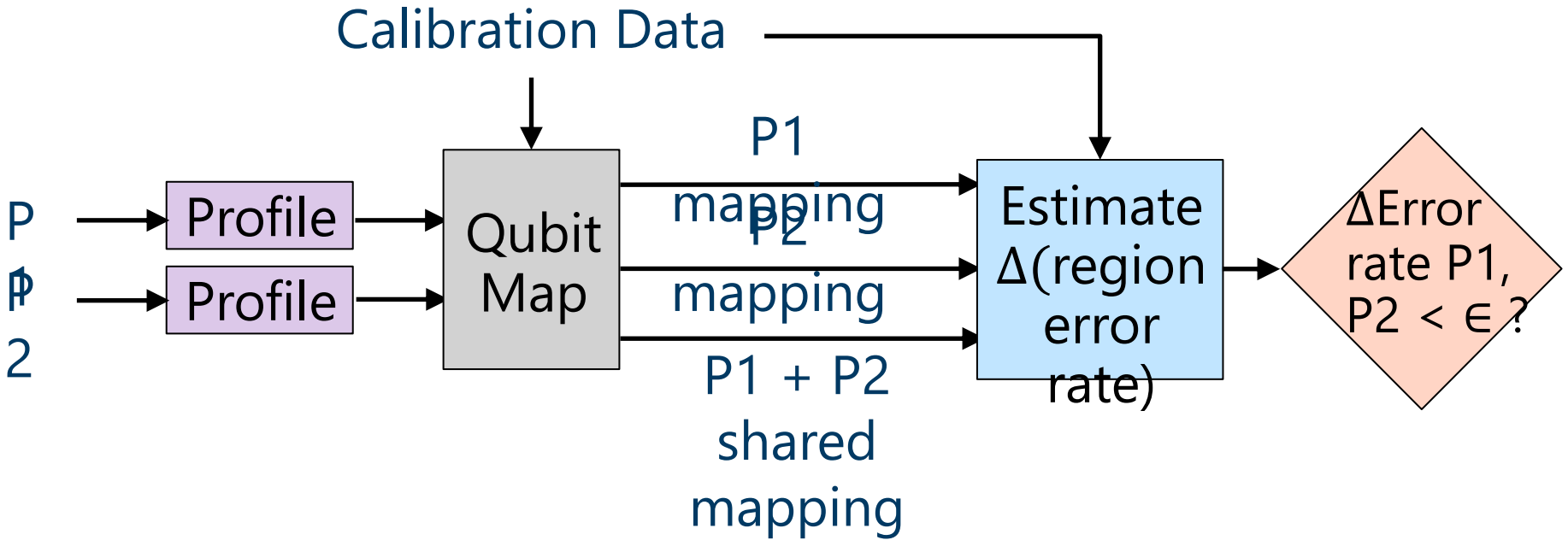

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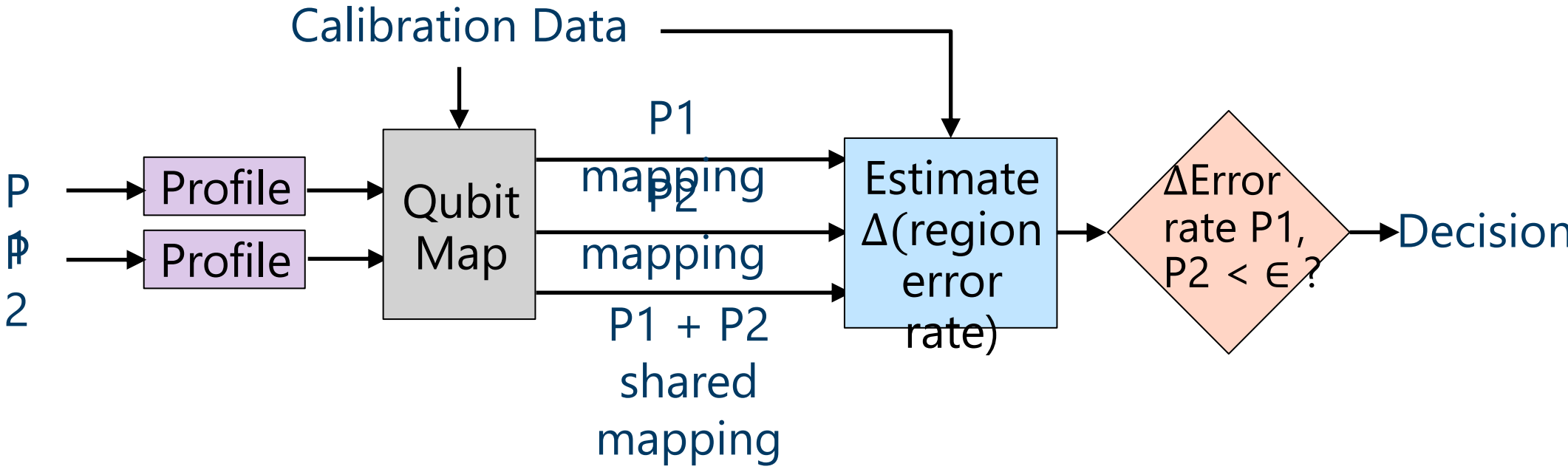

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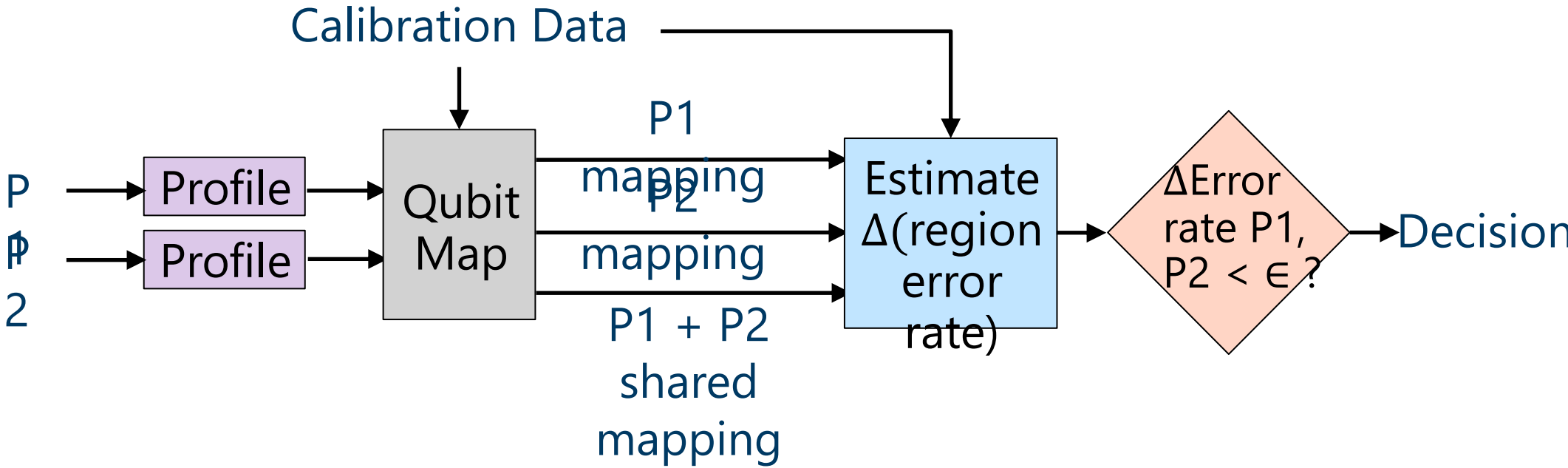

Algorithm ensures fairness while sharing resources between programs

Instruction Scheduling

How to schedule parallel programs?

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Programmers' View

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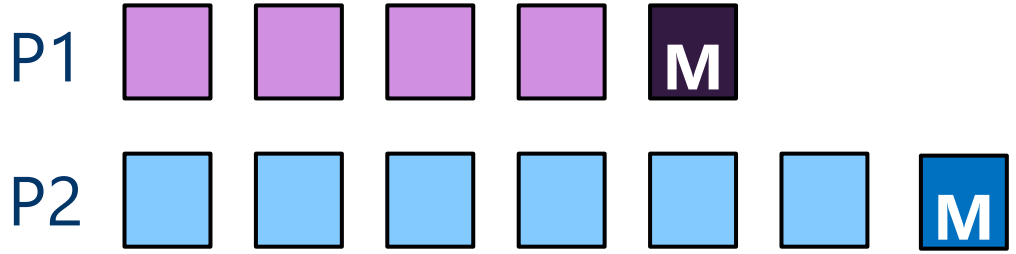

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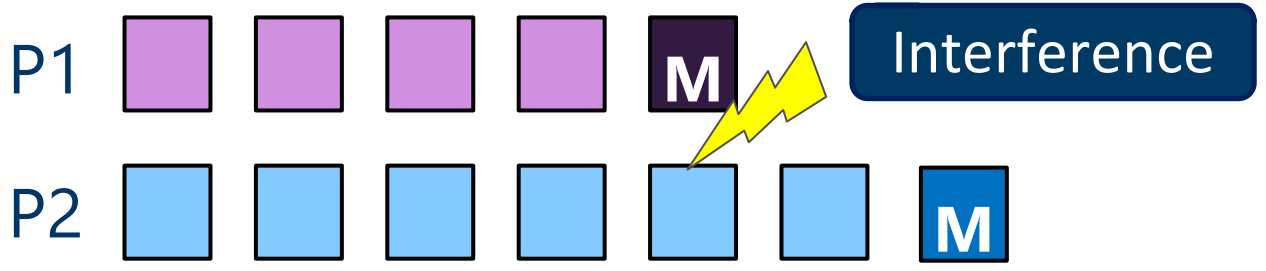

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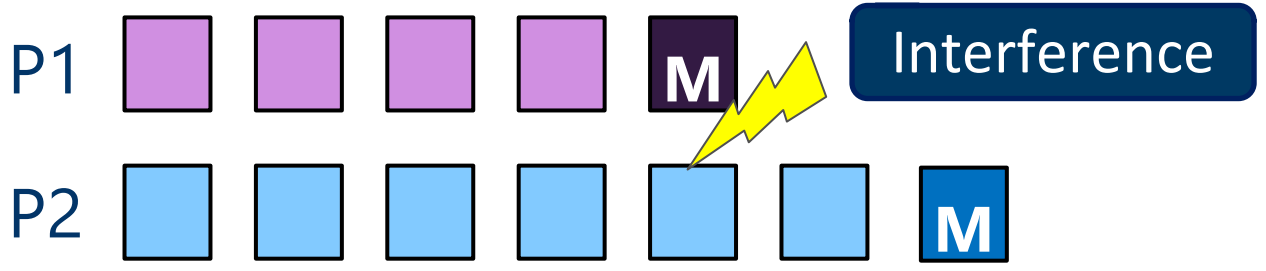

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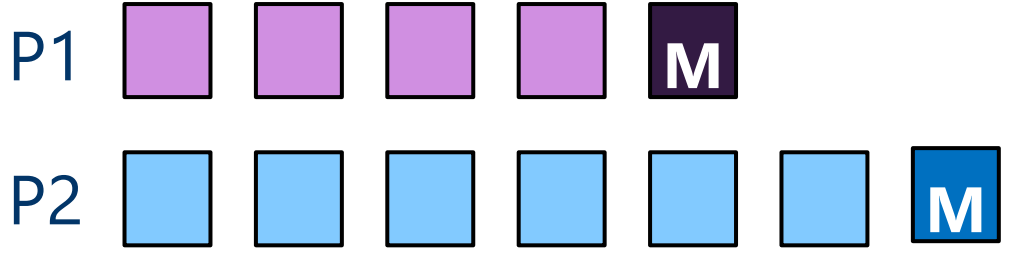

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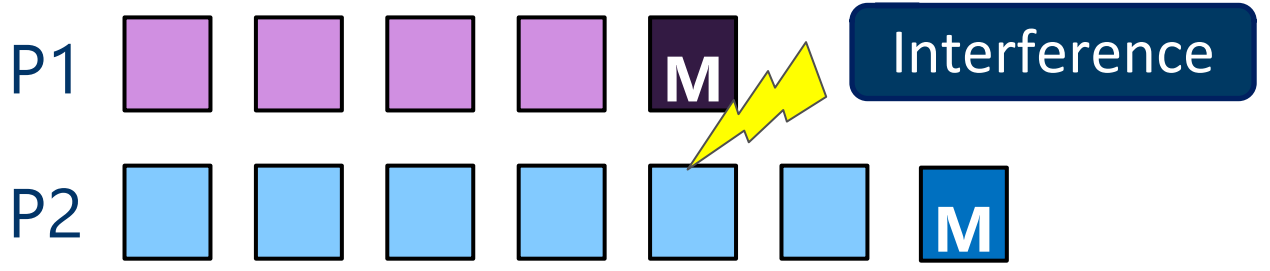

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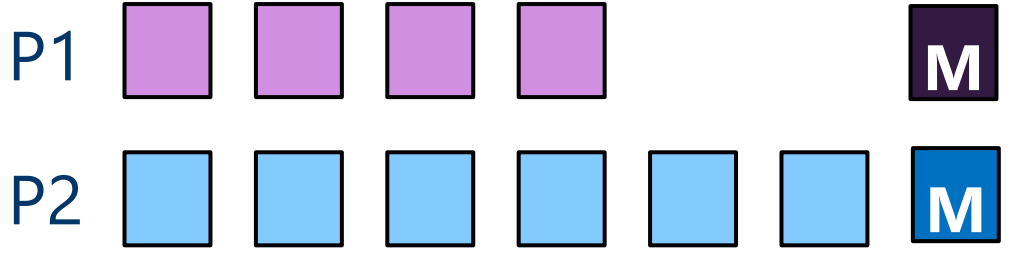

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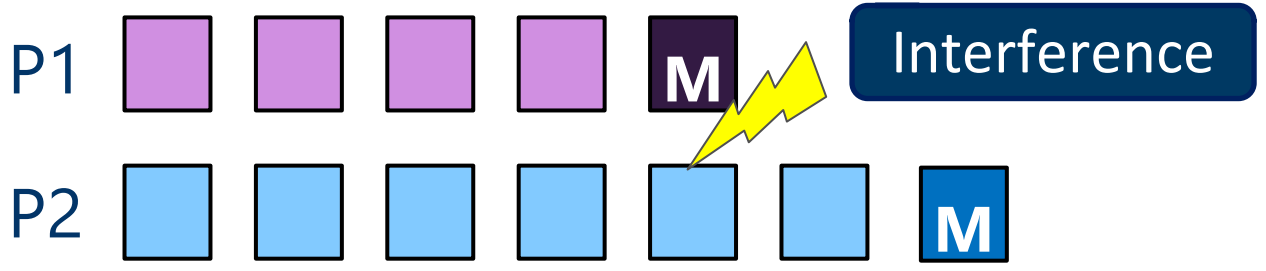

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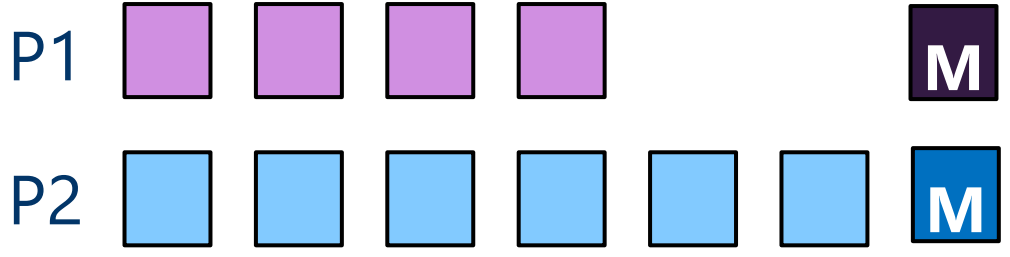

IBM's Compiler schedules measurements after all gates

Instruction Scheduling

How to schedule parallel programs?

