Hybrid Quantum-Classical Systems (Part 1)

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Hybrid Quantum-Classical Systems

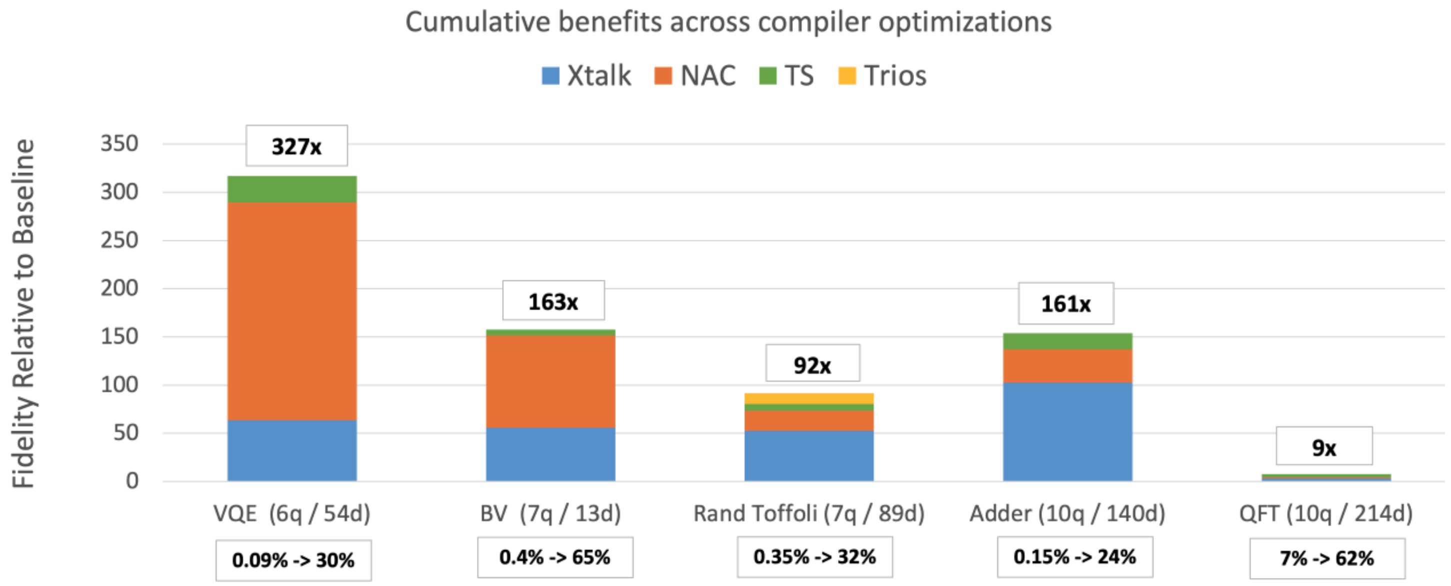
- *Hybrid quantum-classical systems: Systems performing non-trivial tasks on both the classical and quantum resources.*

- *Non-trivial quantum task: The quantum task.*

- *Non-trivial classical task: Any novel pre-processing, post-processing, co-processing, especially those with potential scalability challenges.*

Classical pre-processing before Q execution: 1) Circuit compilation

- Device-aware mapping, routing, scheduling circuit transformation…..



NAC: Noise-Adaptive Compiler Mappings for Noisy Intermediate-Scale Quantum Computers. ASPLOS 2019

Xtalk: Software Mitigation of Crosstalk on Noisy Intermediate-Scale Quantum Computers. ASPLOS 2020

TS: TimeStitch: Exploiting Slack to Mitigate Decoherence in Quantum Circuits. TQC 2022

Trios: Orchestrated Trios: Compiling for Efficient Communication in Quantum Programs with 3-Qubit Gates. ASPLOS 2021

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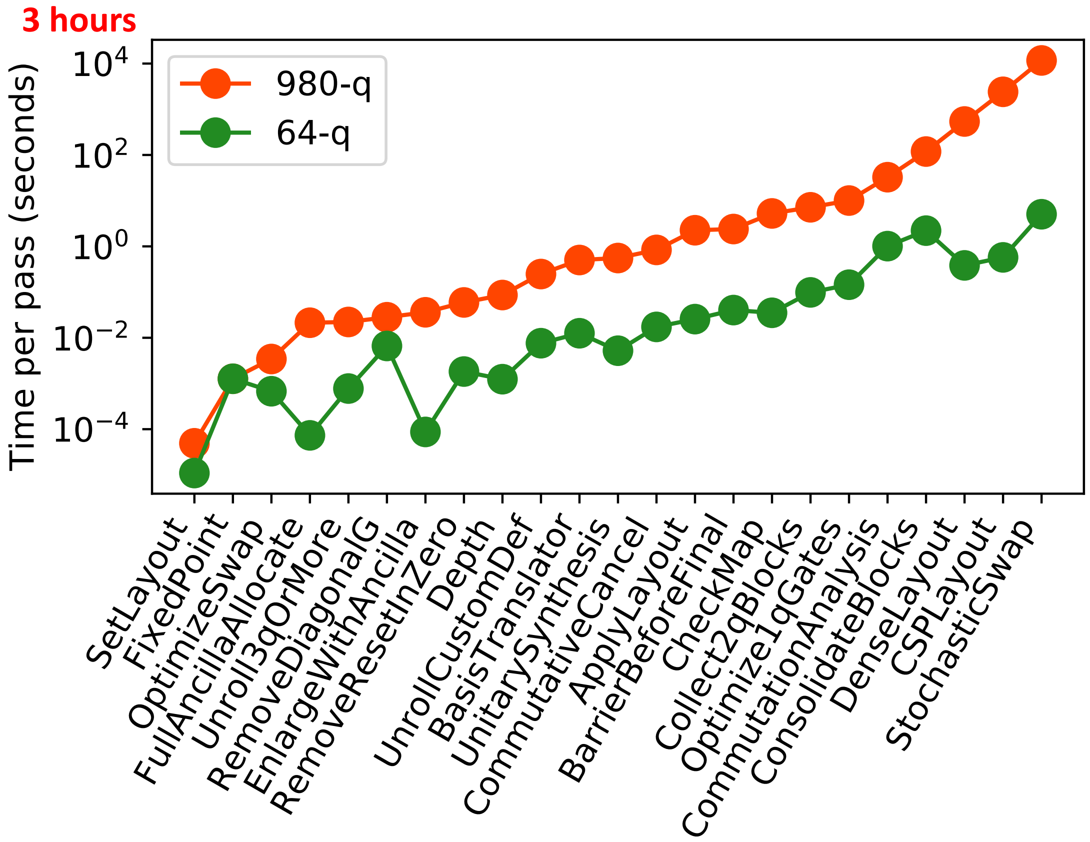
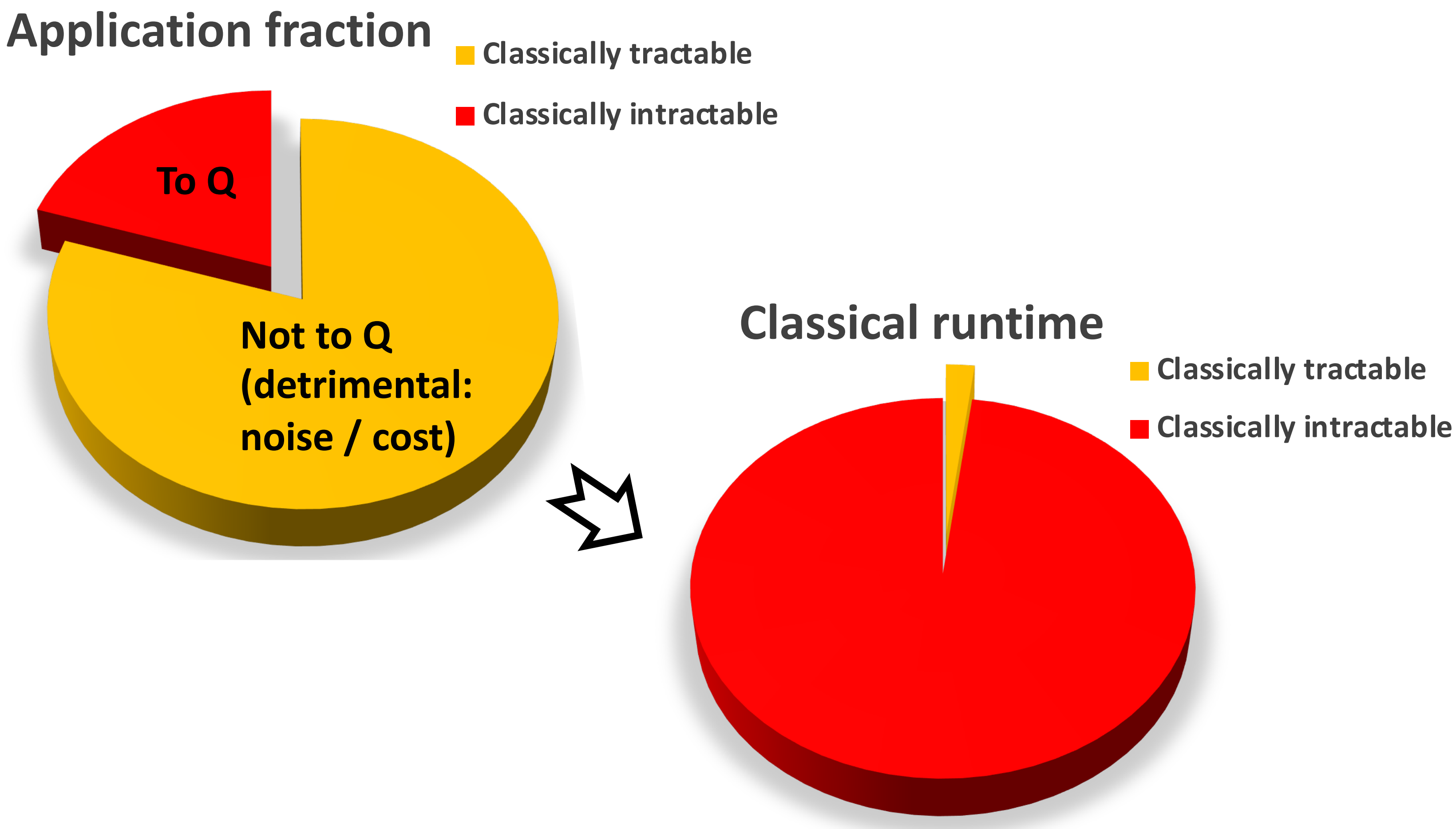
- Device-aware mapping, routing, scheduling circuit transformation…..



