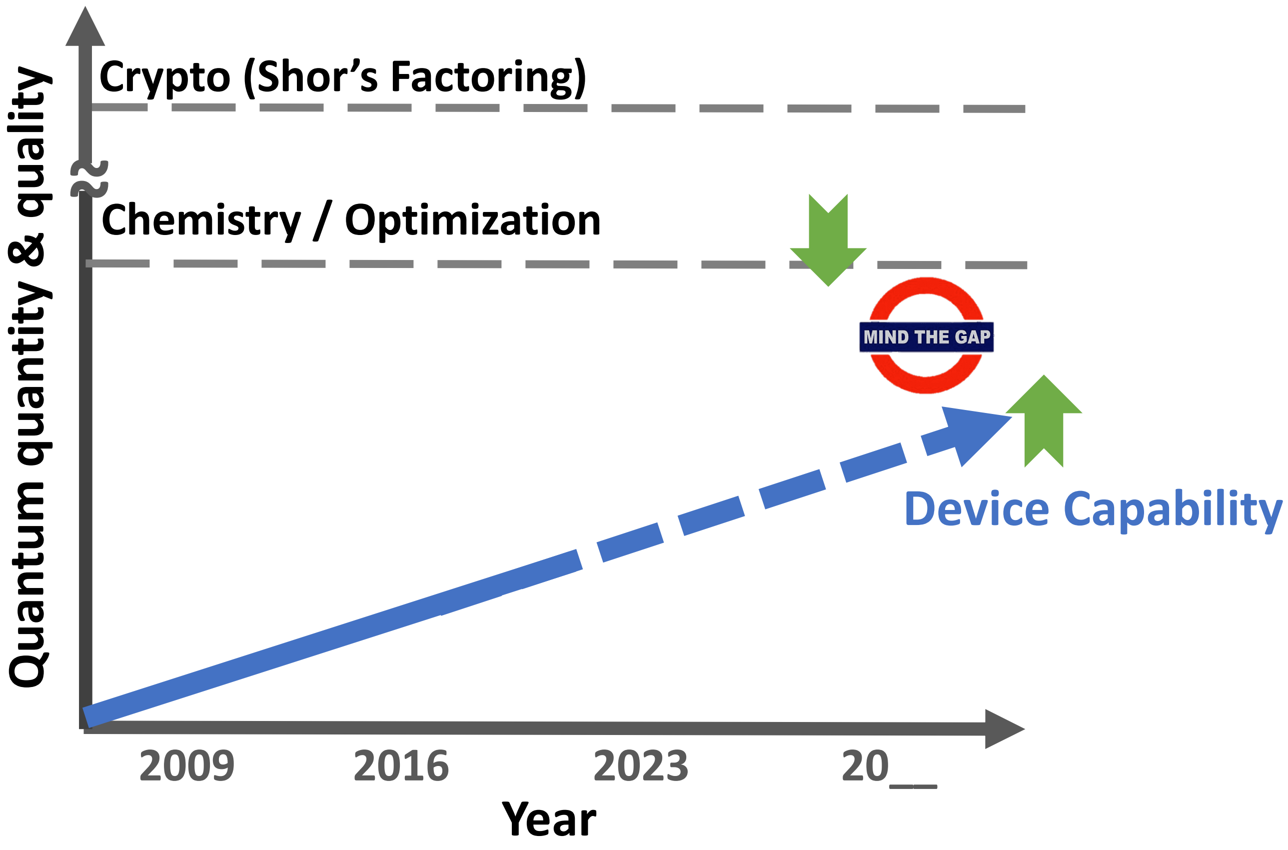
UNIVERSITY OF MICHIGAN

Quantum-Classical Architectures

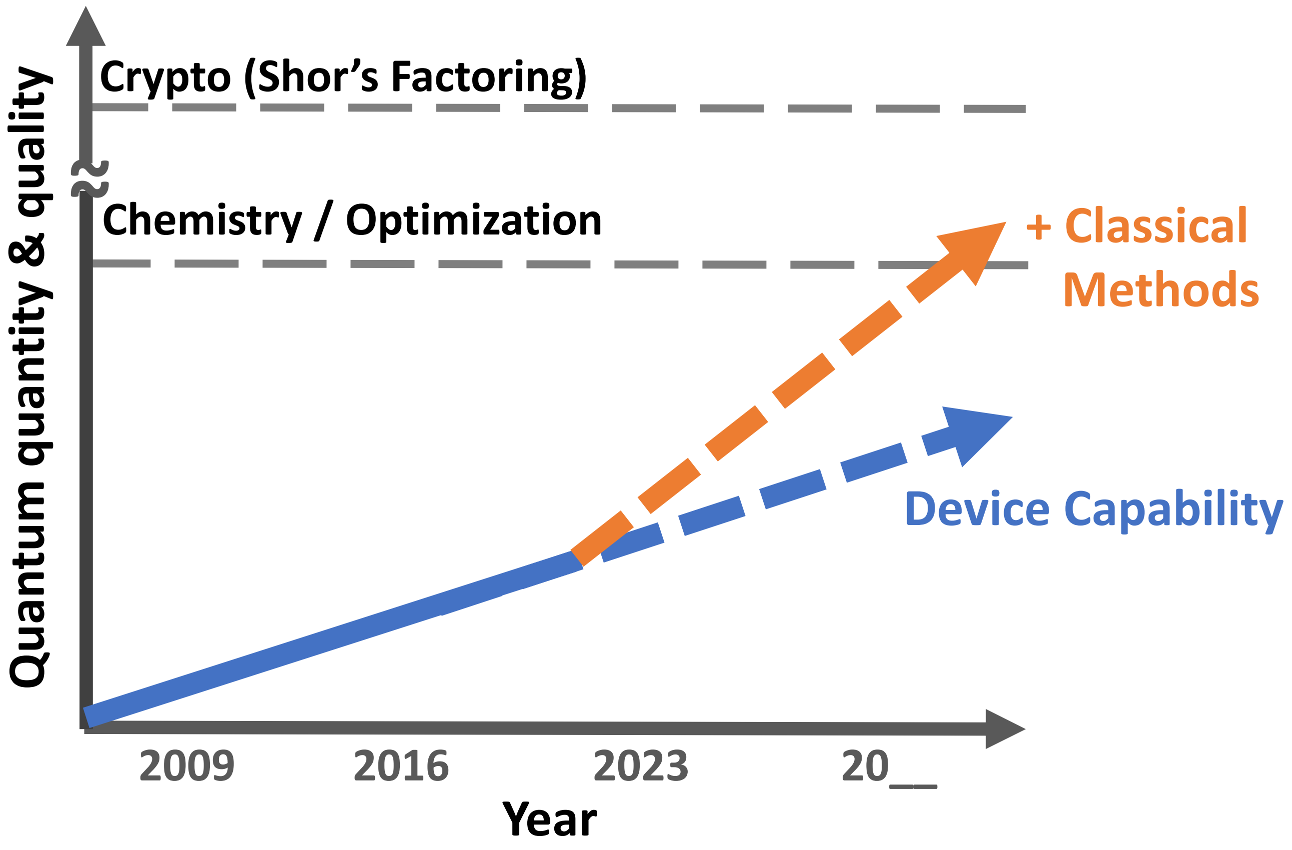
Gokul Subramanian Ravi

Assistant Professor, University of Michigan

Wide gap between application requirements and technology capability



Bridging the gap: Hybrid quantum-classical computing approaches



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

Quantum-classical research directions

Pre-processing | **Quantum Compute** | **Post-processing**

Co-processing

Quantum-classical research directions

Pre-processing

Quantum Compute

Post-processing

Co-processing