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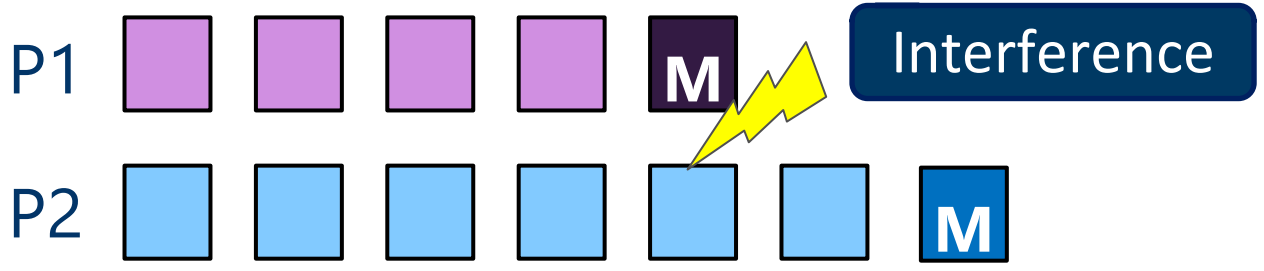

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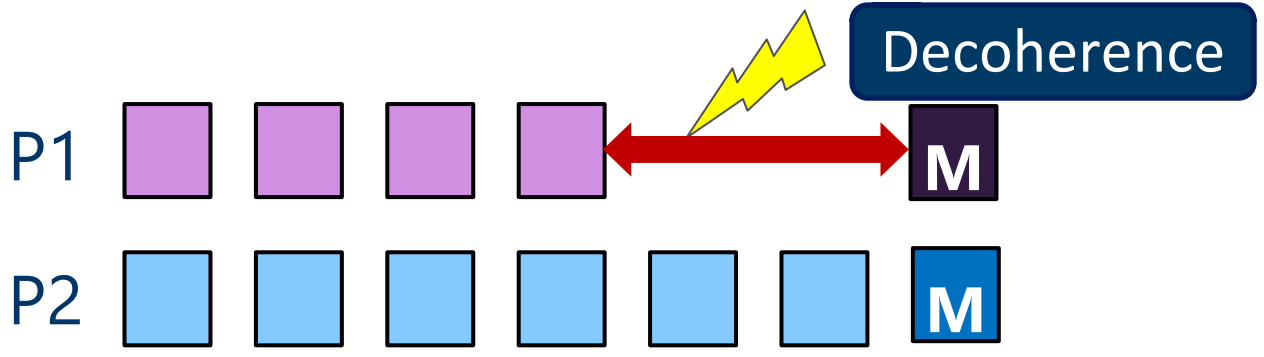

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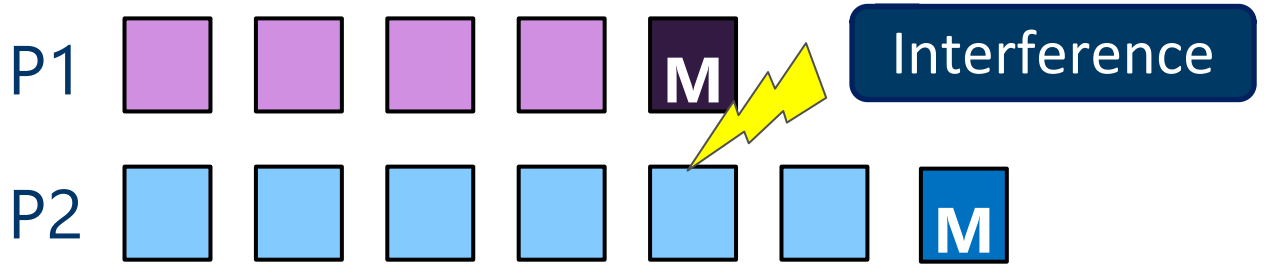

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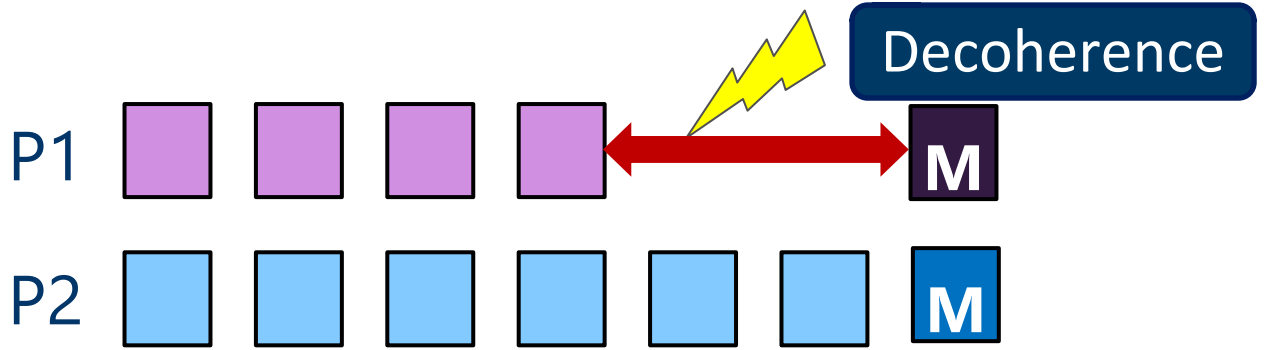
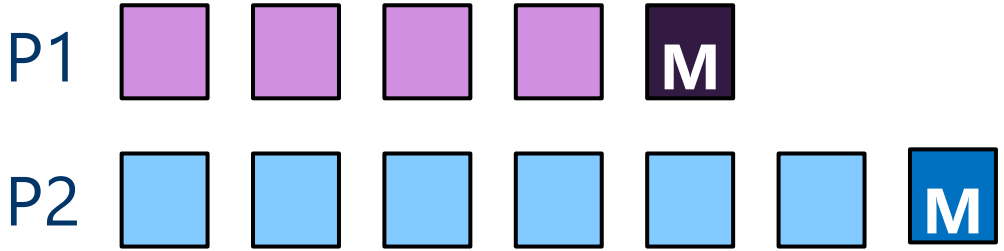


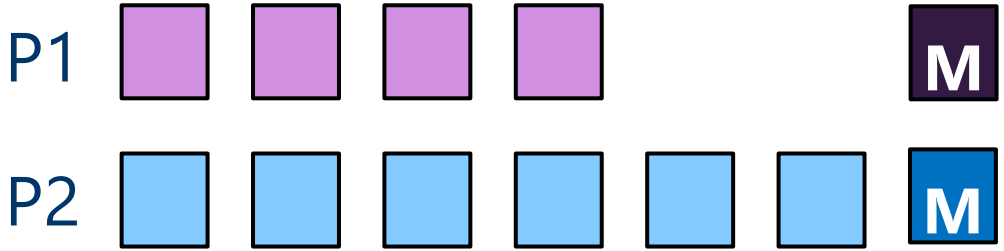
IBM's Compiler schedules measurements after all

Two irregular sized programs can suffer from interference and decoherence

Delayed Instruction Scheduling *(DIS)* Policy

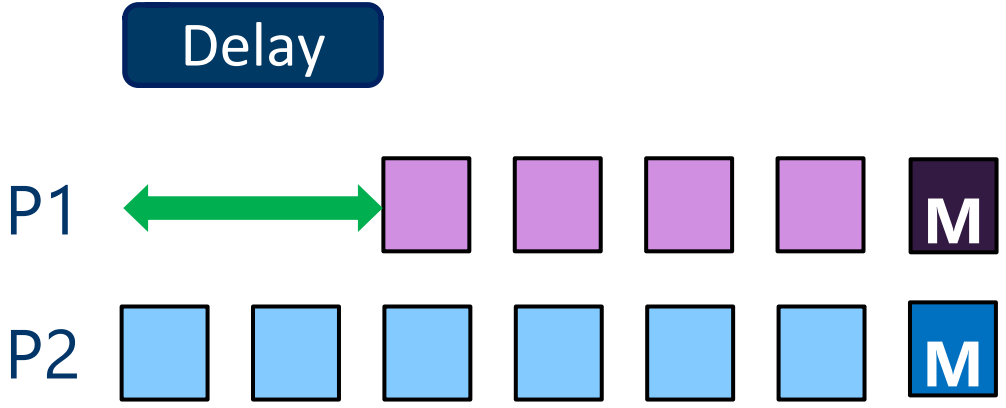


Delayed Instruction Scheduling *(DIS)* Policy



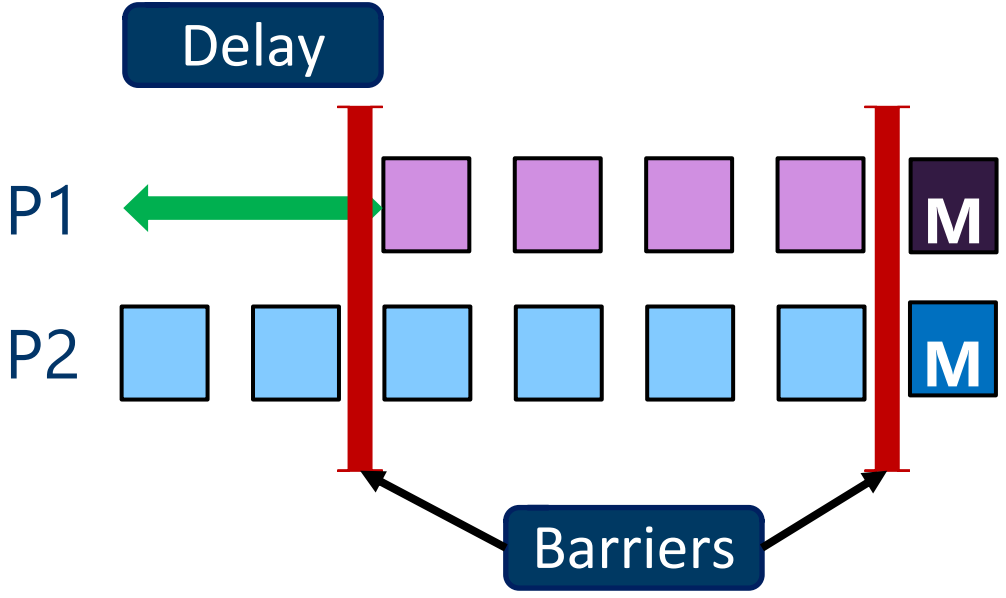
- Measurements at the end
  - Reduces interference

Delayed Instruction Scheduling *(DIS)* Policy



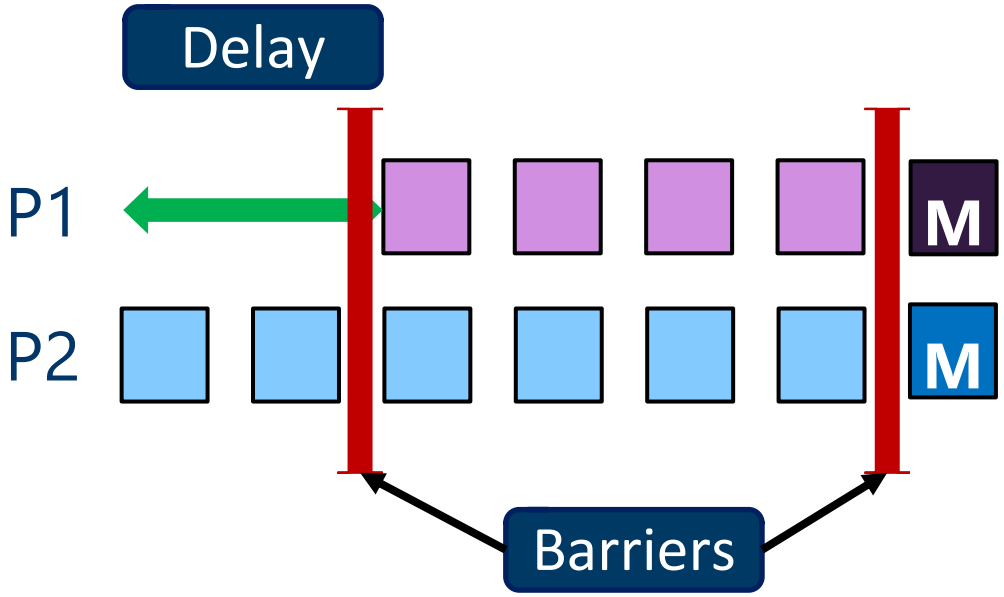
- Measurements at the end
  - Reduces interference
- Delay shorter program
  - Reduces decoherence

Delayed Instruction Scheduling *(DIS)* Policy



- Measurements at the end
  - Reduces interference
- Delay shorter program
  - Reduces decoherence
- Barriers

Delayed Instruction Scheduling *(DIS)* Policy



- Measurements at the end
  - Reduces interference
- Delay shorter program
  - Reduces decoherence
- Barriers

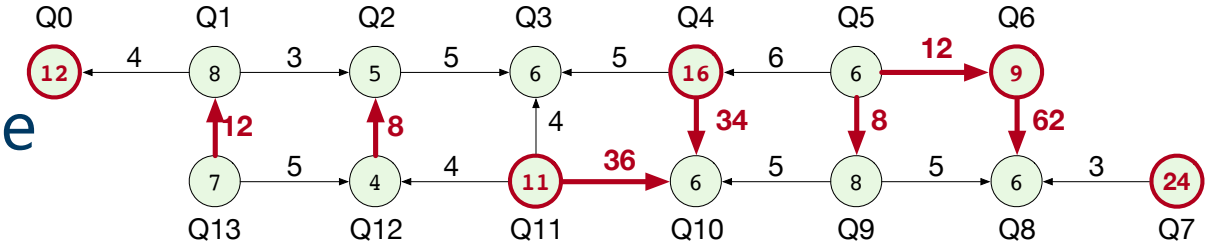
Our proposed *DIS* policy reduces interference and decoherence and is scalable

Outline

- Introduction
- Background and Motivation
- Policies for Multi-Programming
- Evaluation Methodology
- Adaptive Multi-Programming Design
- Results and Conclusion