Quantum Computing in the Cloud: Analyzing job and machine characteristics. IISWC 2021.

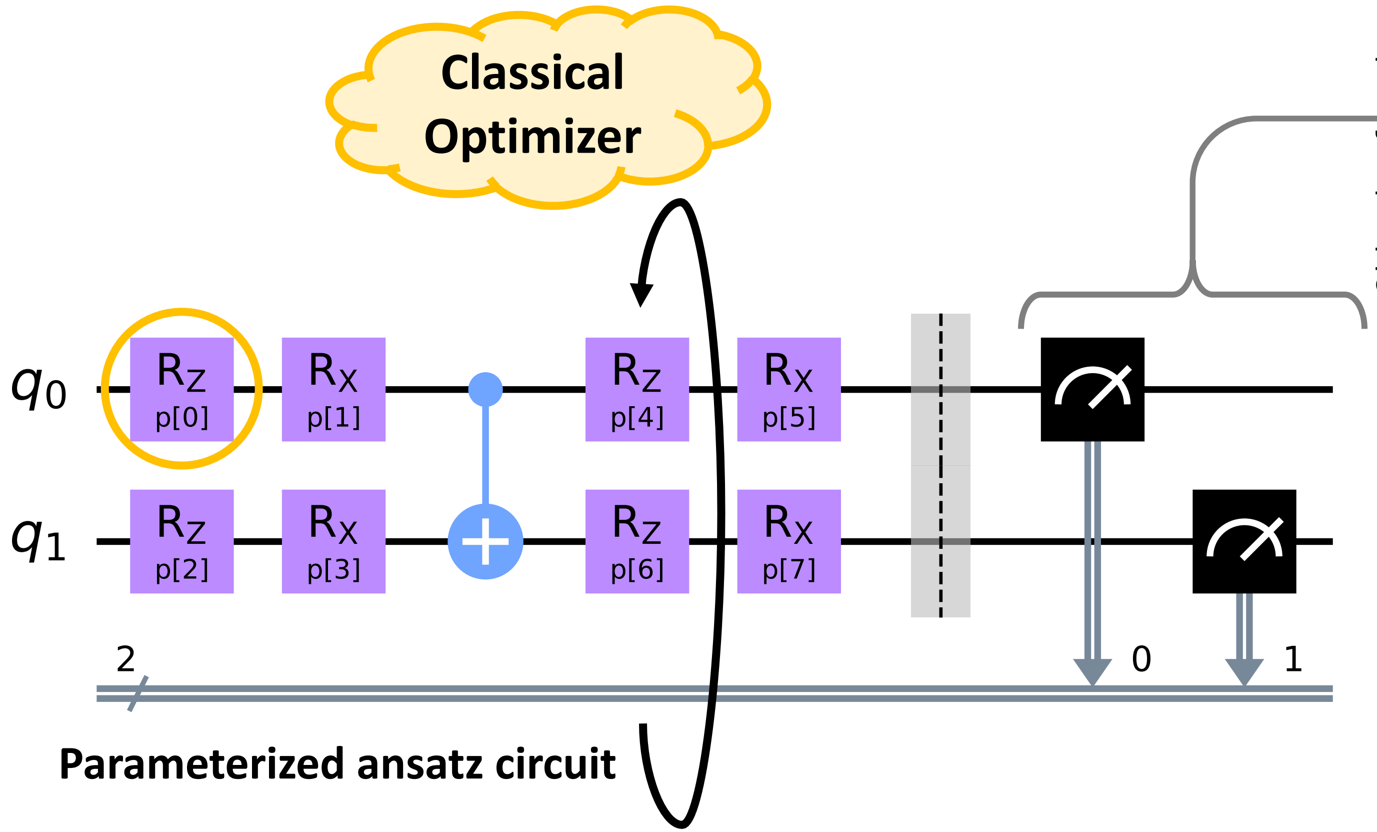
Large-scale circuit compilation requires more sophisticated software and hardware, especially critical for iterative applications.

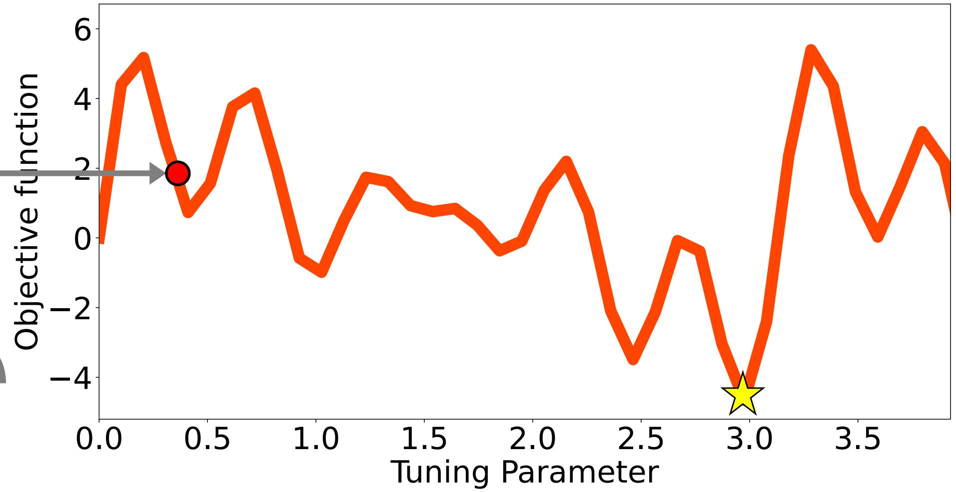
Classical pre-processing before Q execution:
2) Initialization for iterative algorithms



Classical pre-processing before Q execution: 2) Initialization for iterative algorithms

CAFQA: A classical simulation bootstrap for variational quantum algorithms. ASPLOS 2023





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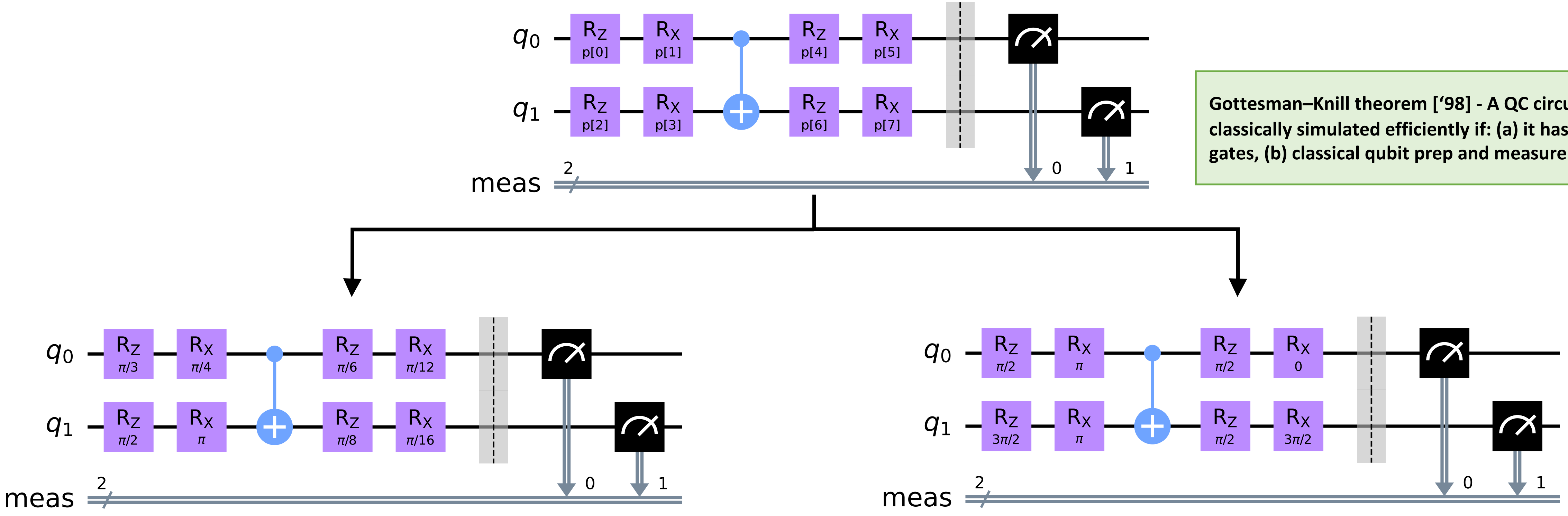
CAFQA: A classical simulation bootstrap for variational quantum algorithms. ASPLOS 2023

Parameterized ansatz circuit



Gottesman–Knill theorem ['98] - A QC circuit can be classically simulated efficiently if: (a) it has only Clifford gates, (b) classical qubit prep and measurement.