Pre-processing

Software:
- Compilation
- State preparation
- Transformation

Hardware:
- Pulse-optimization
- Qubit control

Co-processing

Software:
- Managing hybrid algorithms

Hardware:
- QEC decoding
- QC interface

Post-processing

Software:
- Ensemble methods
- Statistical techniques

Hardware:
- Readout optimization

Software == Coarse granularity?
Hardware == Fine granularity?

Quantum-classical research directions

Pre-processing

Quantum Compute

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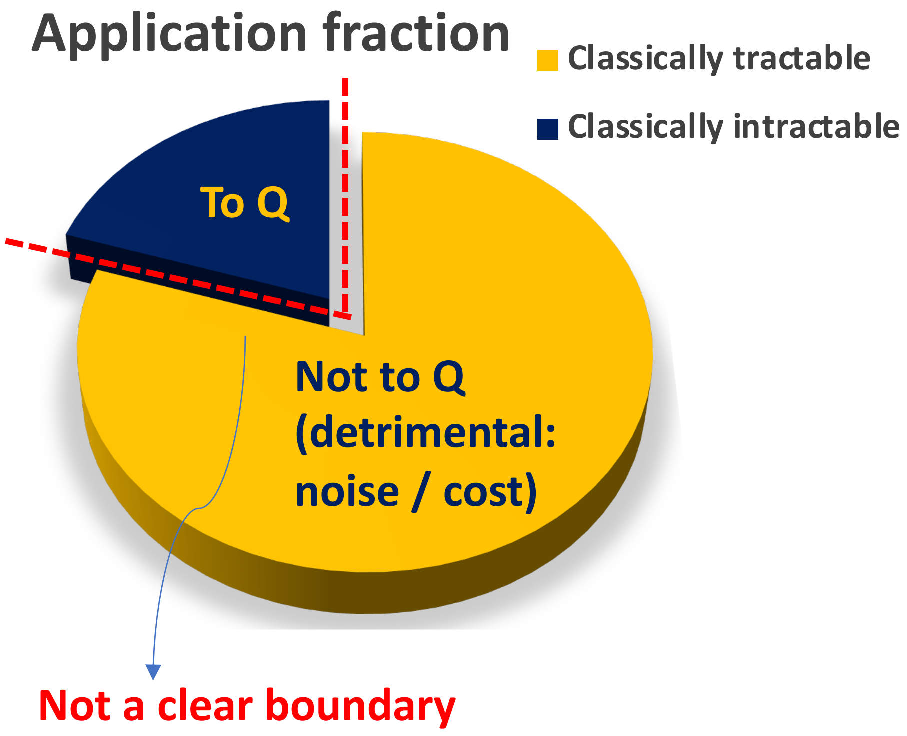
Classical state preparation / initialization