Evaluation Methodology

- IBM Q16
  - 14 qubit public machine

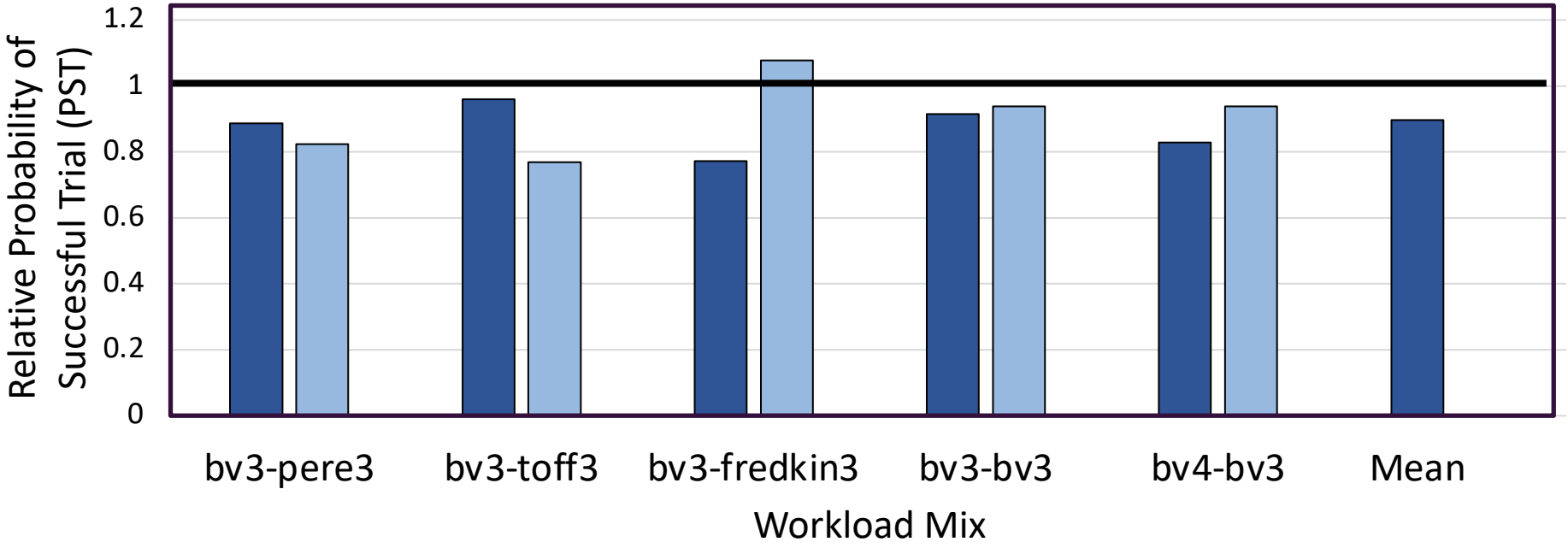


- Benchmarks
  - From prior works

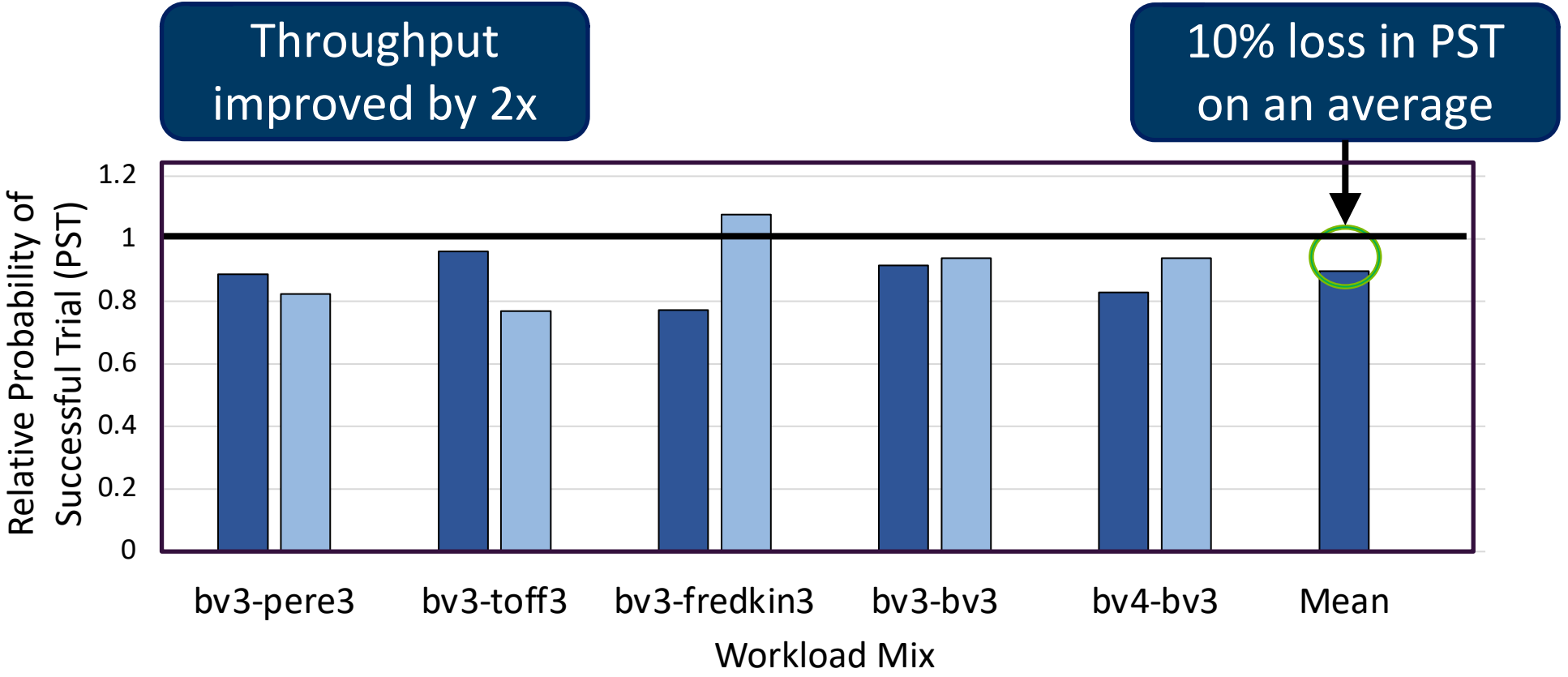
Benchmark	Description	#Insts	#CNOT
bv_n3	Bernstein Vazirani	8	2
bv_n4	Bernstein Vazirani	11	3
Toffoli_n3	Toffoli gate	15	6
Fredkin_n3	Fredkin gate	16	8
Peres_n3	Peres gate	16	7