A classically intractable general circuit

Continuous angles = [0, 2*pi]

A classically simulable Clifford circuit

Discrete angles = {0, pi/2, pi, 3*pi/2}

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2) Initialization for iterative algorithms

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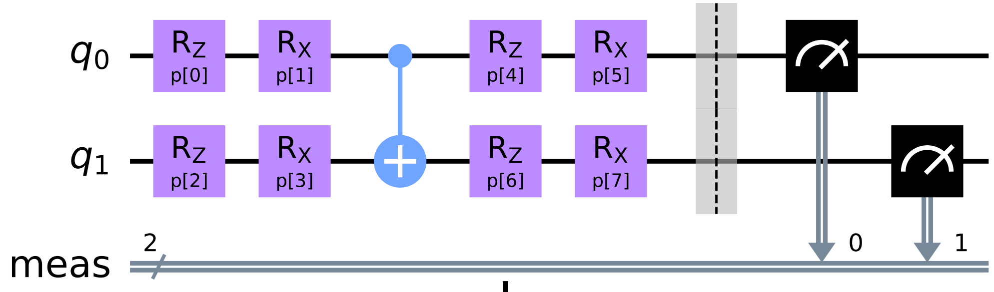
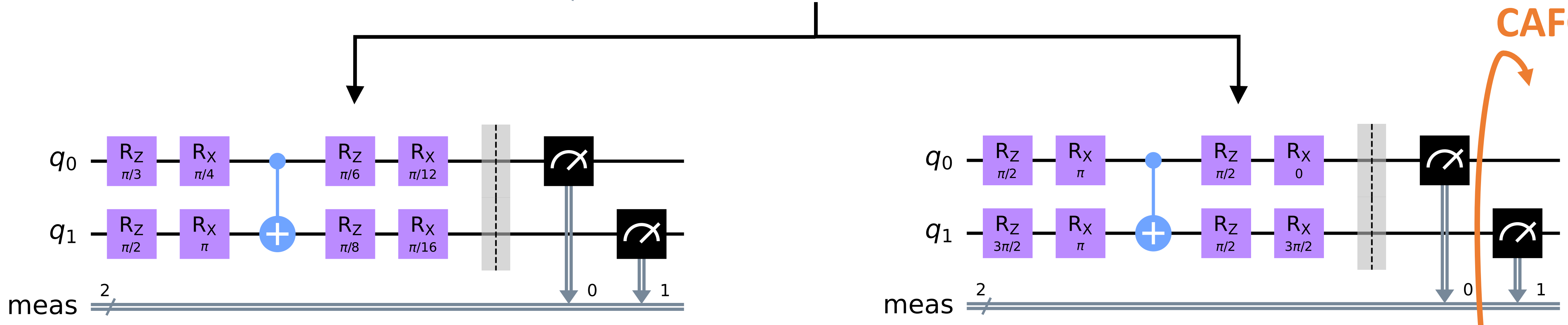
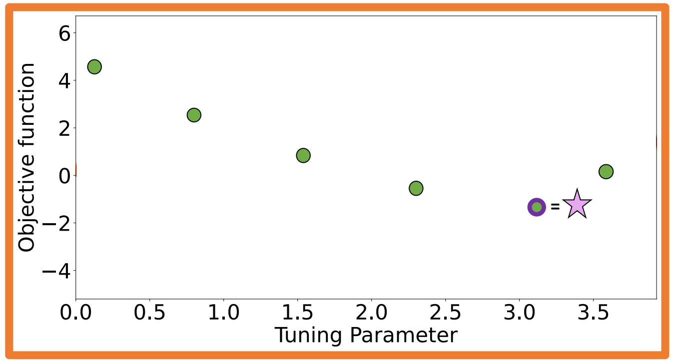
Parameterized ansatz circuit







CAFQA

A classically <u>intractable general</u> circuit

Continuous angles = [0, 2*pi]

A classically <u>simulable Clifford</u> circuit

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Classical pre-processing before Q execution:
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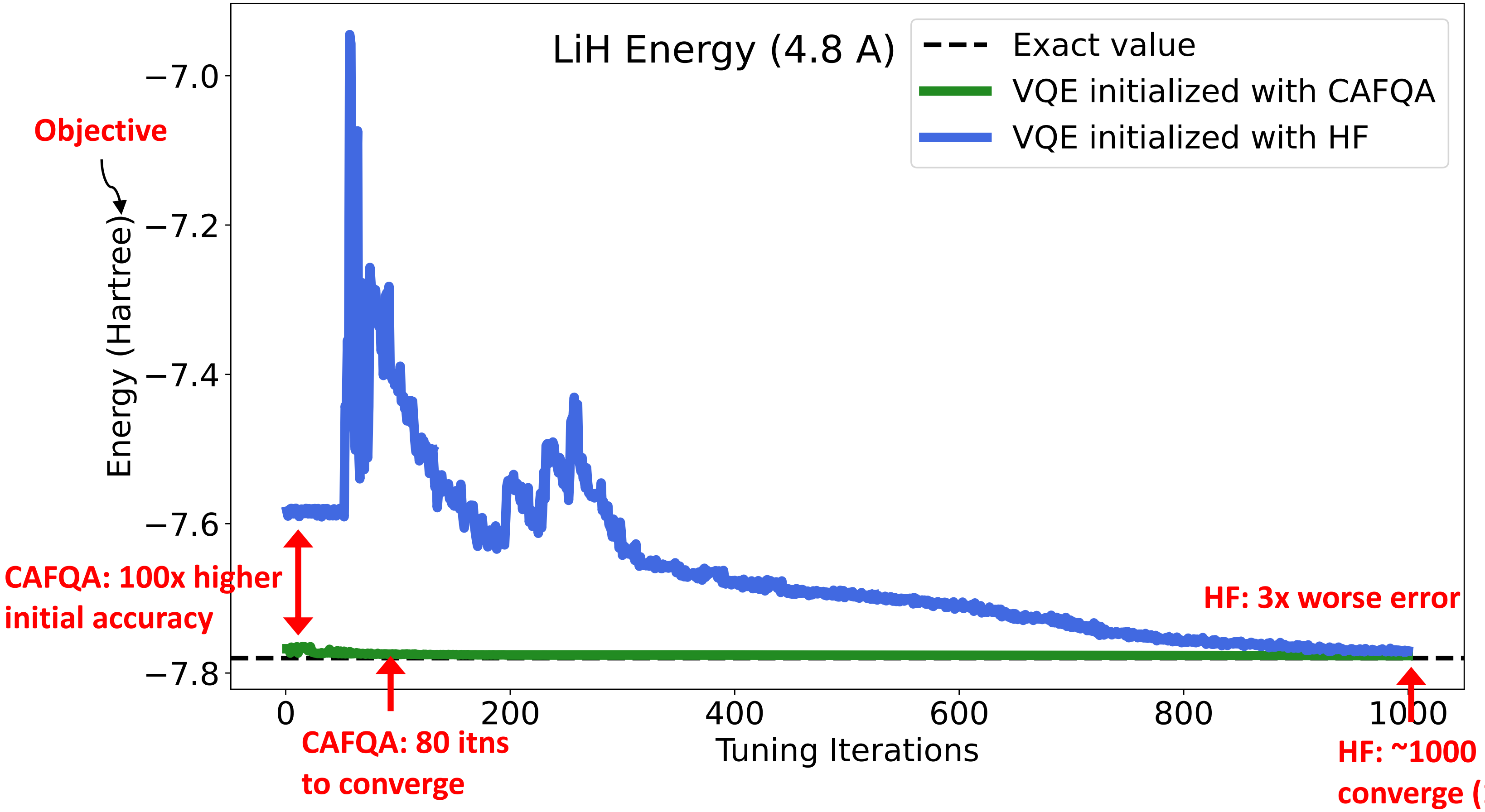
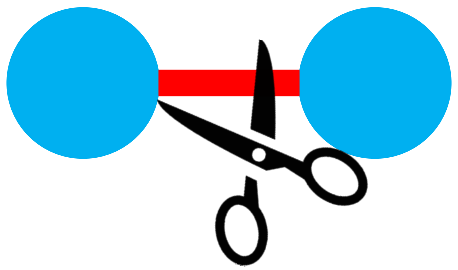
CAFQA: A classical simulation bootstrap for variational quantum algorithms. ASPLOS 2023