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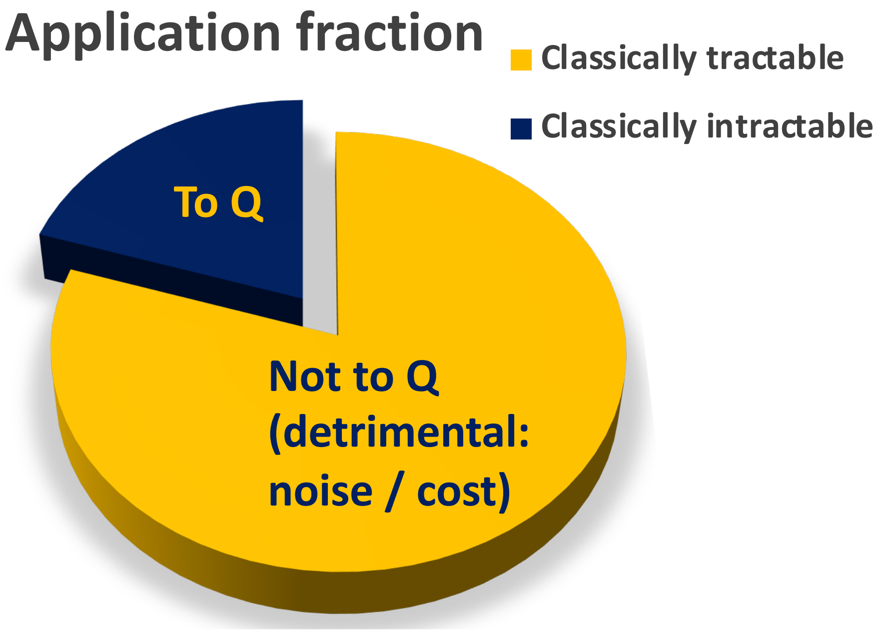
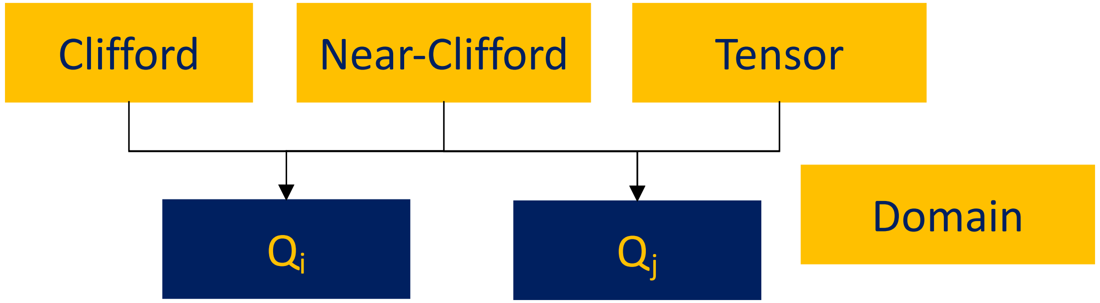


Given a classical compute budget, maximize application-tailored processing to reduce the computational load on the quantum device.

- **Clifford simulation**: scales polynomially, low overheads, 1000s of qubits in seconds, can be run on a laptop, but limited capability.
- **Near-Clifford simulation**: cost and capability both scale exponentially in proportion to *non-cliffordness, might require HPC.*
- **Tensor networks**: cost and capability both scale exponentially in proportion to *entanglement*
- **Domain-specific insights and tools**



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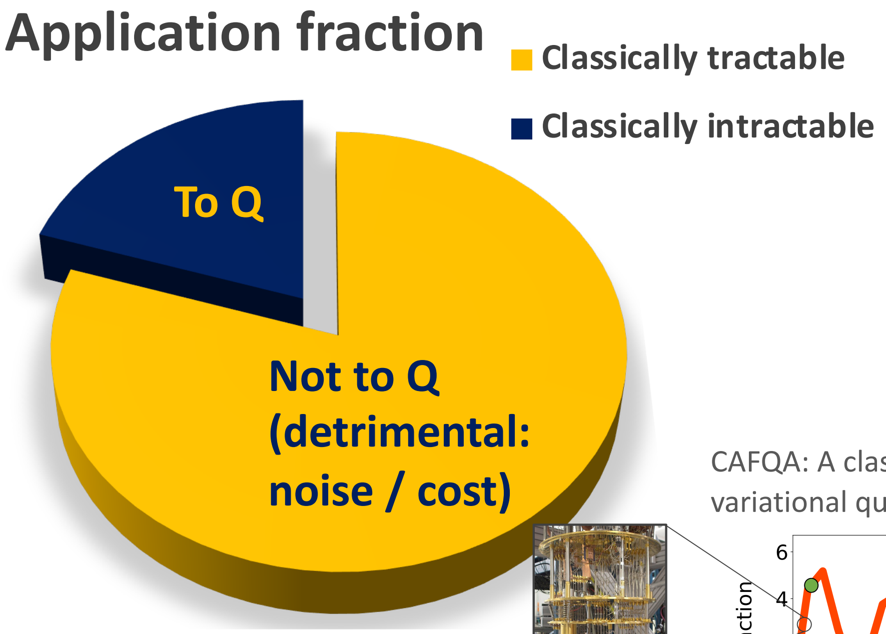