- Baseline: Isolated execution using best qubit mapping

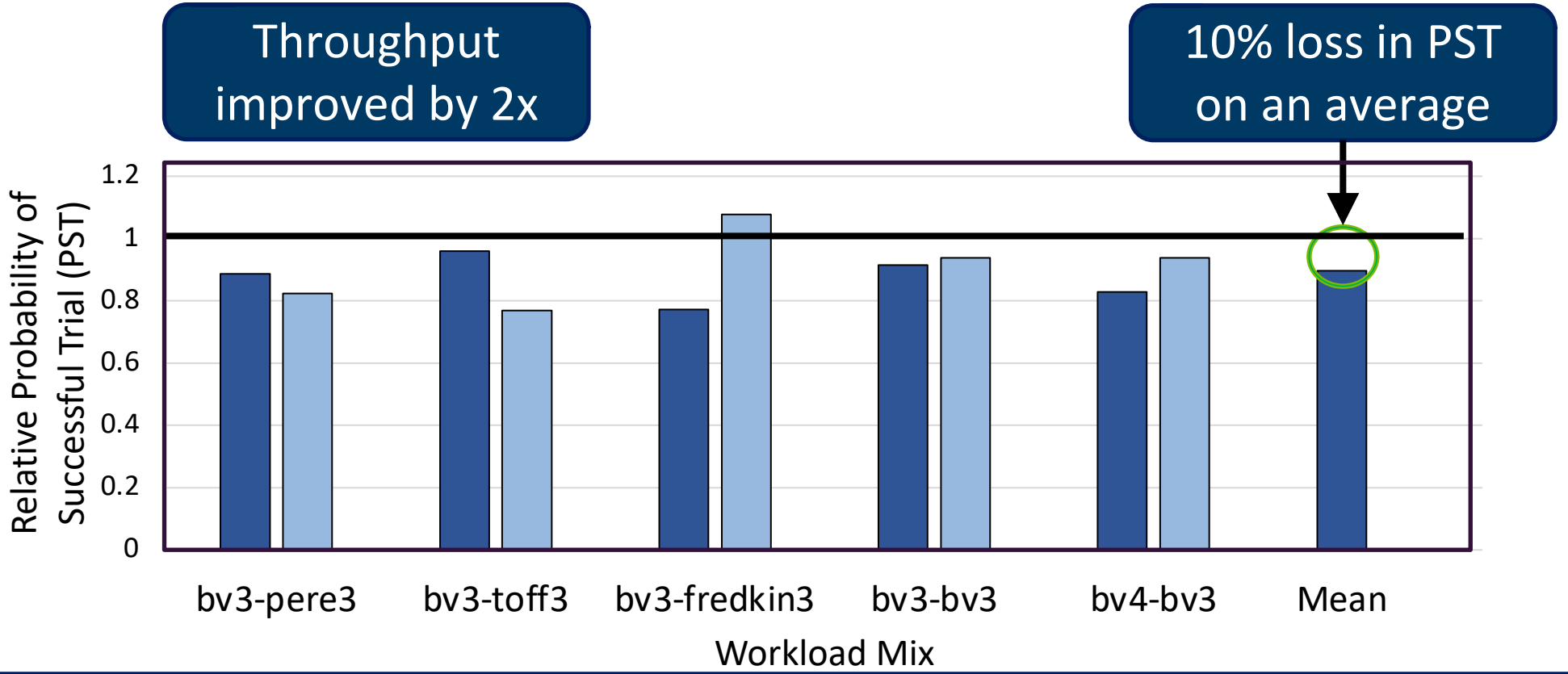
Results of Multi-Programming



Results of Multi-Programming

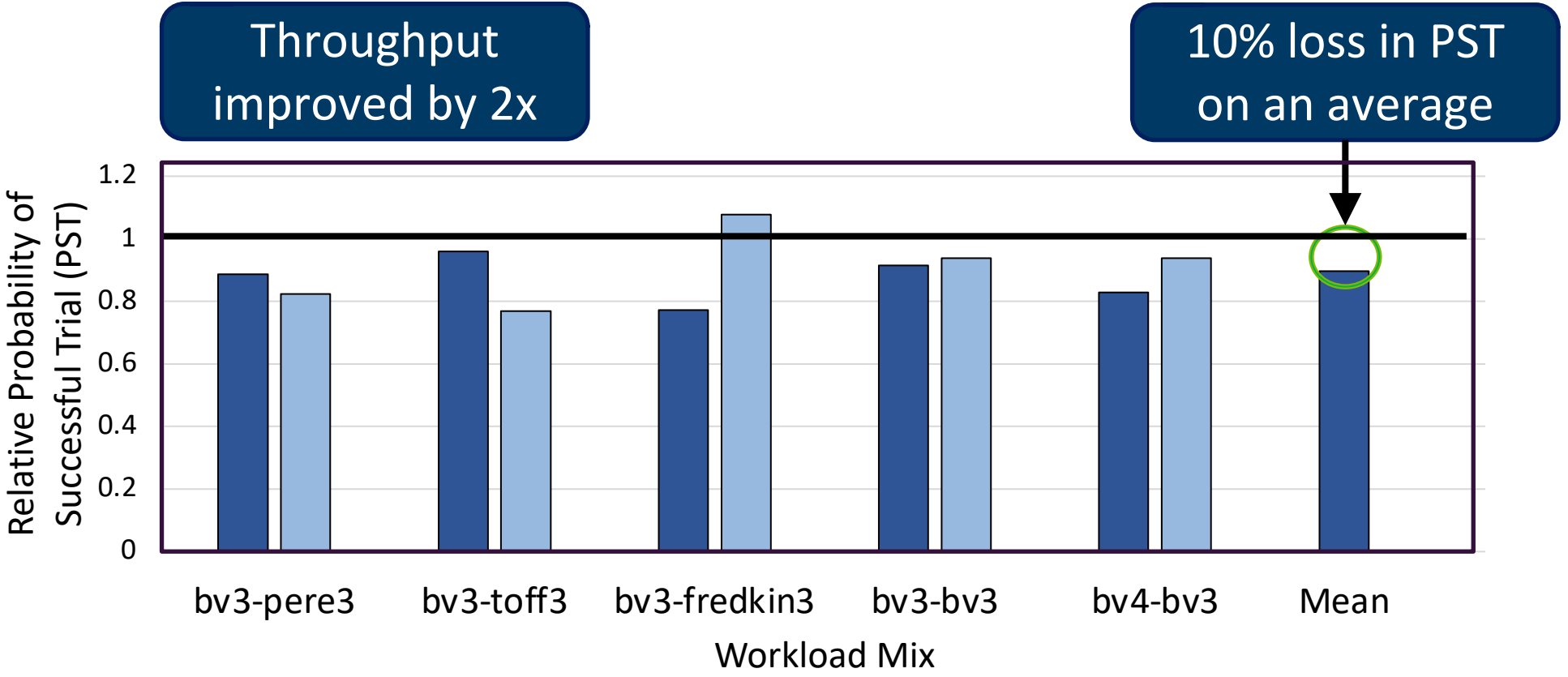


Results of Multi-Programming

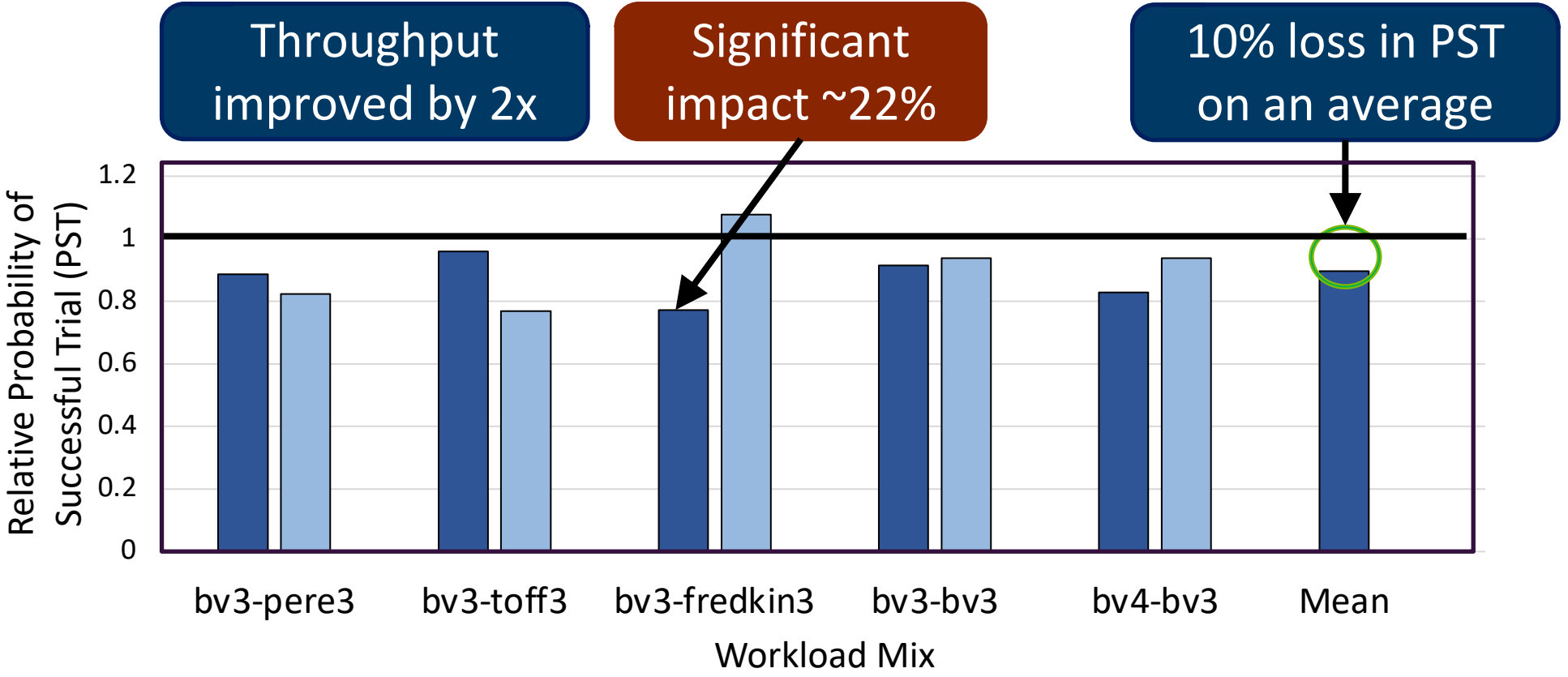


Multi-programming can improve throughput with slight impact on PST

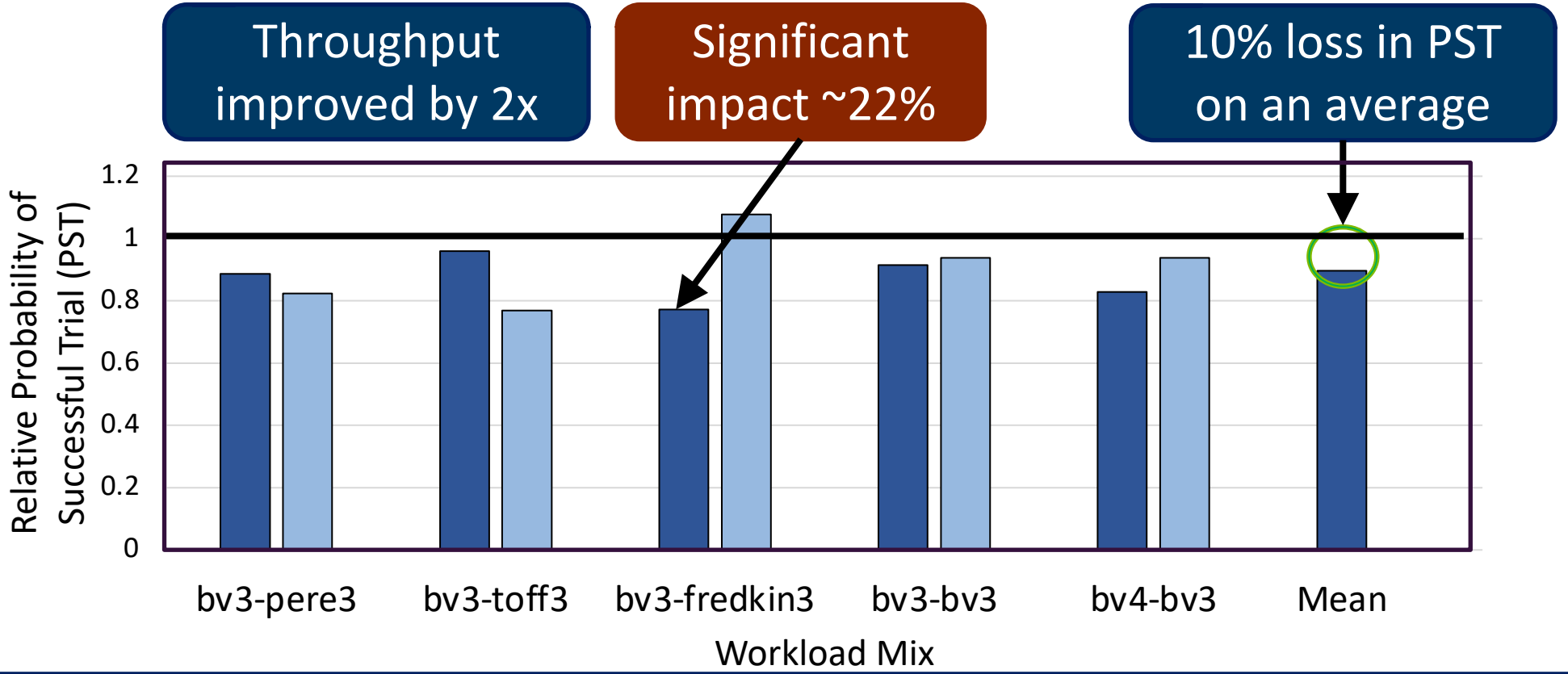
Limiting the Reliability Impact of Multi-Prog



Limiting the Reliability Impact of Multi-Prog



Limiting the Reliability Impact of Multi-Prog



Multi-programming must adapt to minimize significant impact on reliability

Outline

- Introduction
- Background and Motivation
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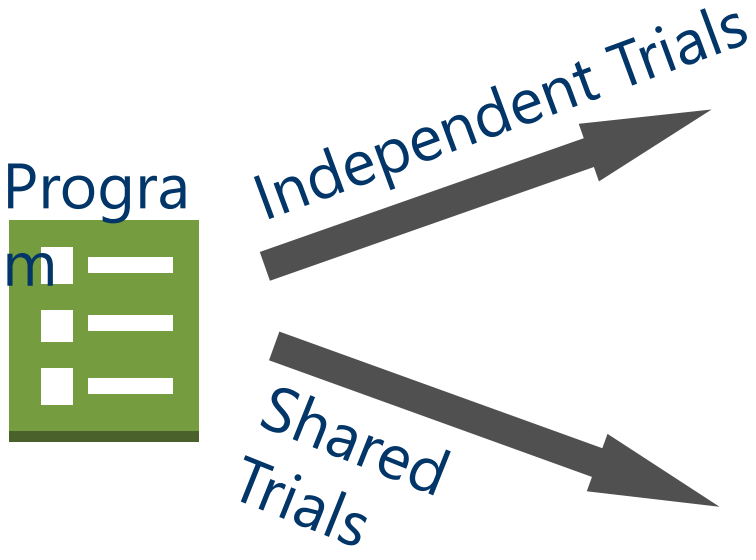
- Results and Conclusion

Runtime Reliability Monitoring

Can we detect impact on reliability at runtime?

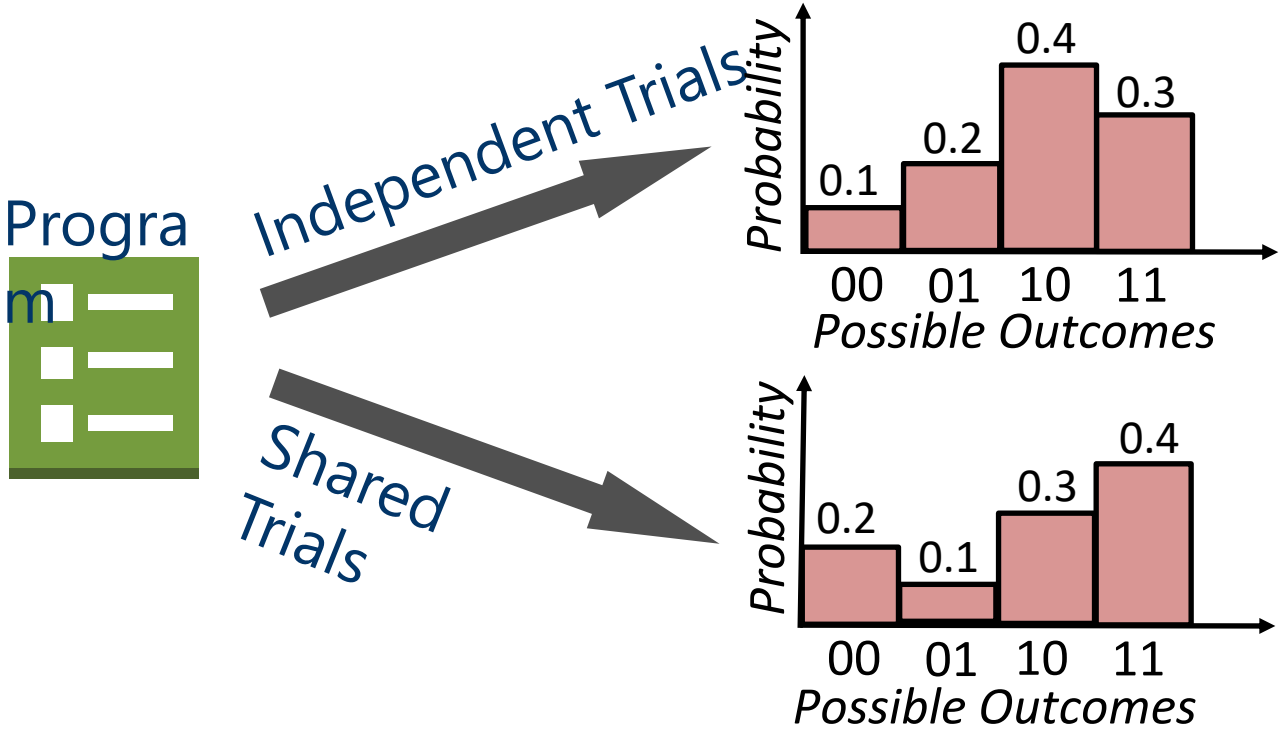
Runtime Reliability Monitoring

Can we detect impact on reliability at runtime?



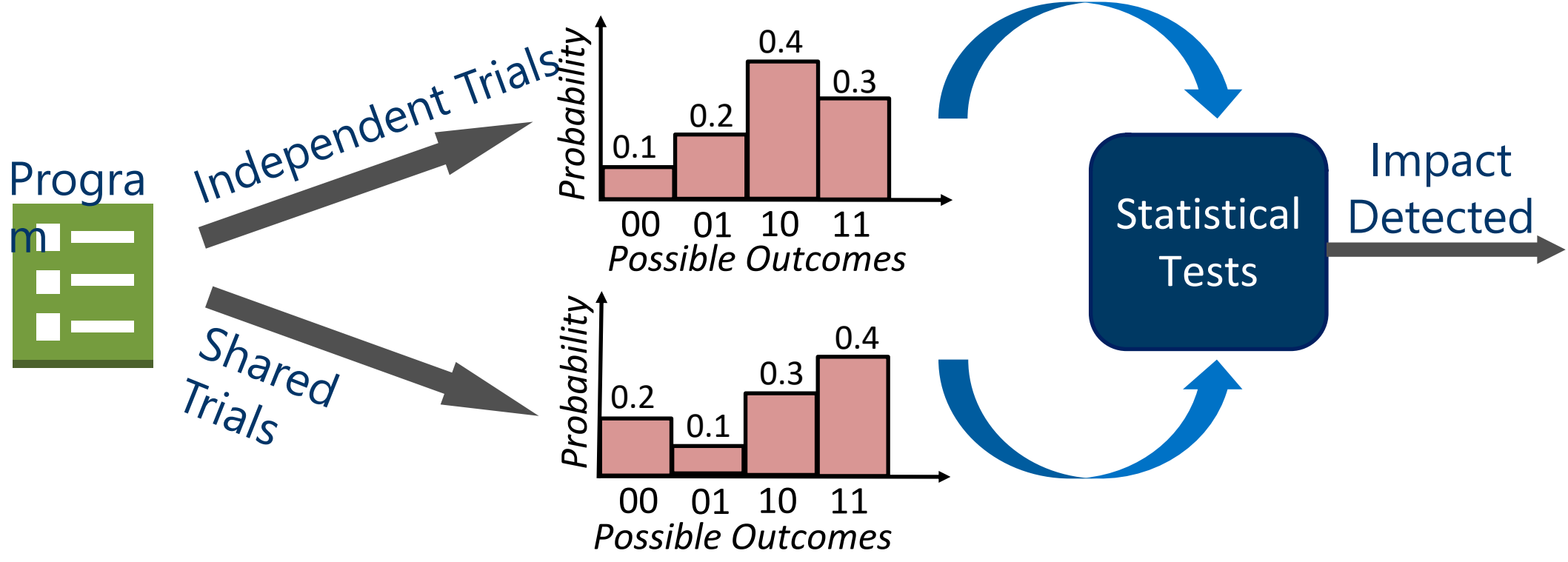
Runtime Reliability Monitoring

Can we detect impact on reliability at runtime?



Runtime Reliability Monitoring

Can we detect impact on reliability at runtime?



Runtime Reliability Monitoring

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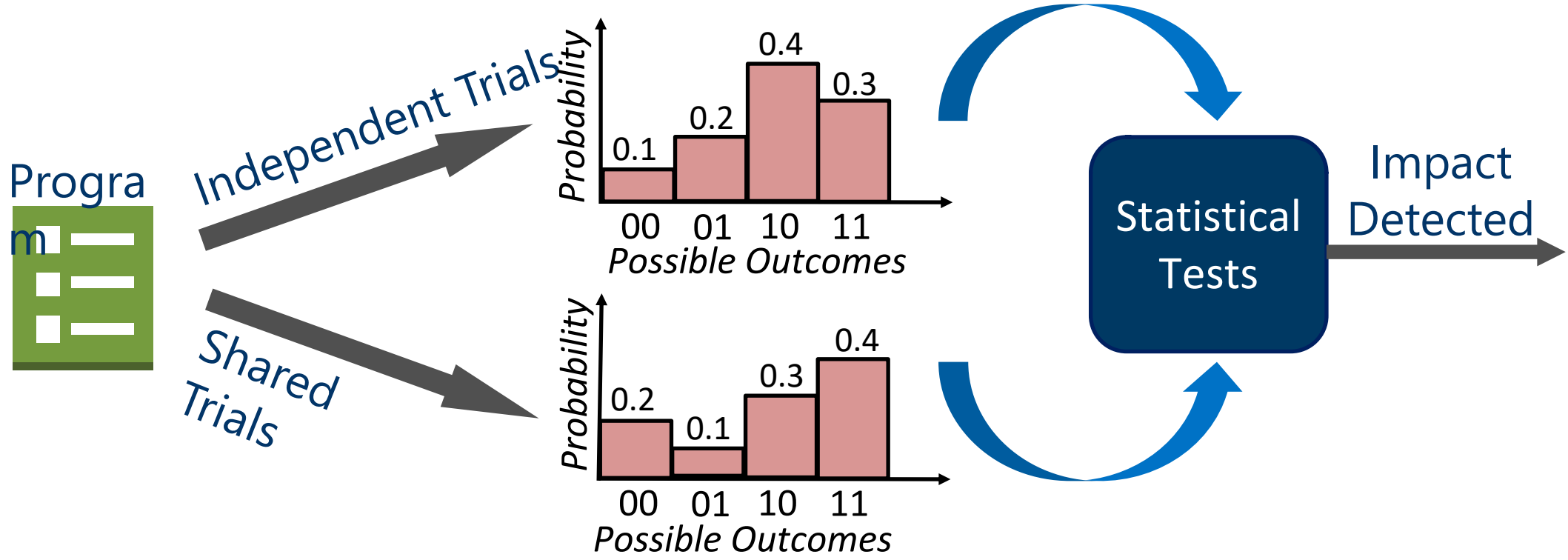

Using statistical tests degradation in program reliability can be captured

Description of the statistical tests

Entropy: measures randomness

Description of the statistical tests

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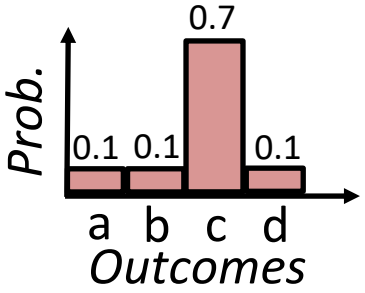
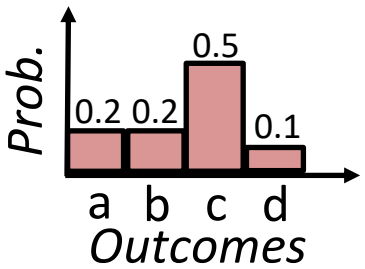