Potential Energy



Classical pre-processing before Q execution:
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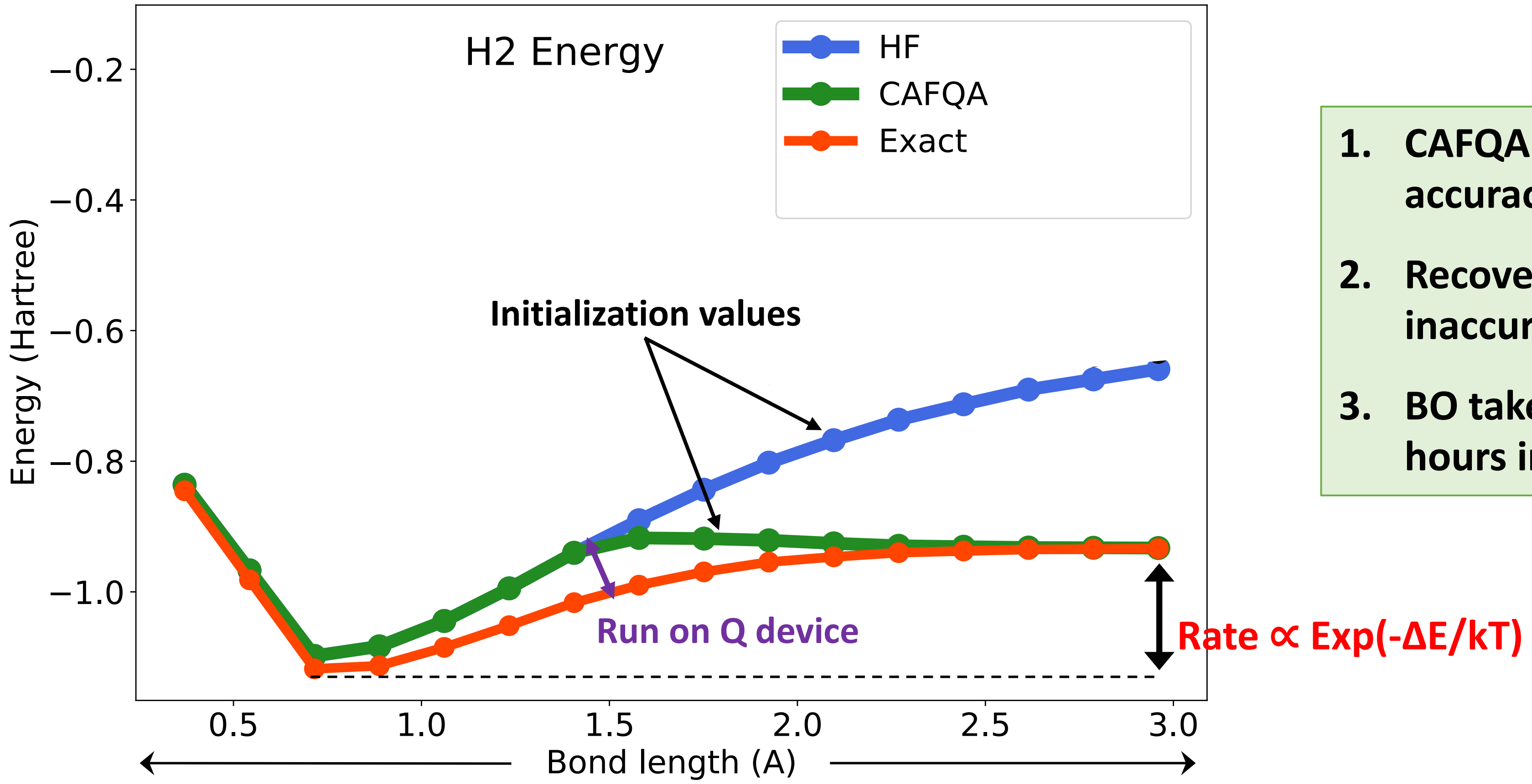
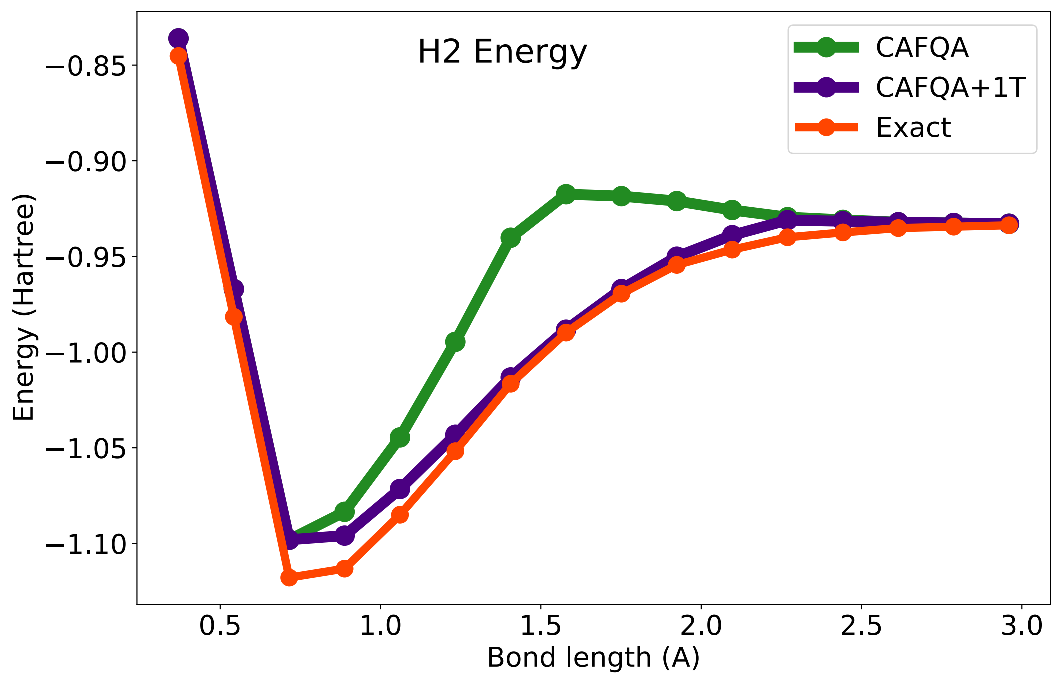
CAFQA: A classical simulation bootstrap for variational quantum algorithms. ASPLOS 2023

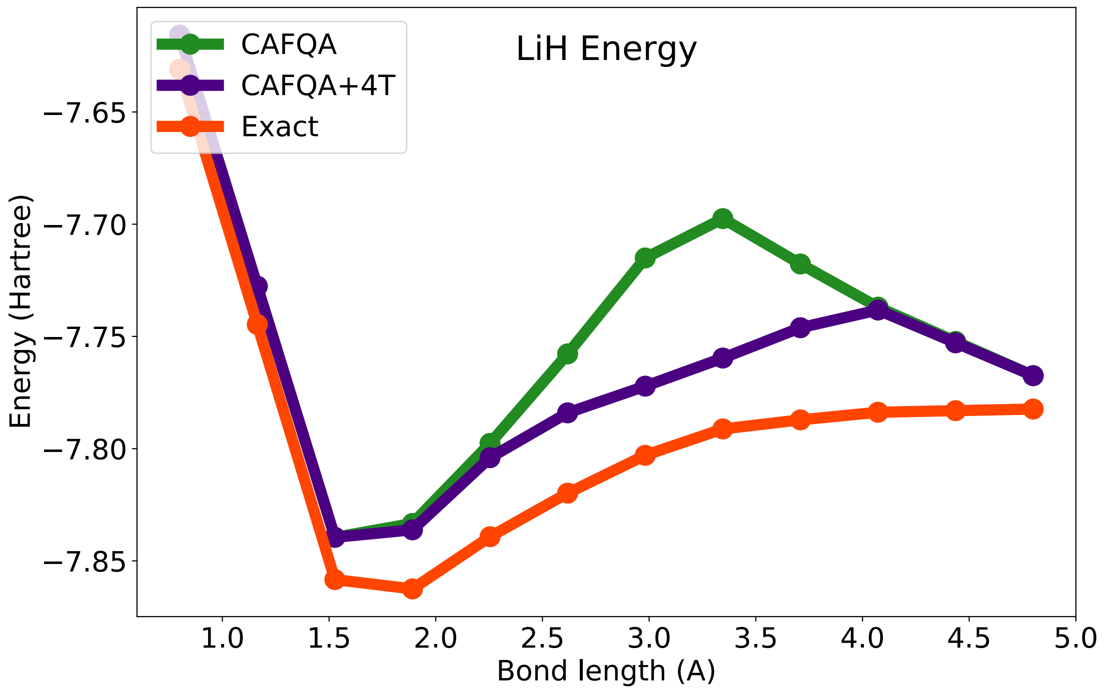


1. **CAFQA achieves 99% mean initialization accuracy (systems up to 34 qubits).**
2. **Recovers up to 99.99% of Hartree-Fock inaccuracy (57x mean).**
3. **BO takes ~2000 iterations (mean), few hours in wall-clock time.**

Classical pre-processing before Q execution: 2) Initialization for iterative algorithms