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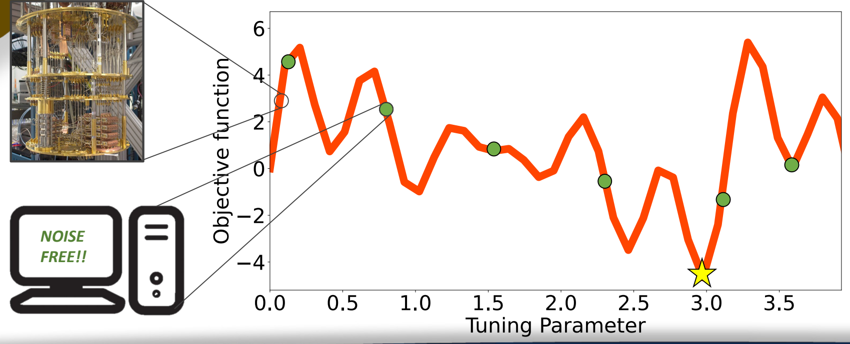
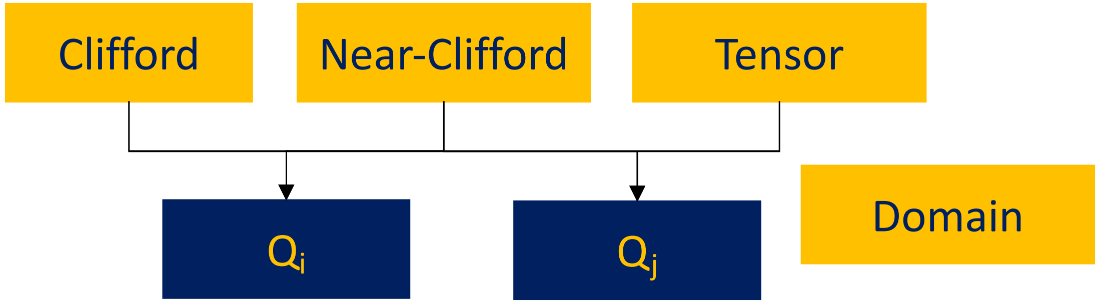
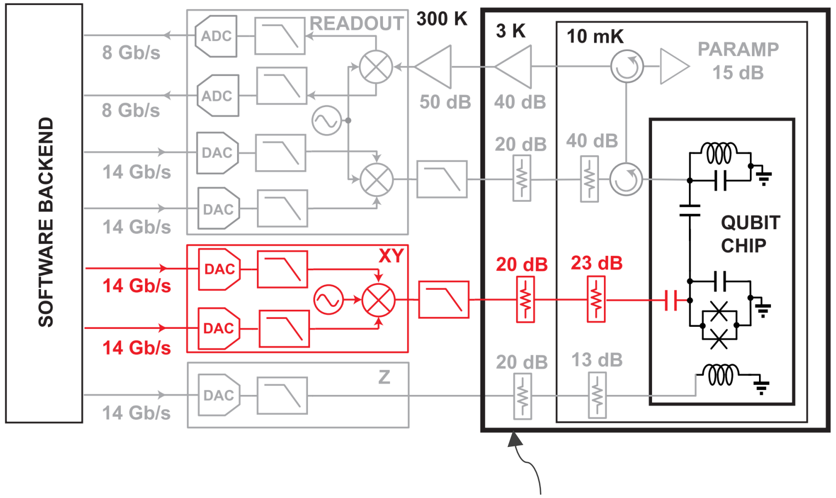
CAFQA: A classical simulation bootstrap for variational quantum algorithms. ASPLOS 2023





Qubit control



Design and Characterization of a 28-nm Bulk-CMOS Cryogenic Quantum Controller Dissipating Less Than 2 mW at 3 K (Google). 2019

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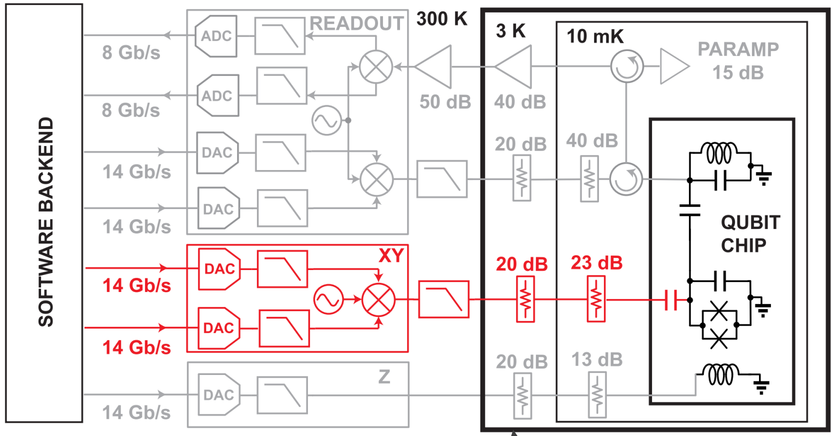