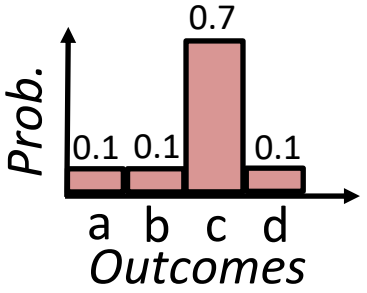
Dist 1



Dist 2

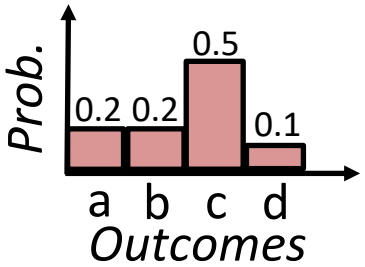
Description of the statistical tests

Entropy: measures randomness



Dist 1

Low Entropy

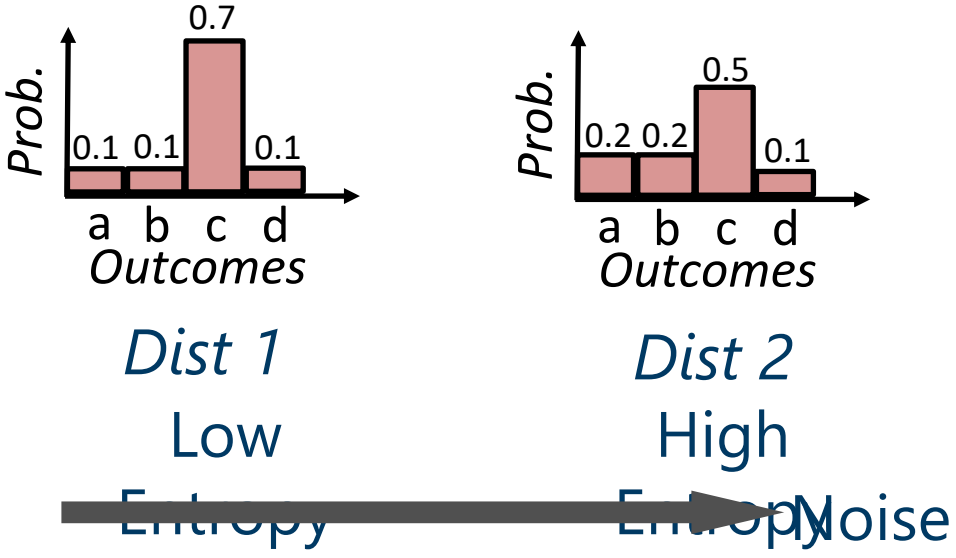


Dist 2

High Entropy

Description of the statistical tests

Entropy: measures randomness



Description of the statistical tests

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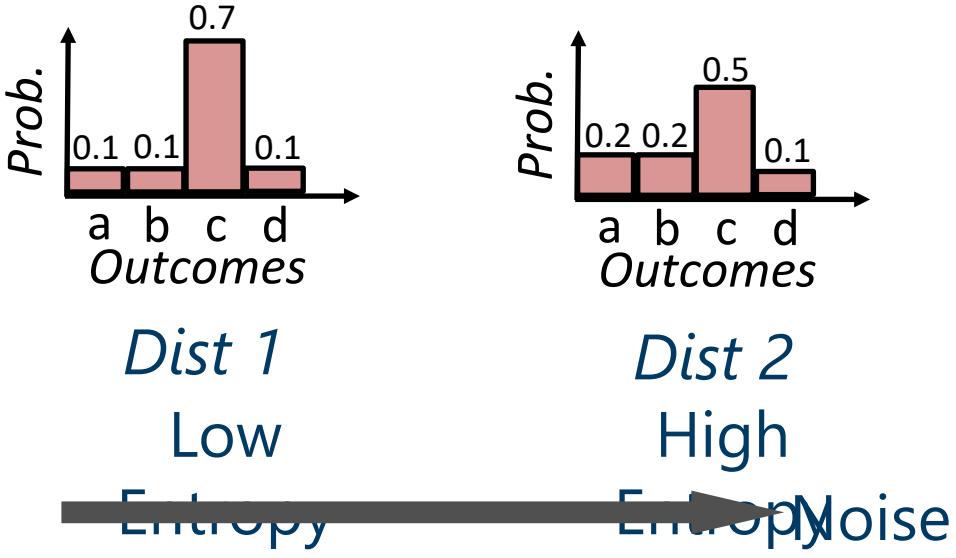


Dist 1

Low Entropy

Dist 2

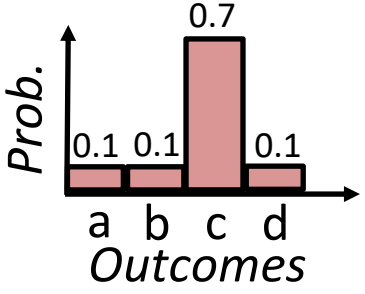
High Entropy

Noise

Compare $Entropy(Shared\ Trials)$ and $Entropy(Independent\ Trials)$

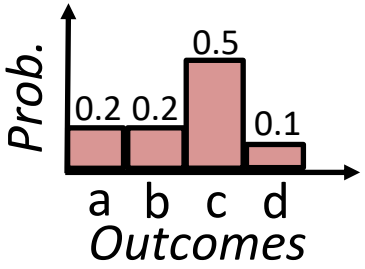
Description of the statistical tests

Entropy: measures randomness



Dist 1

Low Entropy



Dist 2

High Entropy

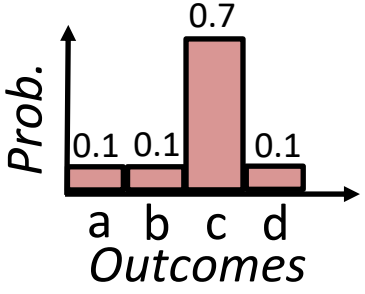
Noise

Compare $Entropy(Shared\ Trials)$ and $Entropy(Independent\ Trials)$

Hellinger Distance: measures correlation between distributions

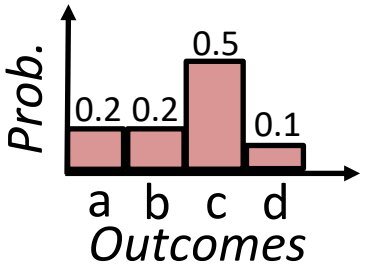
Description of the statistical tests

Entropy: measures randomness



Dist 1

Low Entropy



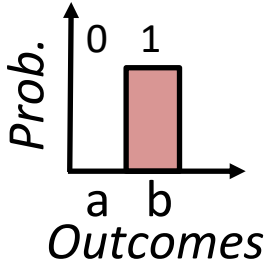
Dist 2

High Entropy

Noise

Compare $Entropy(Shared\ Trials)$ and $Entropy(Independent\ Trials)$

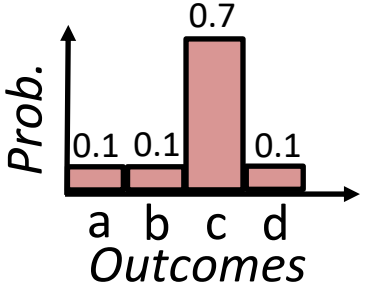
Hellinger Distance: measures correlation between distributions



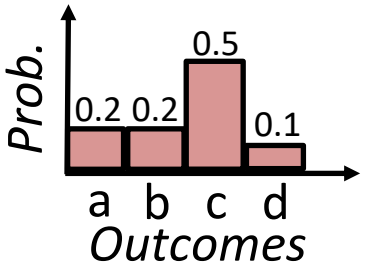
D1

Description of the statistical tests

Entropy: measures randomness



Dist 1



Dist 2

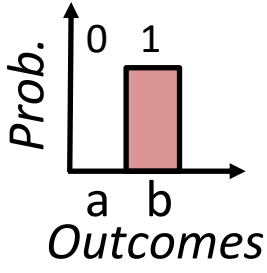
Low Entropy

High Entropy

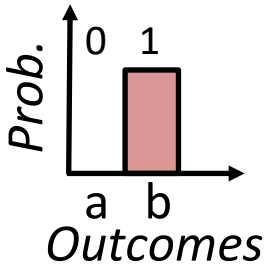
Noise

Compare $Entropy(Shared\ Trials)$ and $Entropy(Independent\ Trials)$

Hellinger Distance: measures correlation between distributions



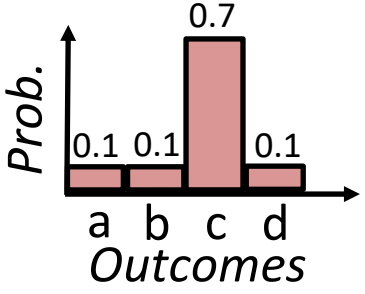
D1



D2

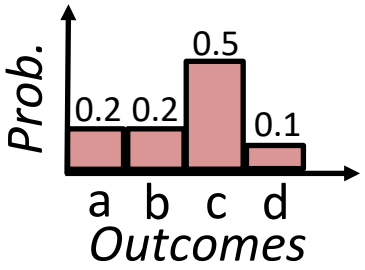
Description of the statistical tests

Entropy: measures randomness



Dist 1

Low Entropy



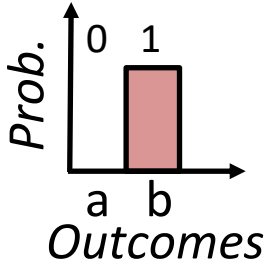
Dist 2

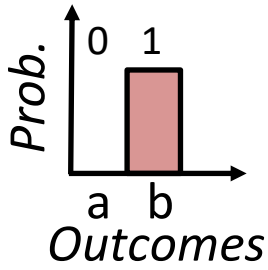
High Entropy

Noise

Compare $Entropy(Shared\ Trials)$ and $Entropy(Independent\ Trials)$

Hellinger Distance: measures correlation between distributions



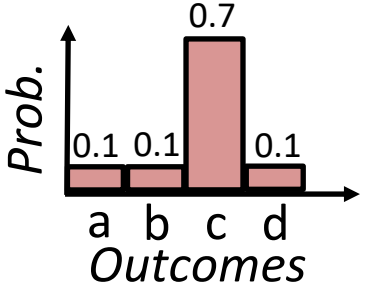


D1 *D2*

HD=0

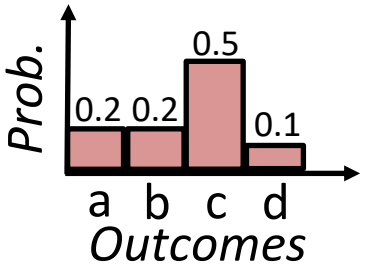
Description of the statistical tests

Entropy: measures randomness



Dist 1

Low Entropy



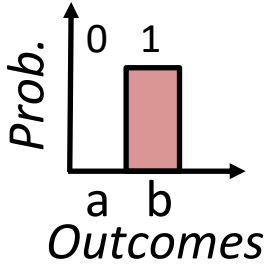
Dist 2

High Entropy

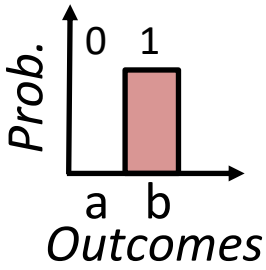
Noise

Compare $Entropy(Shared\ Trials)$ and $Entropy(Independent\ Trials)$

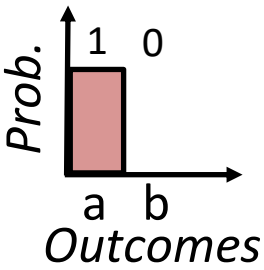
Hellinger Distance: measures correlation between distributions



D1



D2



D3

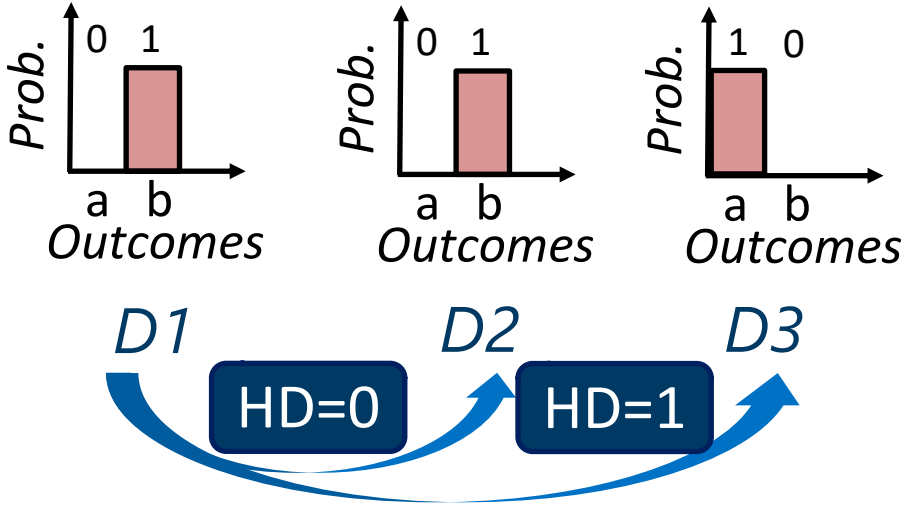
HD=0

Description of the statistical tests

Entropy: measures randomness

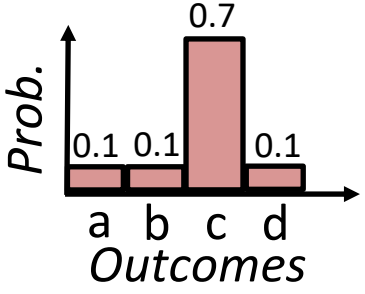
Compare $Entropy(Shared\ Trials)$ and $Entropy(Independent\ Trials)$

Hellinger Distance: measures correlation between distributions



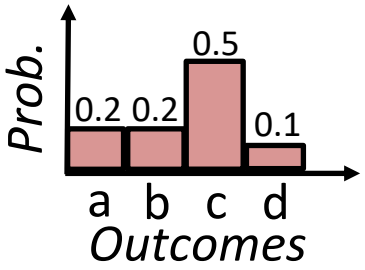
Description of the statistical tests

Entropy: measures randomness



Dist 1

Low Entropy



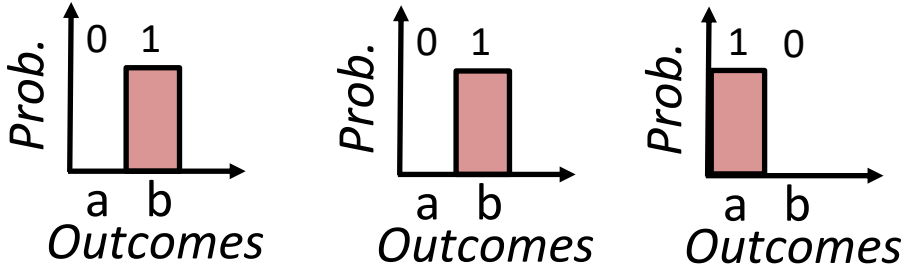
Dist 2

High Entropy

Noise

Compare $Entropy(Shared\ Trials)$ and $Entropy(Independent\ Trials)$

Hellinger Distance: measures correlation between distributions



D1 *D2* *D3*

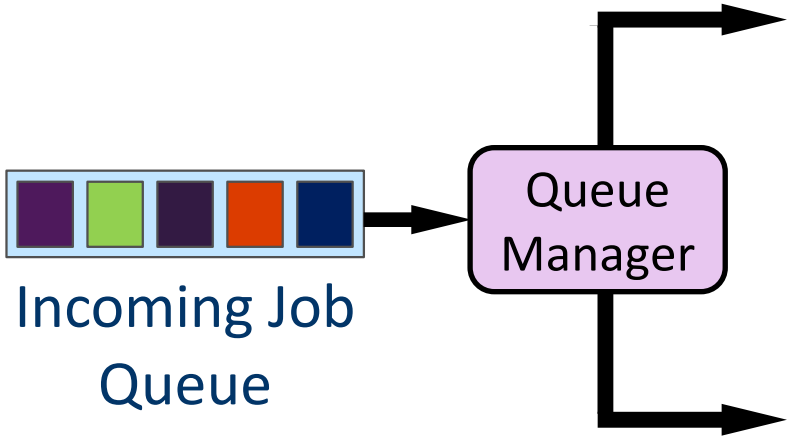
HD=0 HD=1

How similar or dissimilar are the shared and independent trials?