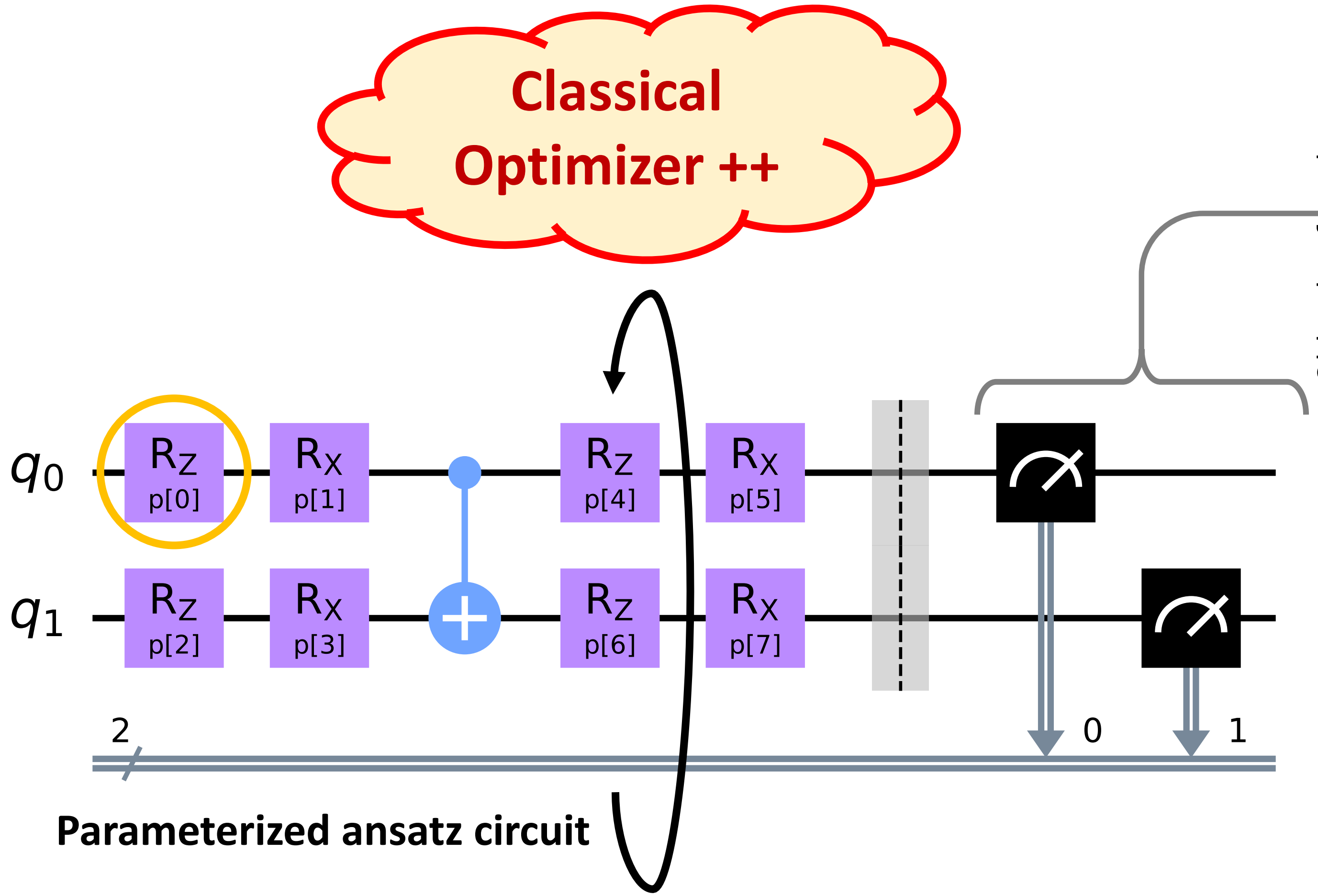
CAFQA: A classical simulation bootstrap for variational quantum algorithms. ASPLOS 2023

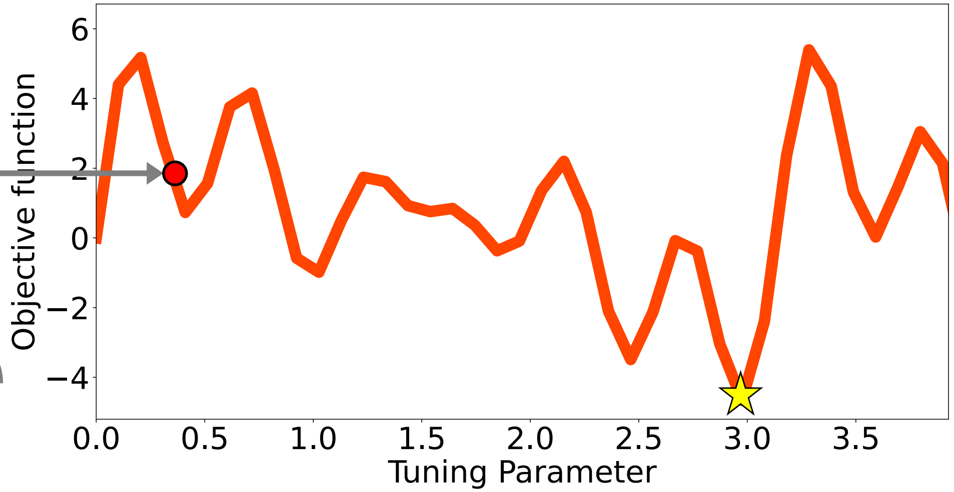


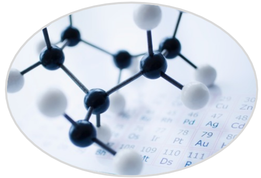


Systematically push to max classical limit (say, defined by number of non-Clifford T gates)
What is the classical limit?: Laptop vs Desktop vs Supercomputer
Interesting circuit optimization and hybrid resource management questions
+ HPC community

Classical co-processing alongside Q execution:
1) Everything to do with variational algorithms







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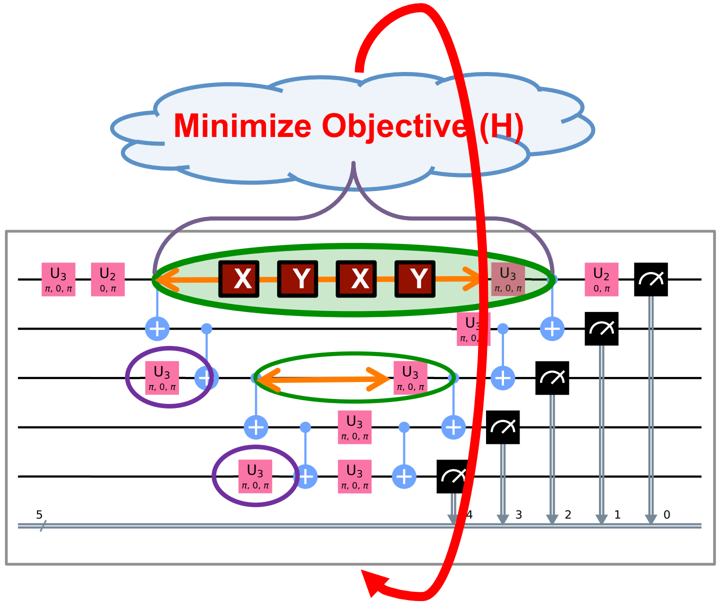
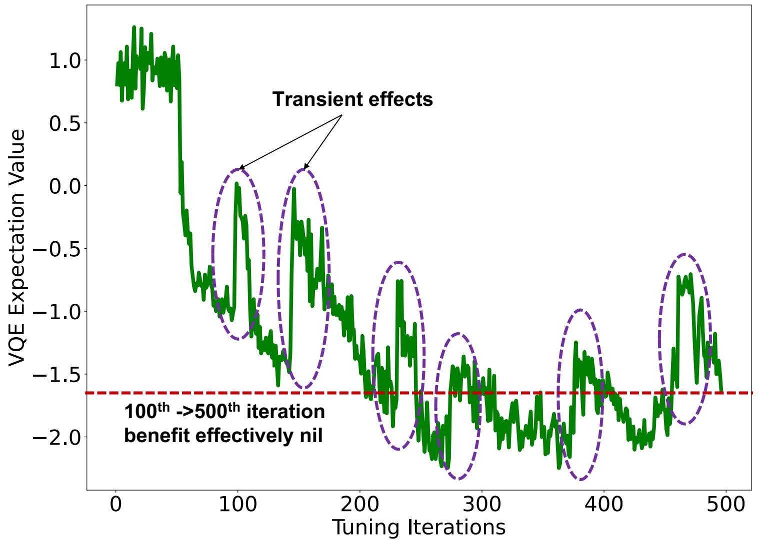
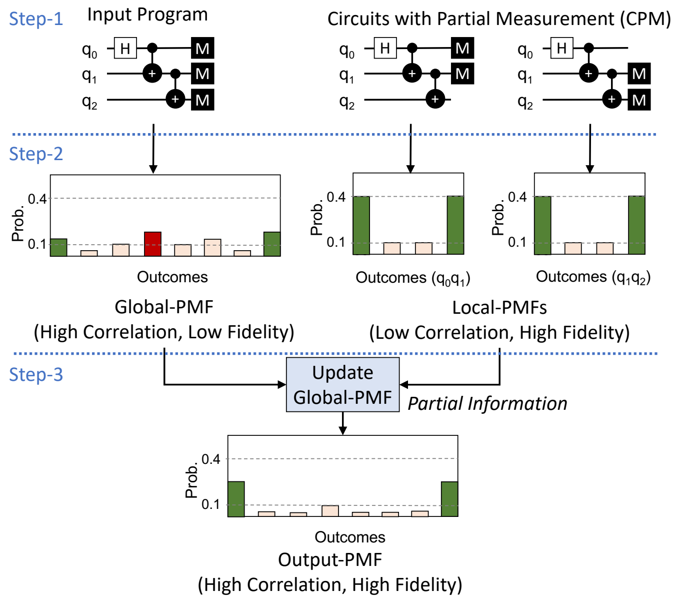