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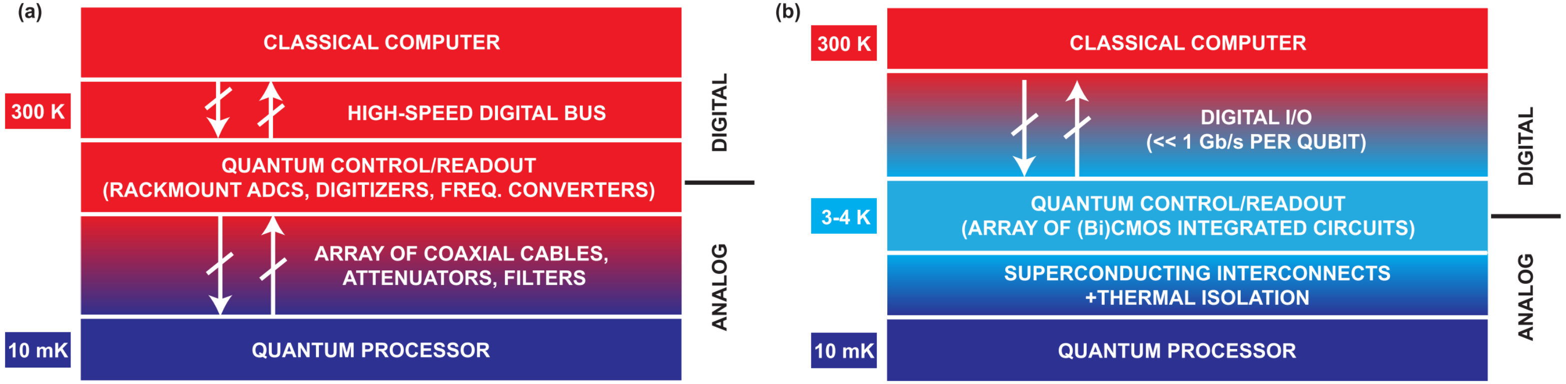
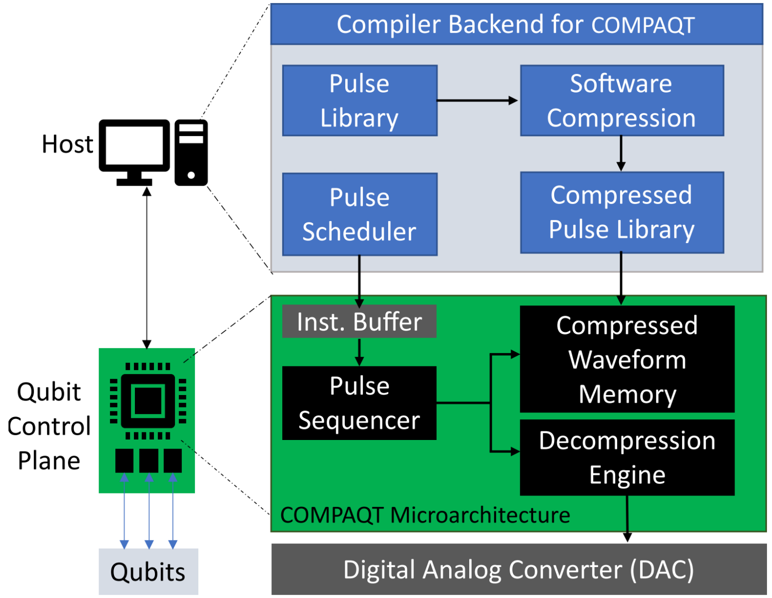
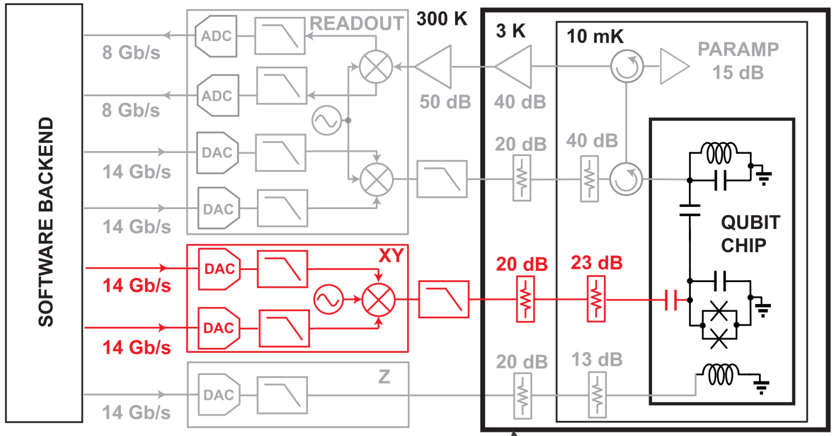