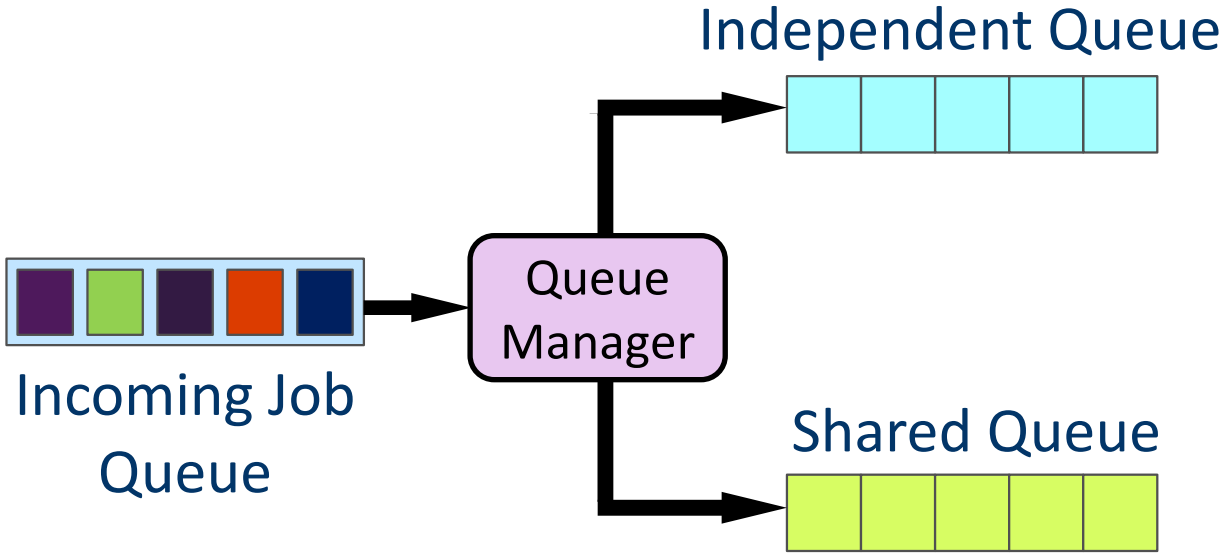
AMP Design Implementation

Incoming Job Queue

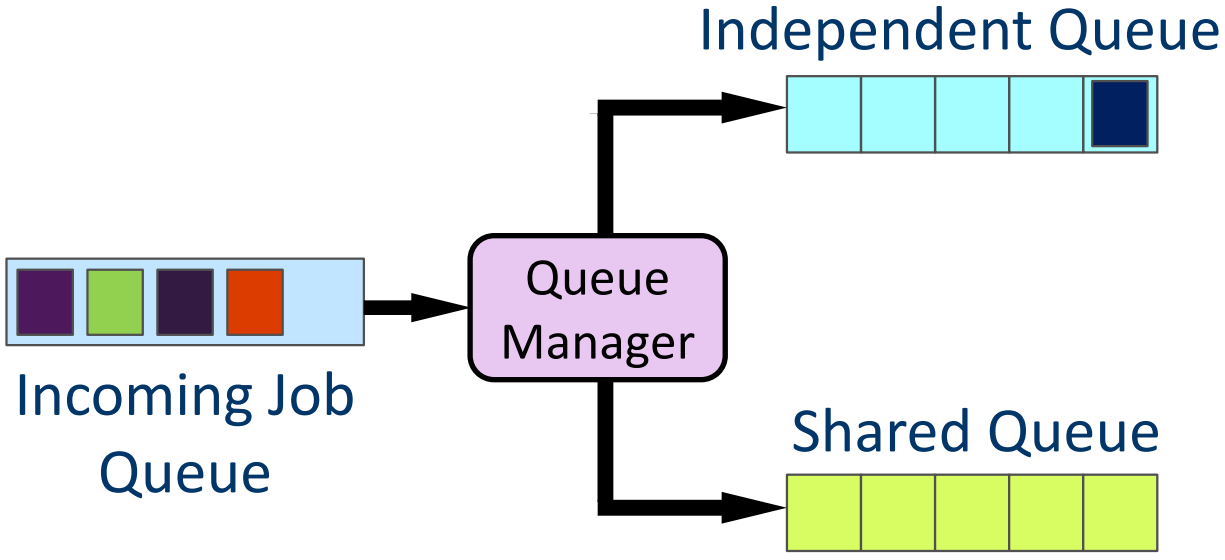
AMP Design Implementation



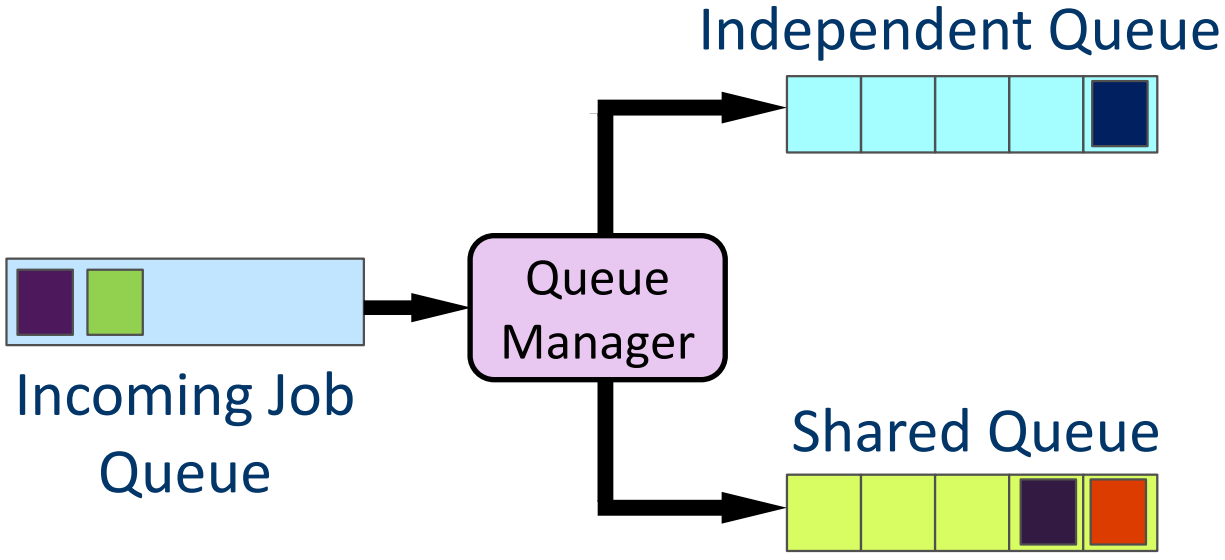
AMP Design Implementation



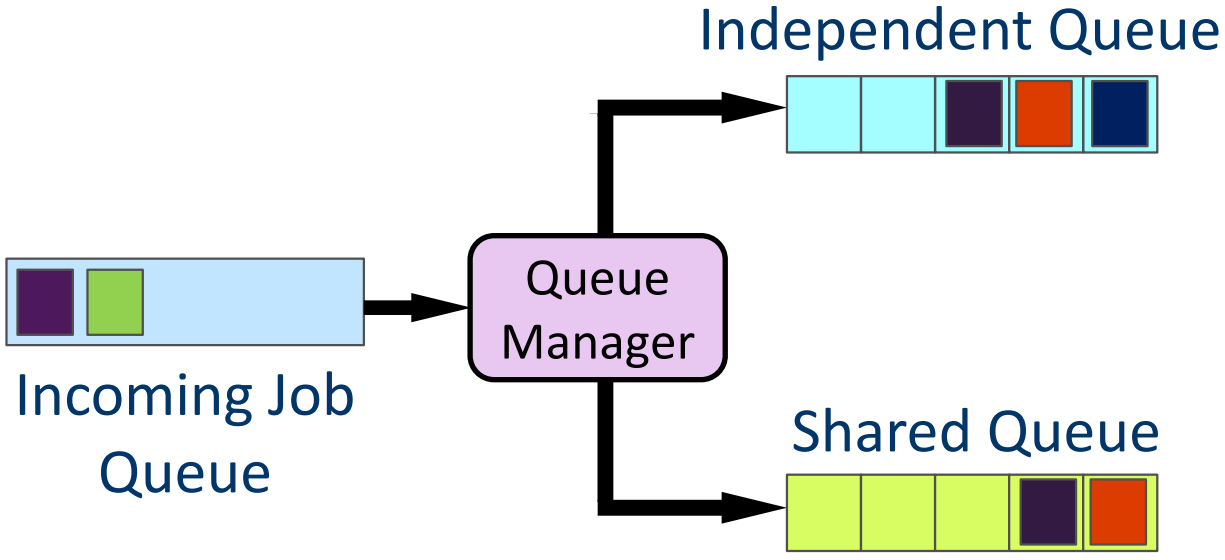
AMP Design Implementation



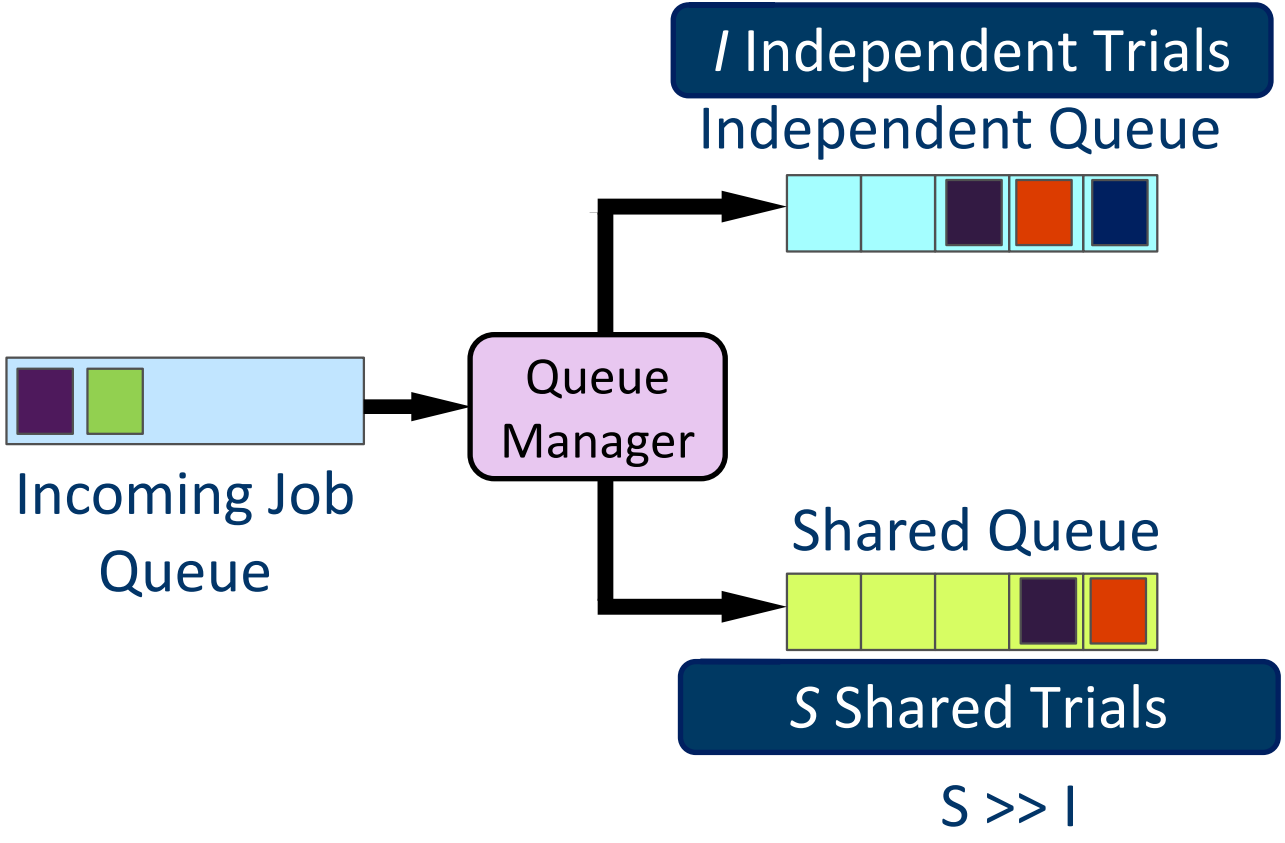
AMP Design Implementation



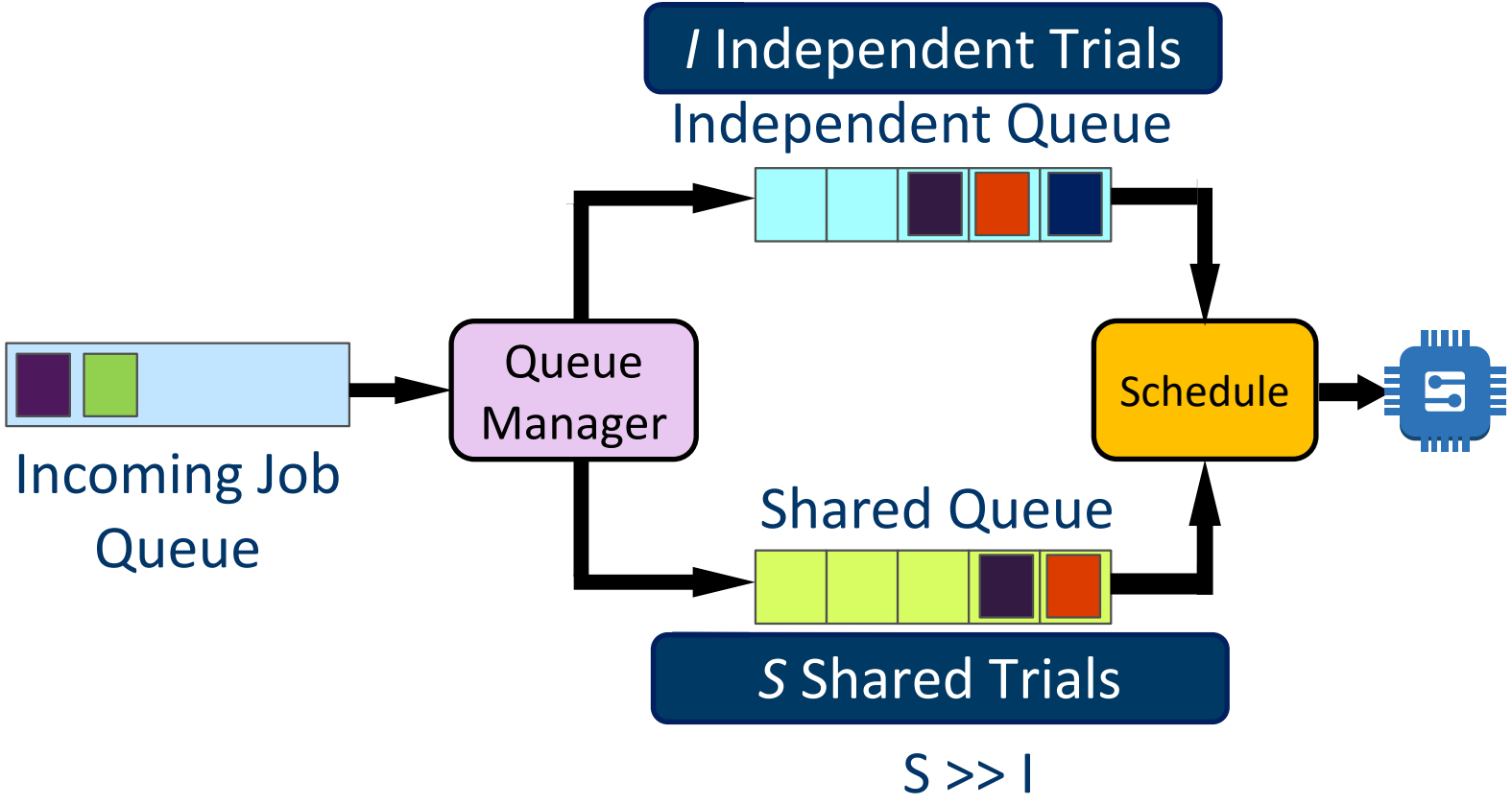
AMP Design Implementation



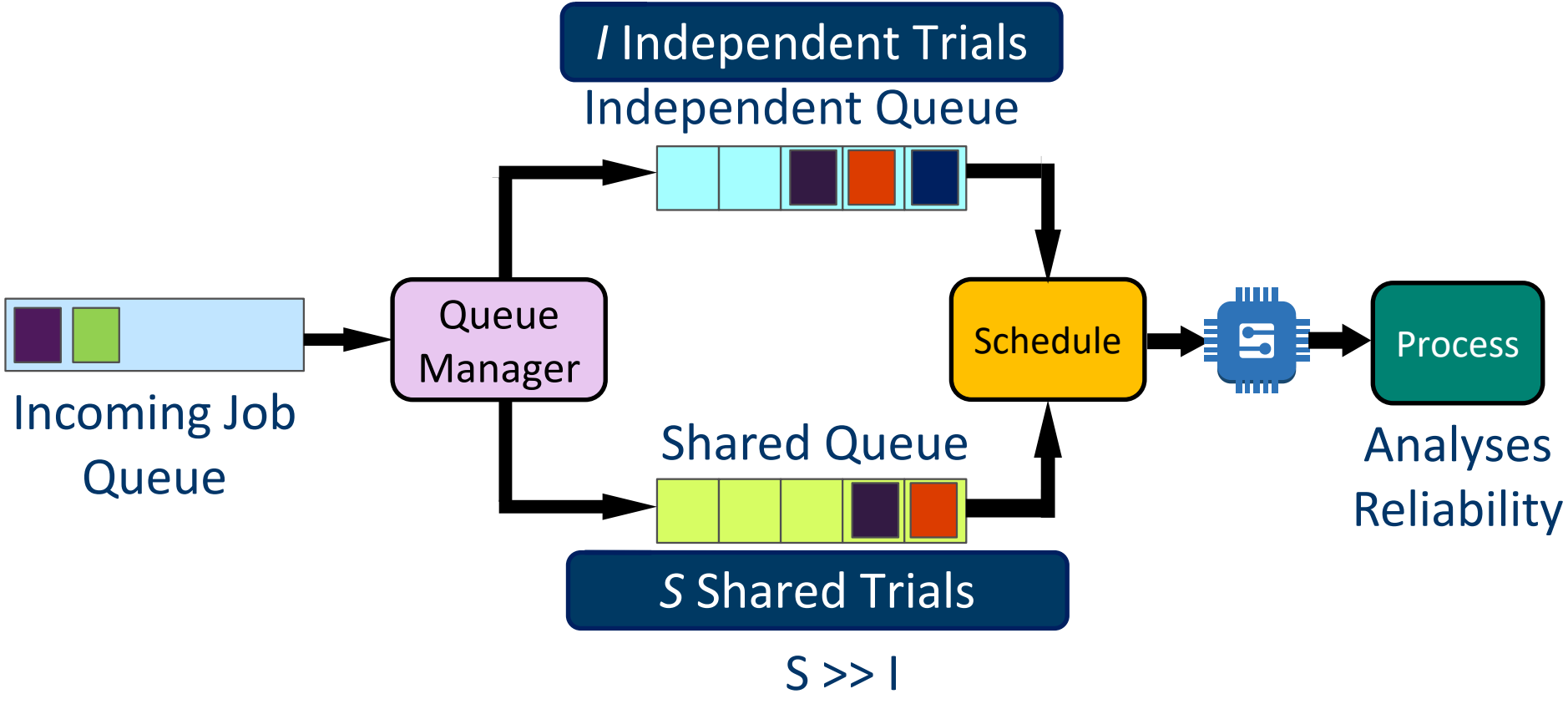
AMP Design Implementation



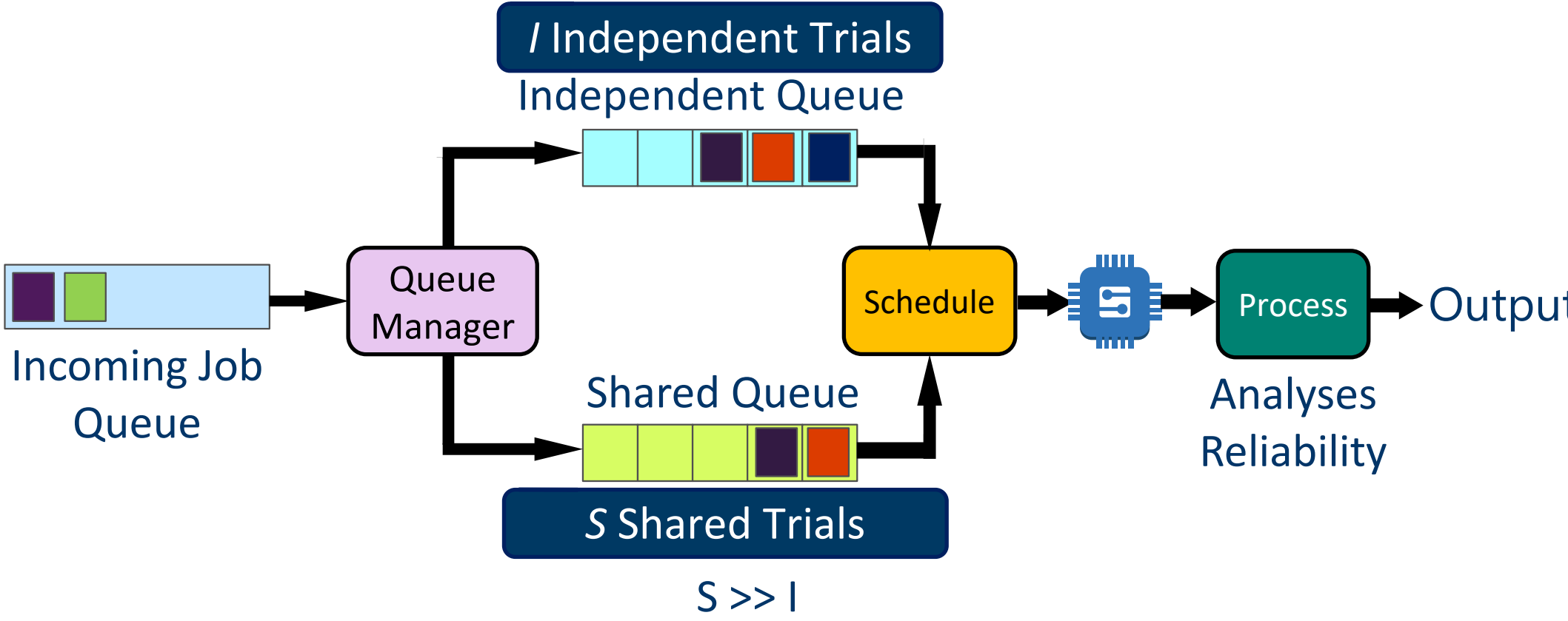
AMP Design Implementation



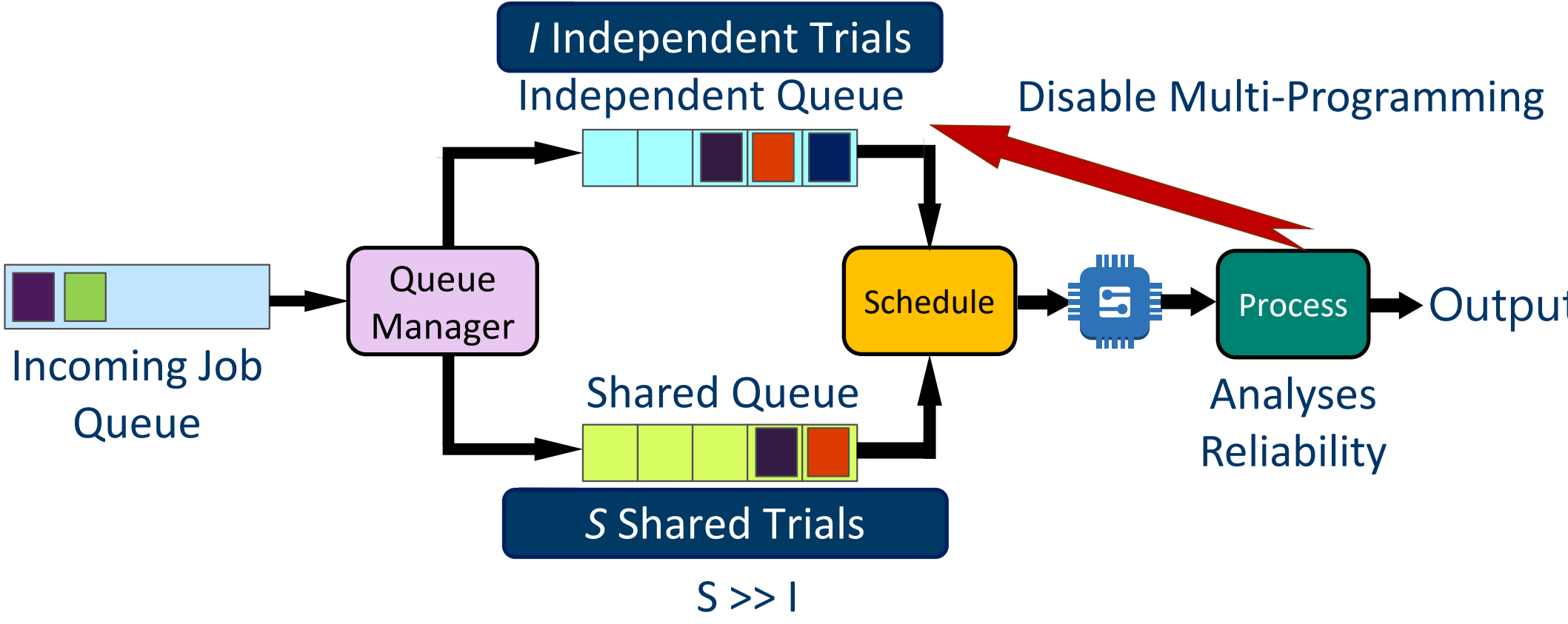
AMP Design Implementation