VAQEM: A Variational Approach to Quantum Error Mitigation. HPCA 2022



Navigating the Dynamic Noise Landscape of Variational Algorithms with QISMET. ASPLOS 2023

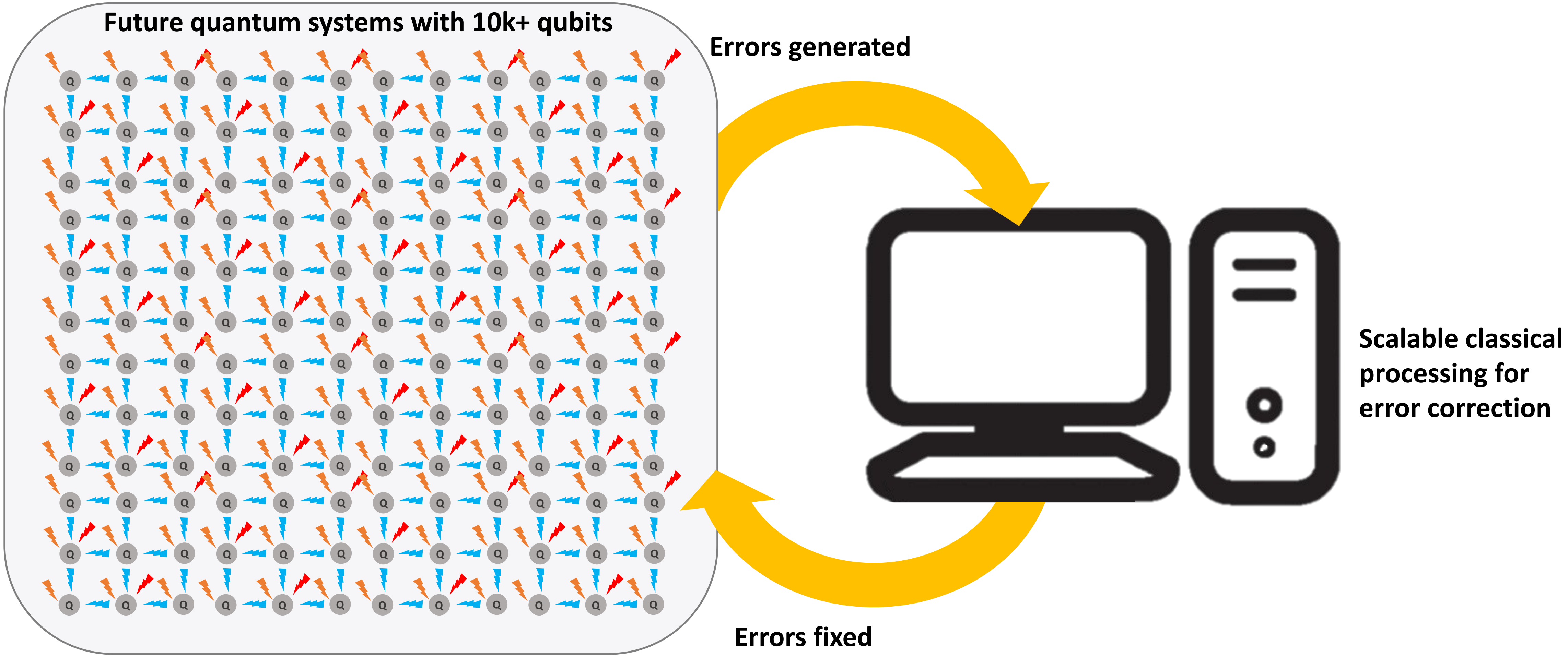


VarSaw: Application-tailored Measurement Error Mitigation for Variational Quantum Algorithms. ASPLOS 2024

Increased tuning parameters and additional features makes optimizer and related classical processing efficiency critical. Non-trivial hw/sw resources.

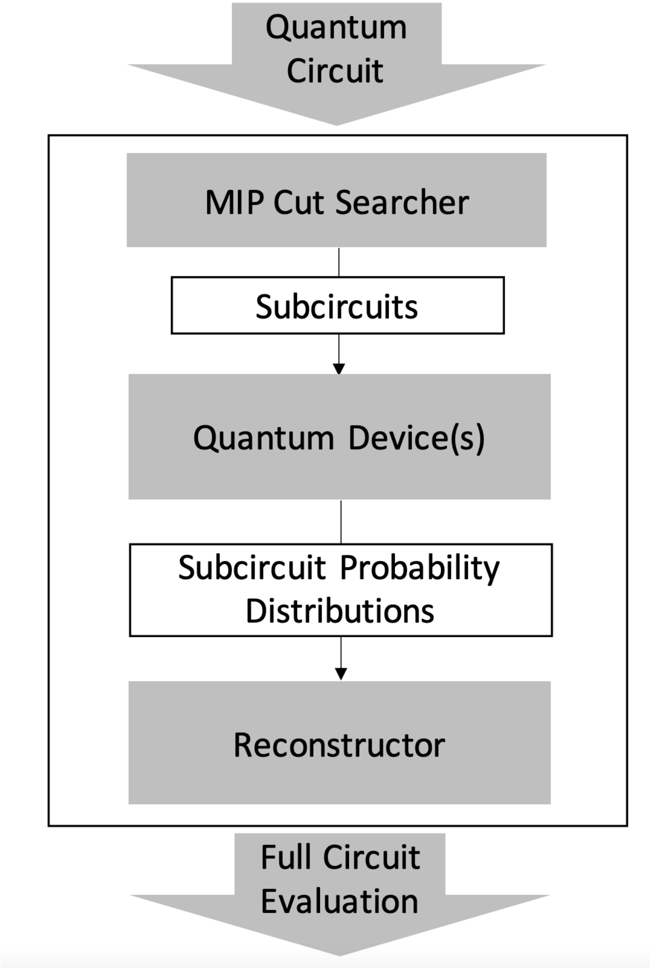
Classical co-processing alongside Q execution:
2) Everything to do with QEC decoding

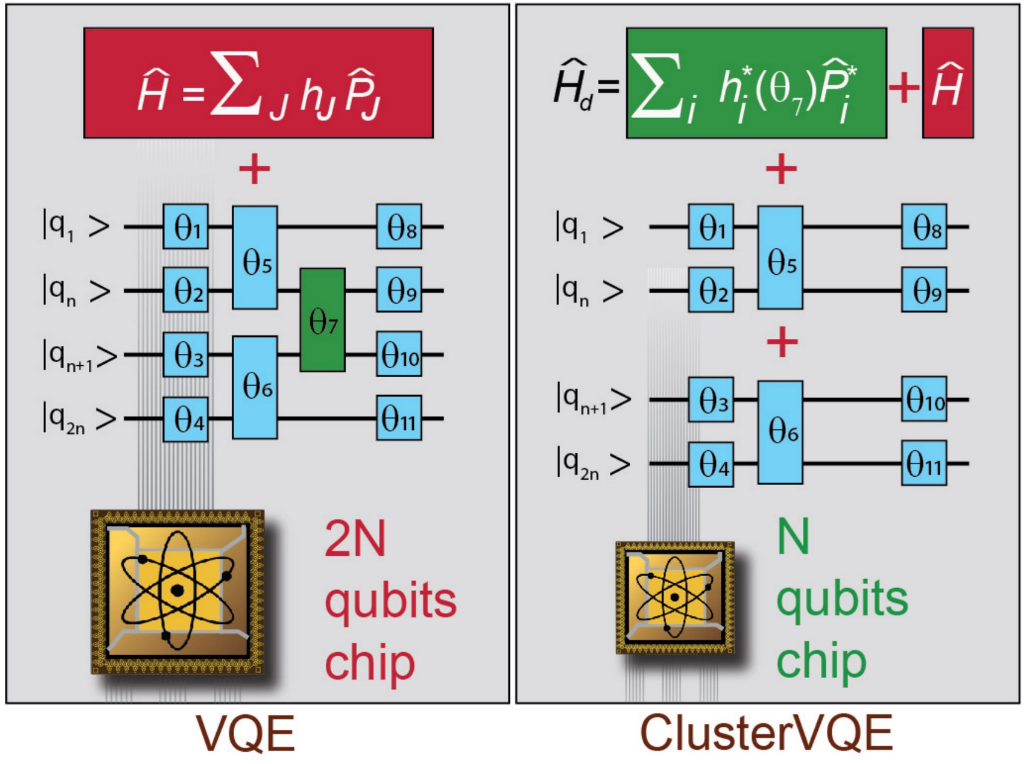
Clique: Better Than Worst-Case Decoding for Quantum Error Correction. ASPLOS 2023