Qubit control

COMPAQT: Compressed Waveform Memory Architecture for Scalable Qubit Control. MICRO 2022





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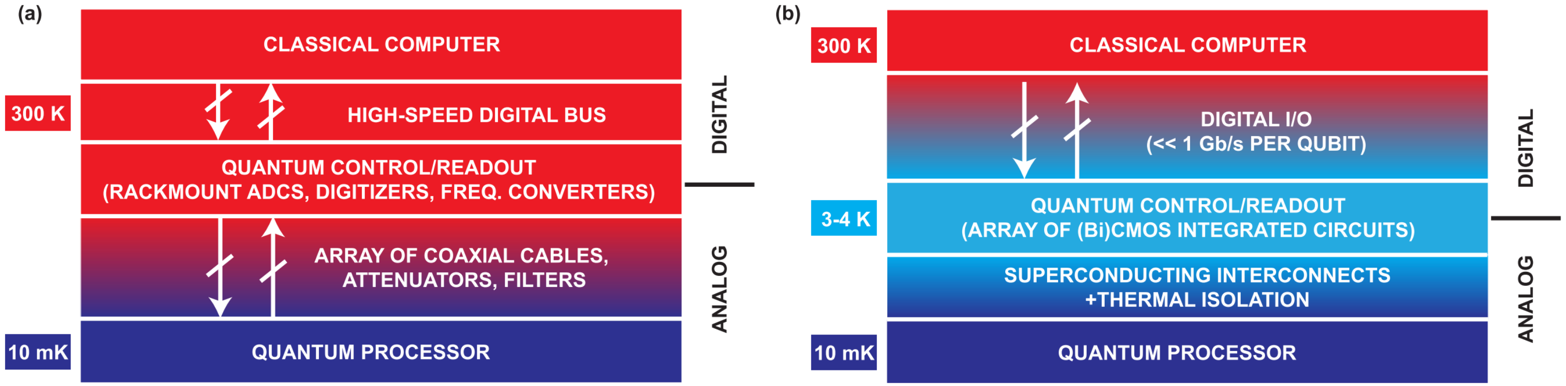

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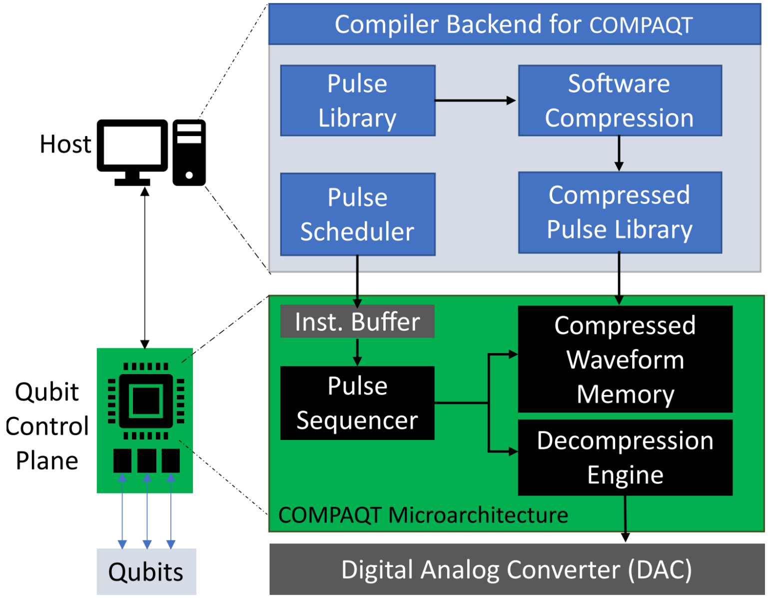