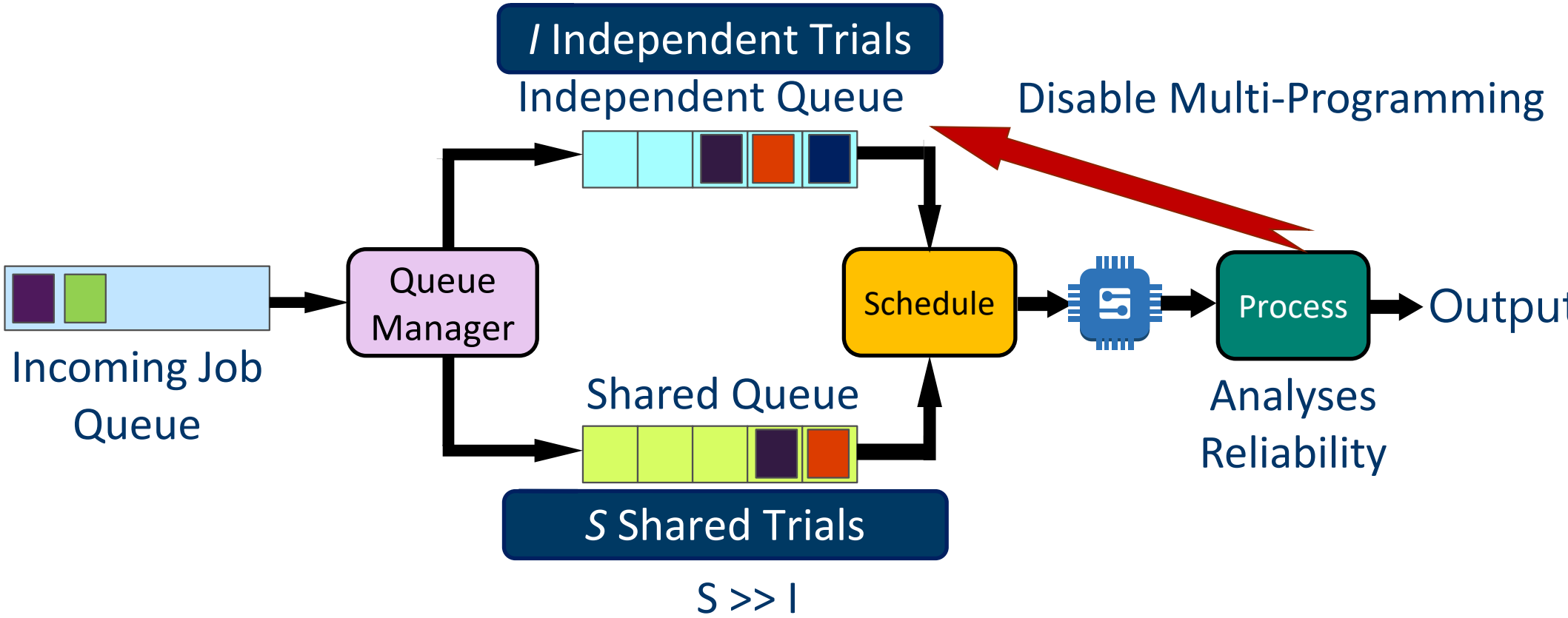
AMP Design Implementation



AMP Design Implementation



AMP Design Implementation

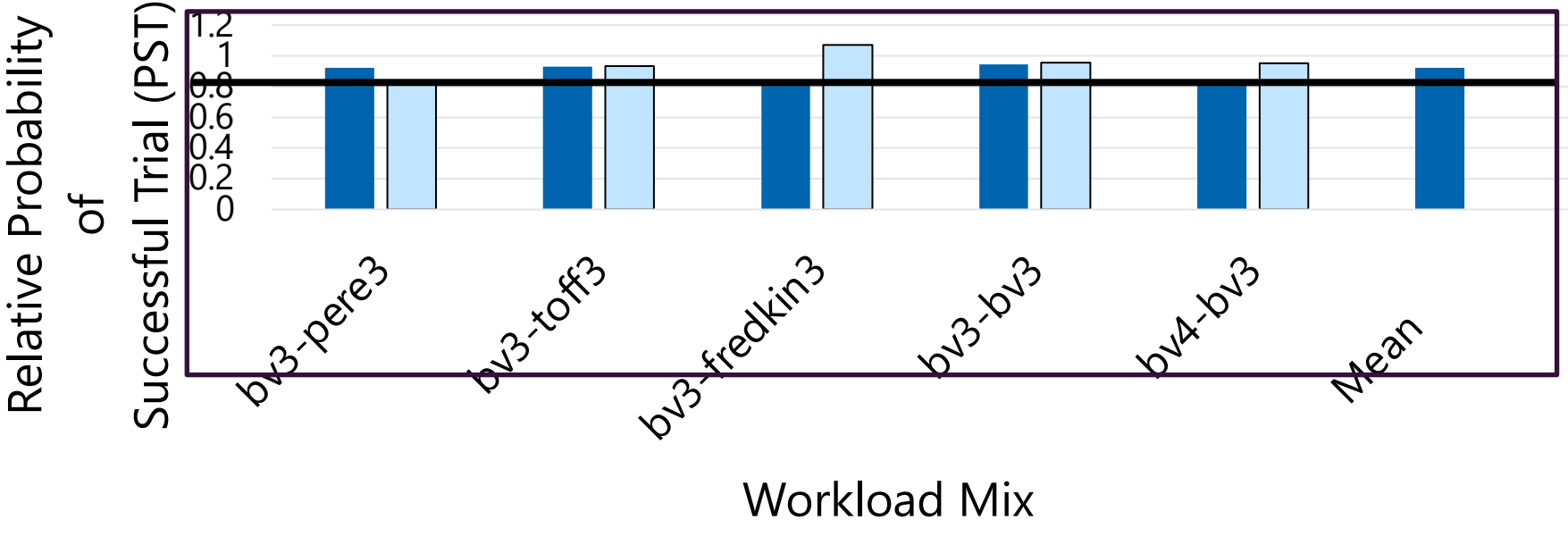


Multi-programming is adaptive to mitigate severe impact on reliability

Outline

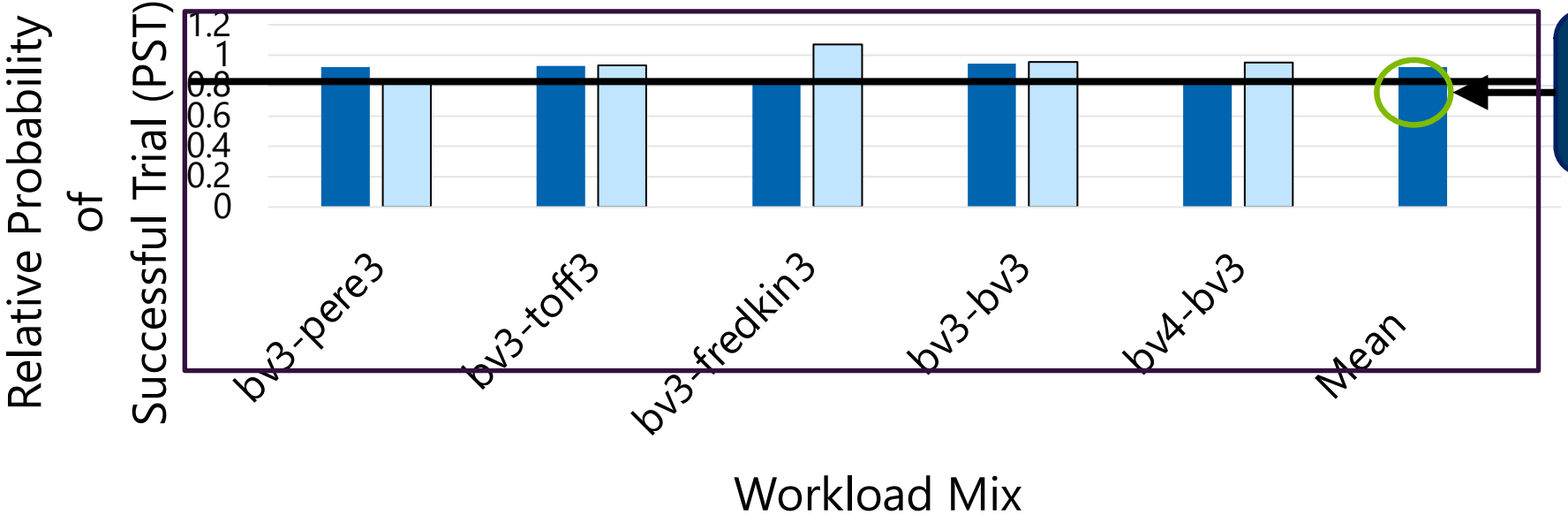
- Introduction
- Background and Motivation
- Policies for Multi-Programming
- Evaluation Methodology
- Adaptive Multi-Programming Design
- Results and Conclusion

Final Results



Mode: S=6K, I=2K

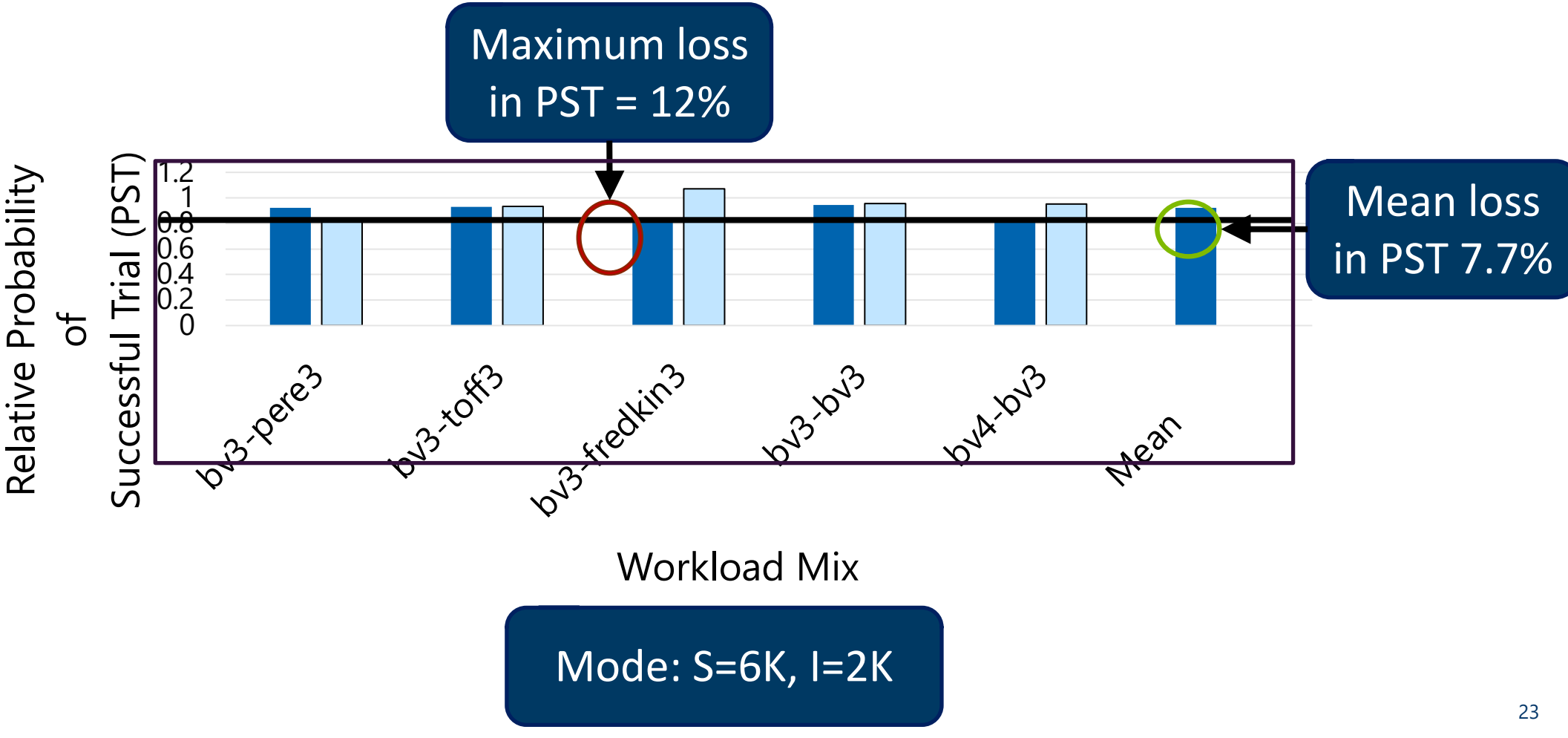
Final Results



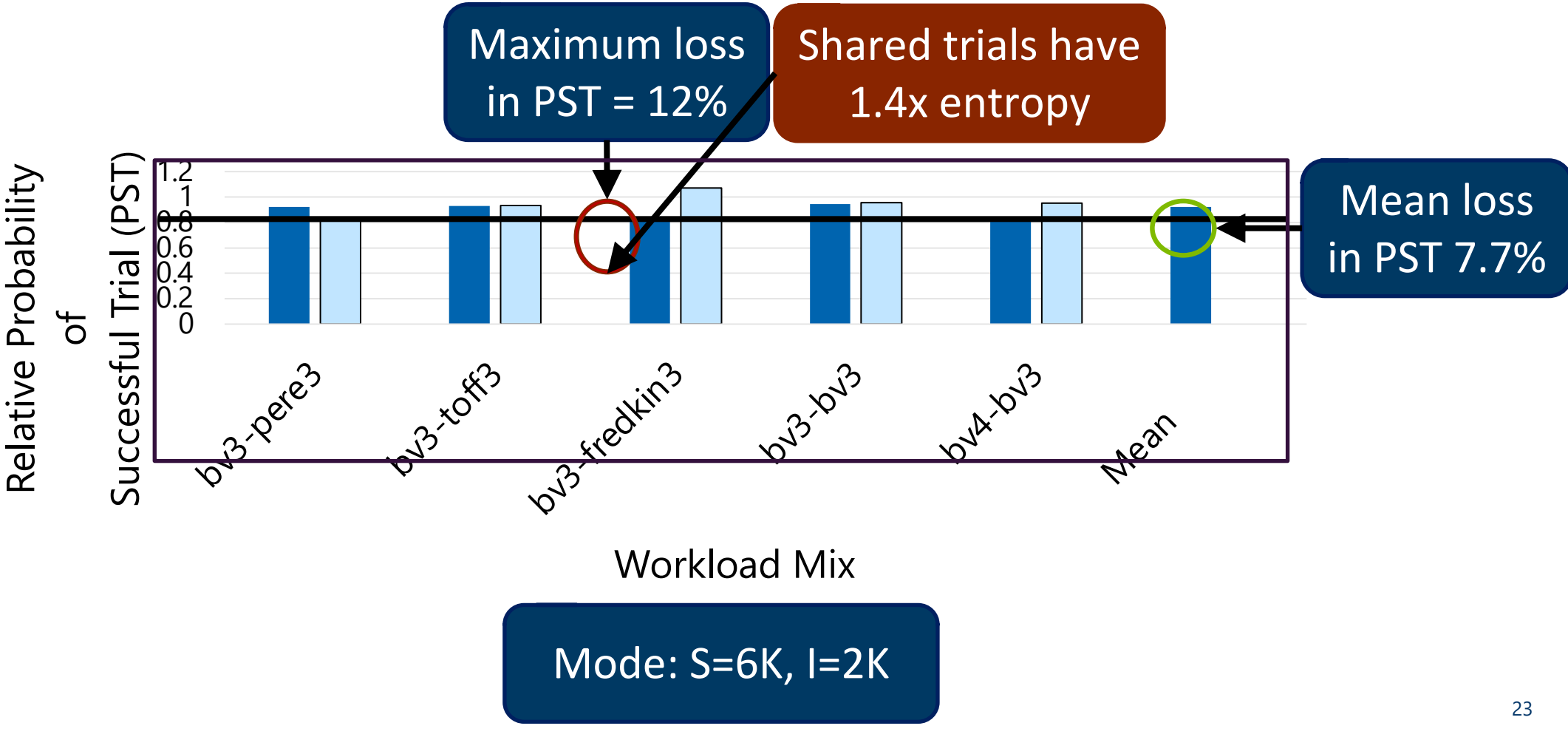
Mean loss in PST 7.7%

Mode: S=6K, I=2K

Final Results



Final Results