Classical post-processing after Q execution: 1) circuit cutting/knitting

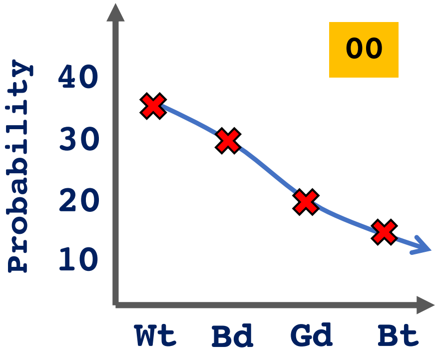
CutQC: using small Quantum computers for large Quantum circuit evaluations, ASPLOS 2021
Variational Quantum Eigensolver with Reduced Circuit Complexity, June 2021



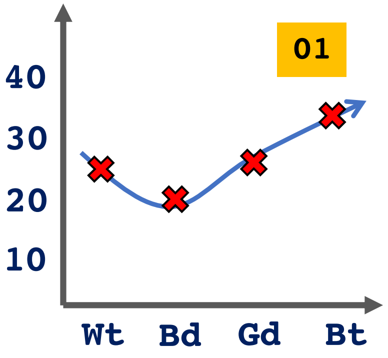


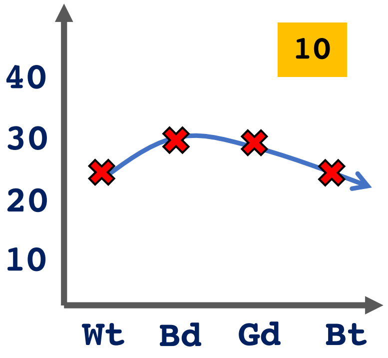
Classical post-processing after Q execution:
2) output interpretation techniques

Quancorde: Boosting fidelity with Quantum Canary Ordered Diverse Ensembles. ICRC 2022

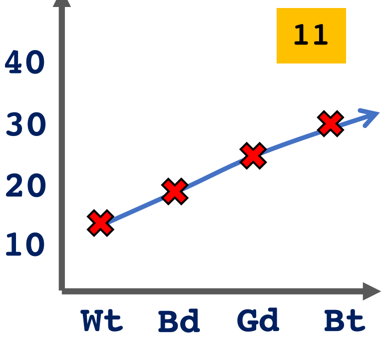


Worst		Bad		Good		Best	
00	35%	00	30%	00	20%	00	15%
01	25%	01	20%	01	25%	01	35%
10	25%	10	30%	10	30%	10	20%
11	15%	11	20%	11	25%	11	30%





Highly correlated

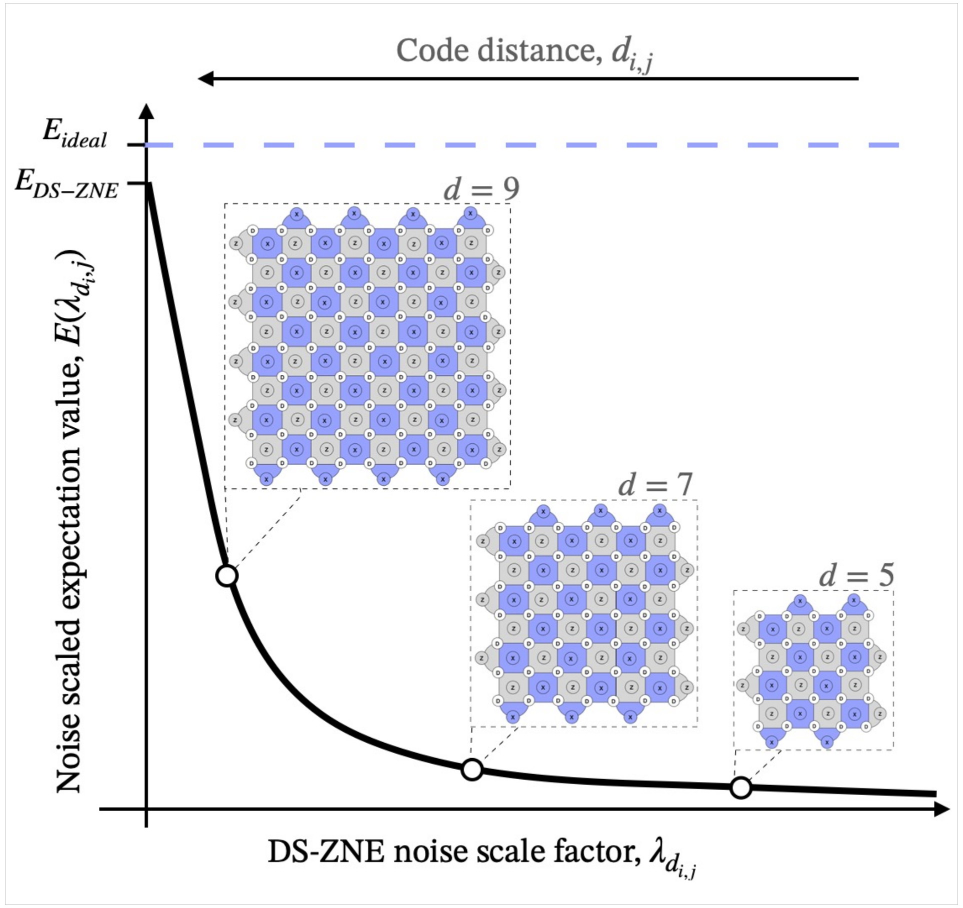


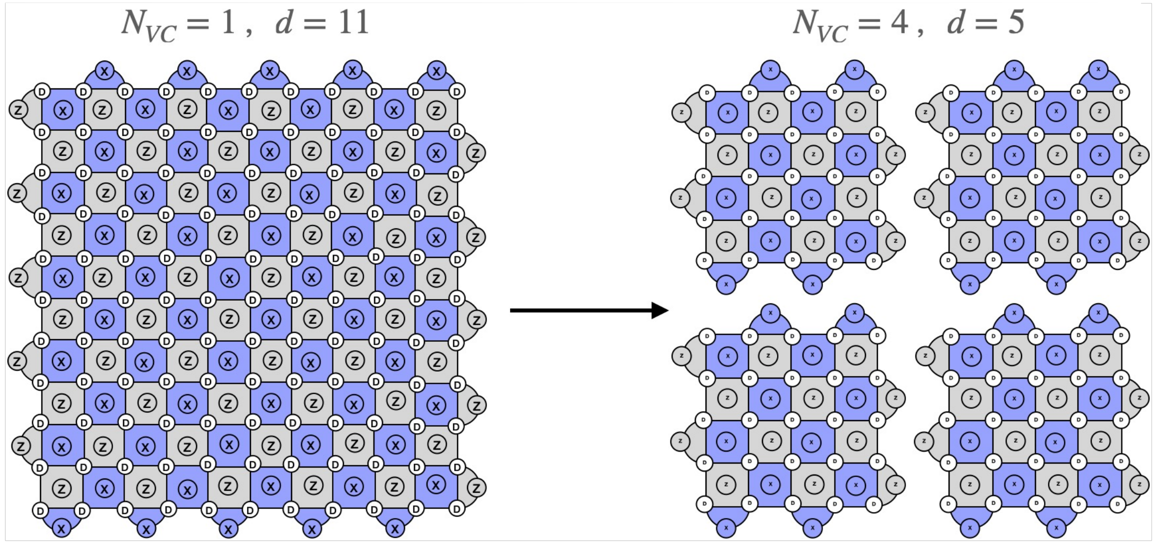
Occurrence of some outputs more correlated to machine goodness!!

More likely to have overlap with the noise-free result

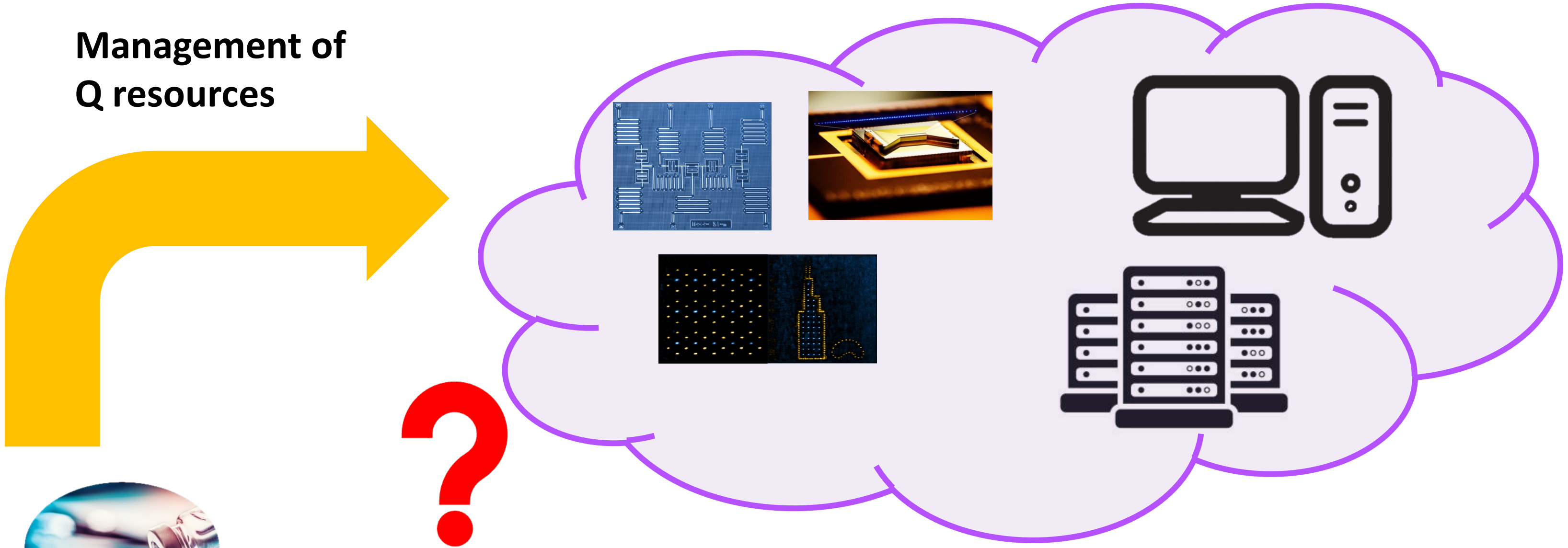
Classical post-processing after Q execution: 2) output interpretation techniques