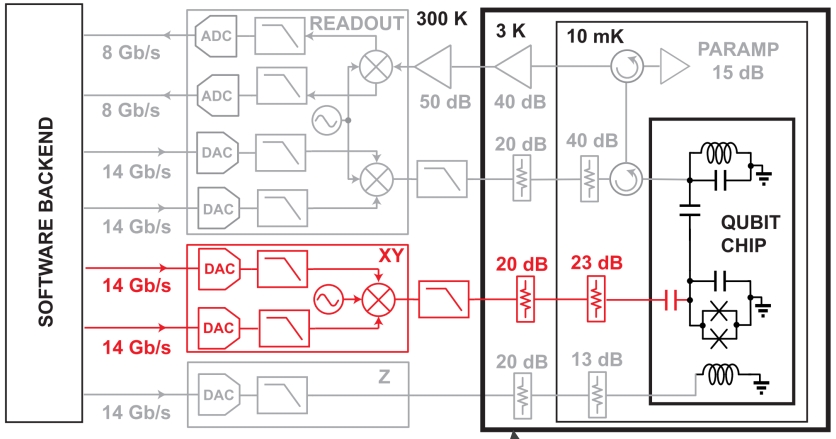

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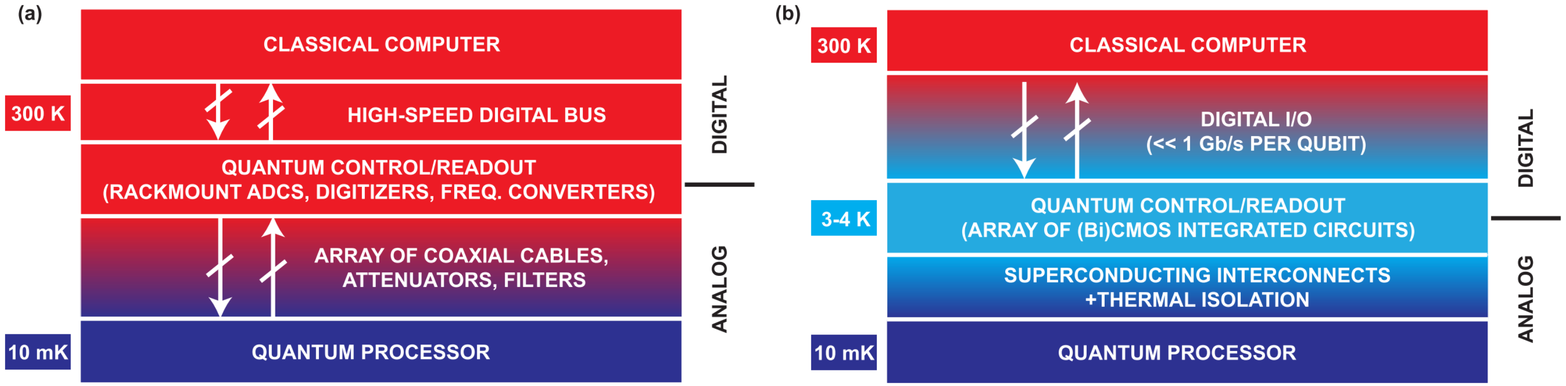
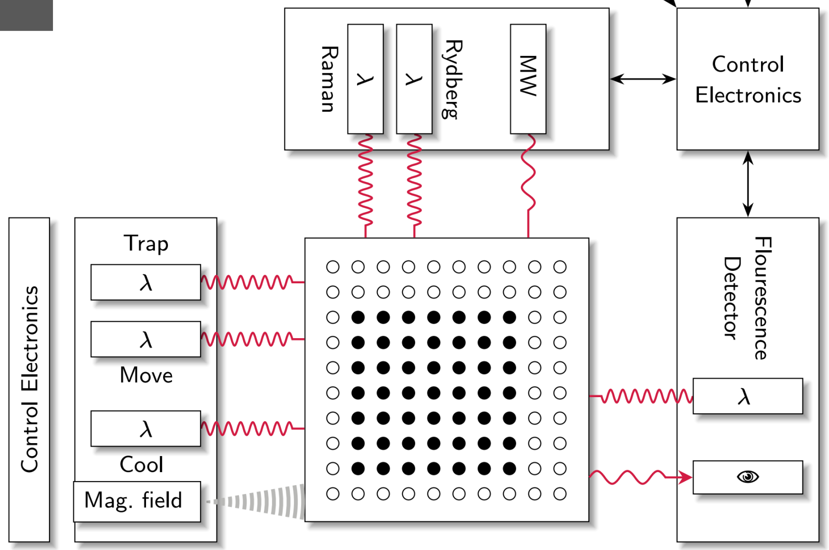


Neutral Atom Quantum Computing Hardware: Performance and End-User Perspective. 2023



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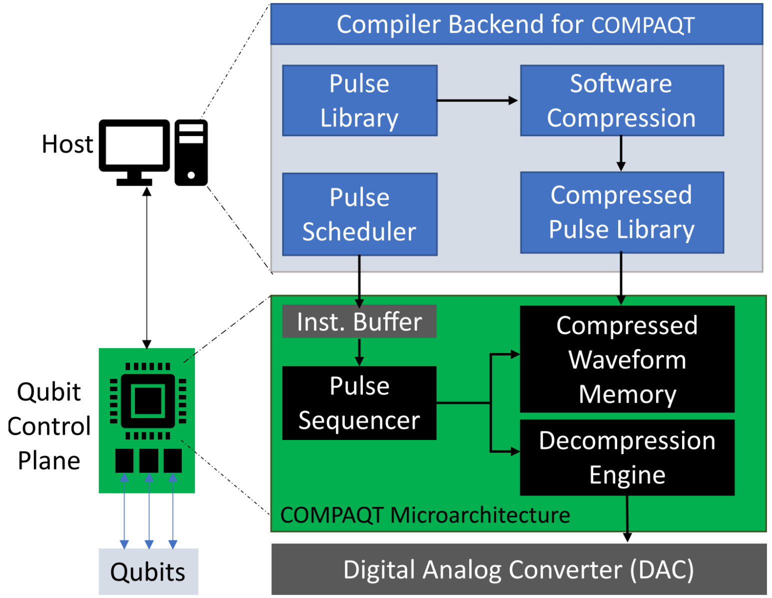
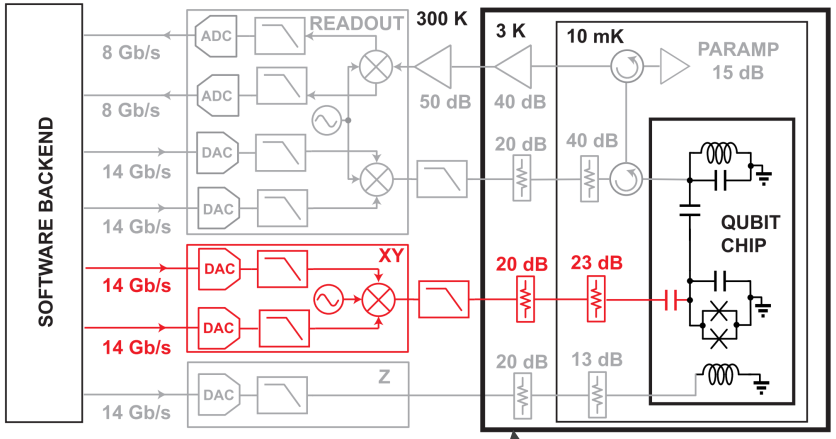