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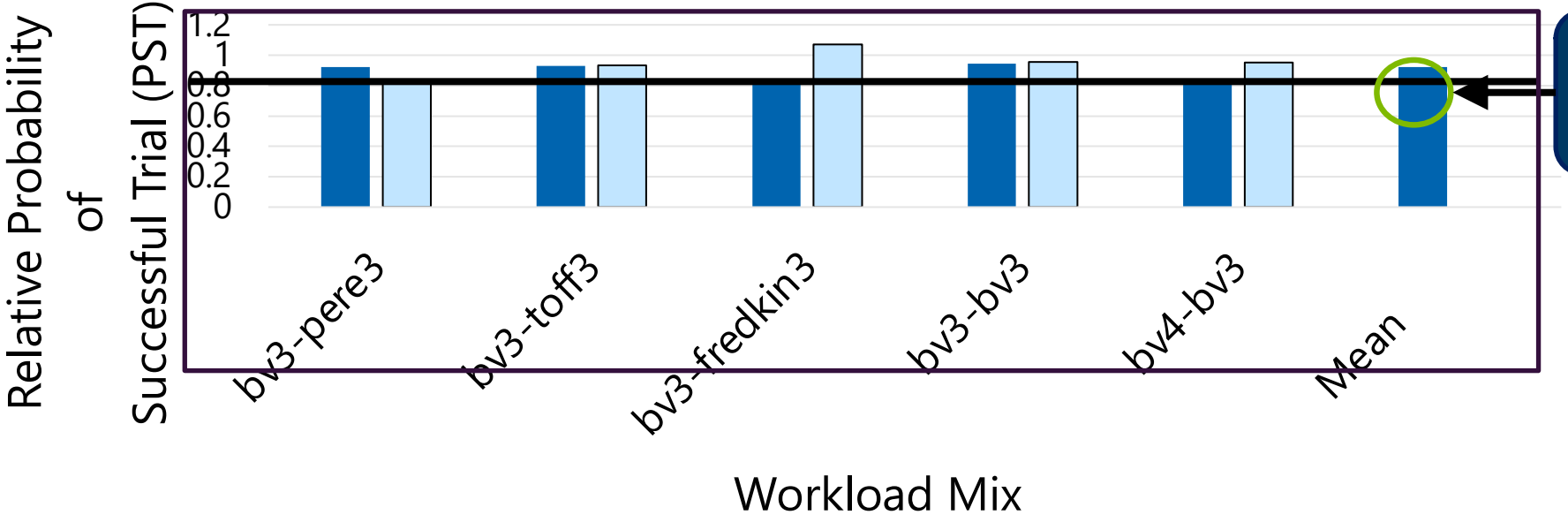

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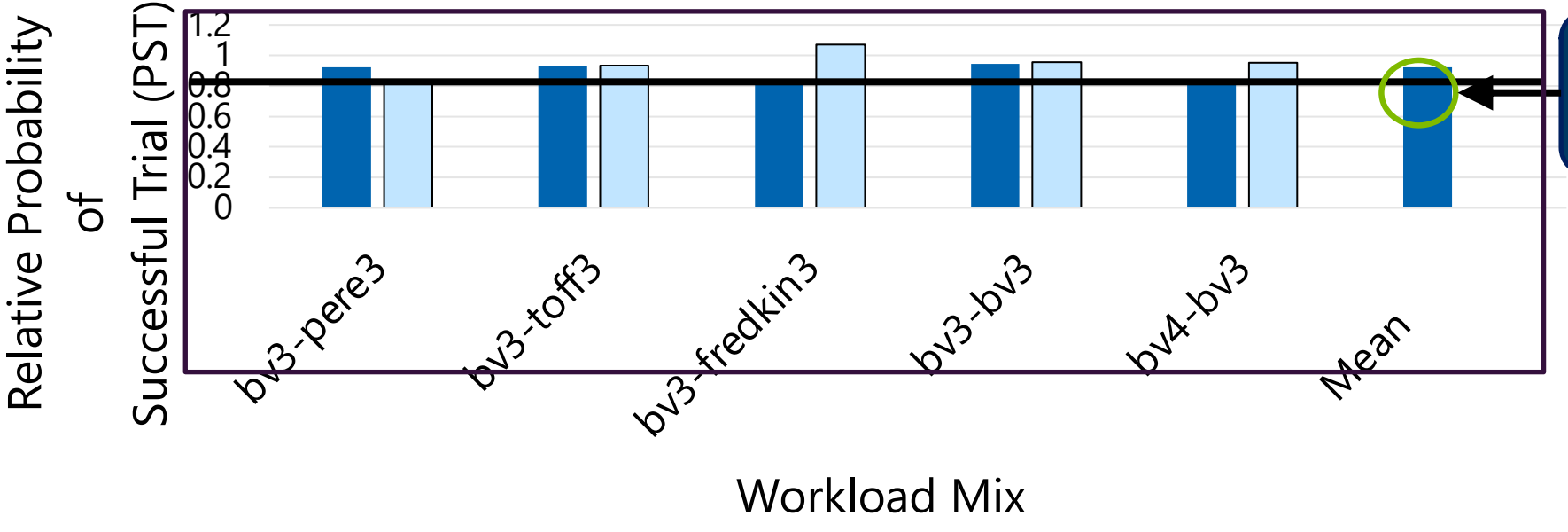

Mean loss in PST 7.7%

Mode: S=6K, I=2K

Throughput improved by 1.6x

Conclusion

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- We proposed multi-programming to improve NISQ machine throughput and utilization
- We designed scalable policies for fair resource allocation, minimizing interference, and adaptive multi-programming
- Our solutions can be implemented by both user and service provider
- Machine throughput can be improved up to 2x with minimal loss in PST

Thank You!