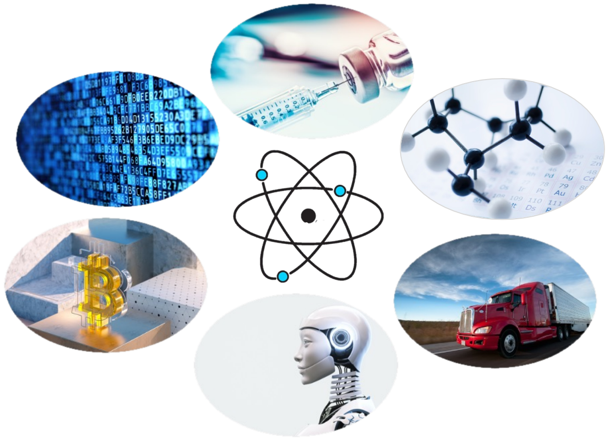
DS-ZNE: Zero noise extrapolation on logical qubits by scaling the error correction code distance





Resource Management for Hybrid and Heterogeneous Systems





Adaptive Job and Resource Management for the Growing Quantum Cloud. QCE 2021.

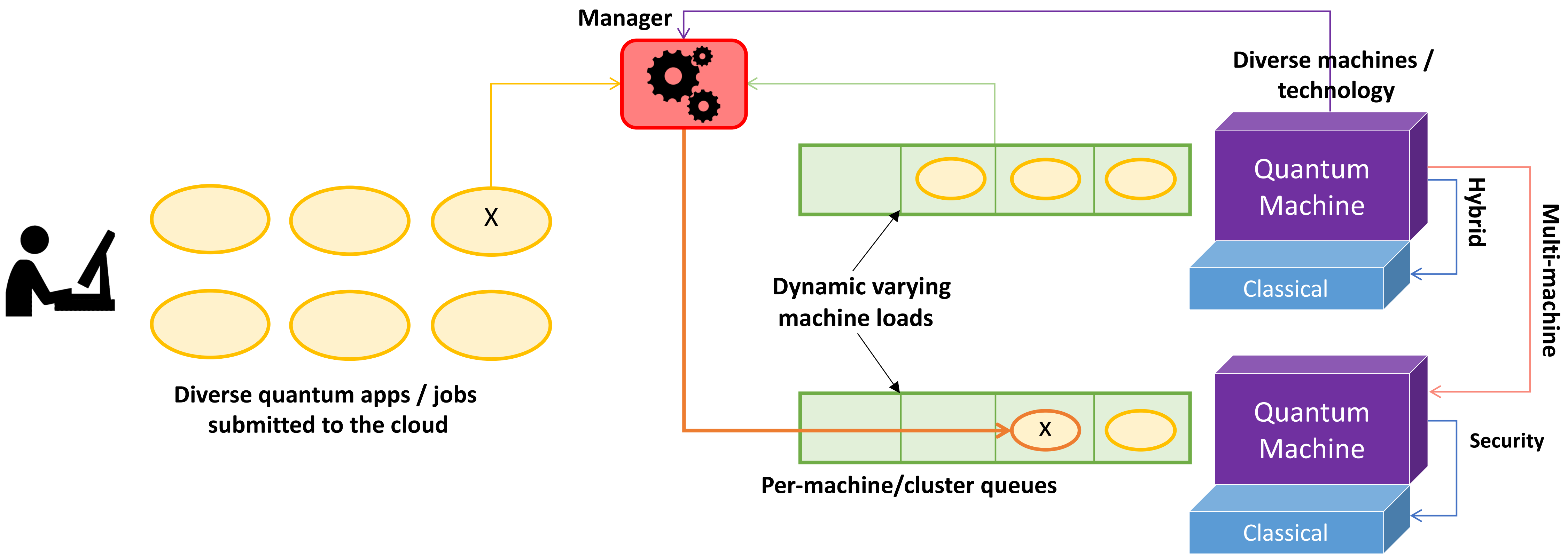
Quantum Computing in the Cloud: Analyzing Job and Machine Characteristics. IISWC 2021.

SupermarQ: A Scalable Quantum Benchmark Suite. HPCA 2022.

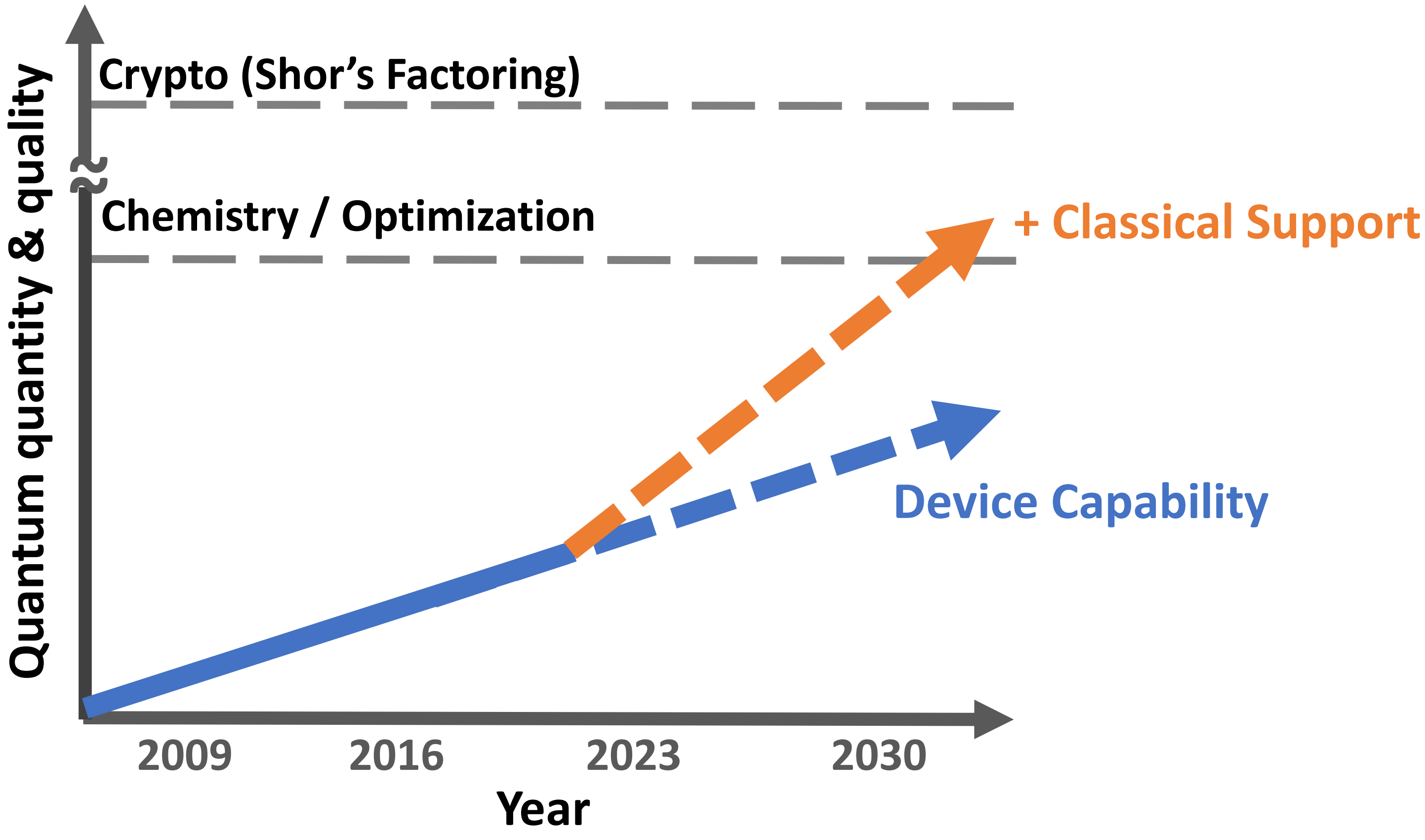
OPTRAN: Choosing an Optimal Pass Set for Quantum Transpilation.

Resource Management for Hybrid and Heterogeneous Systems

Best Q machines for app? Best hybrid systems for app? Throughput vs fidelity? FT + NISQ? QOS guarantees?



Bridging the quantum gap: Hybrid quantum + classical computing approaches



1. PL and Compilation
2. Computer Architecture
3. Feedback-based Optimization
4. High performance computing
5. QEC decoding hw/sw design
6. Classical simulation
7. Multi-chip computing
8. Cloud resource management

Thank you!

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