Software and hardware methods to reduce control overheads as we scale to millions of qubits.



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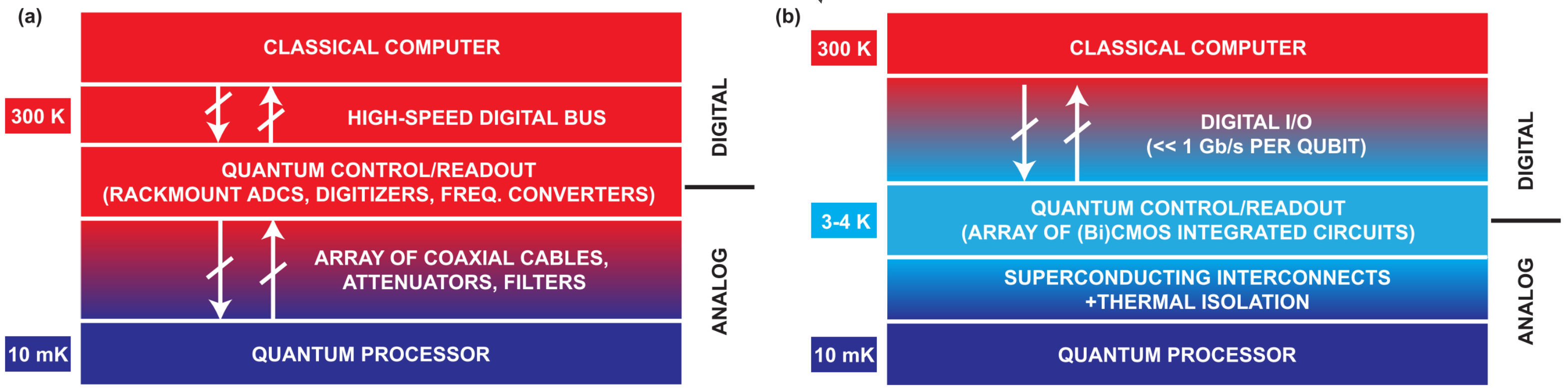

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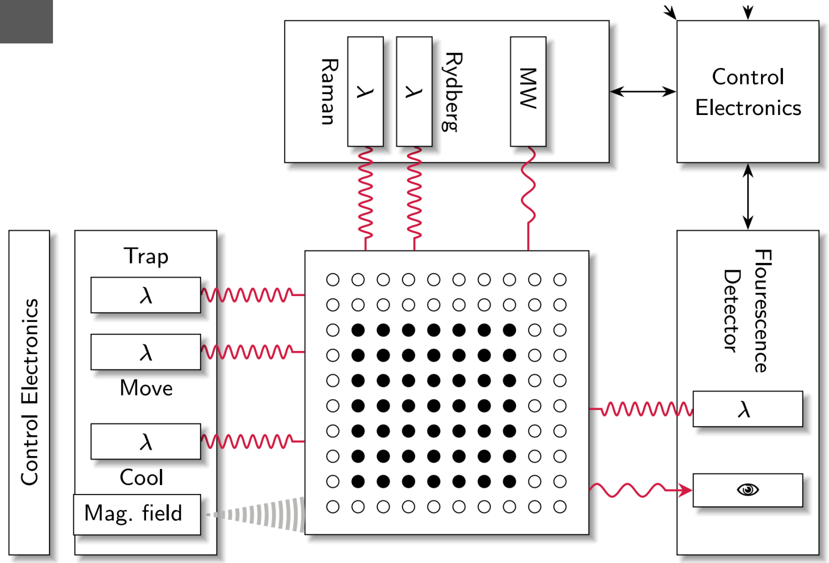


Quantum-classical research directions

Quantum Compute

Co-processing

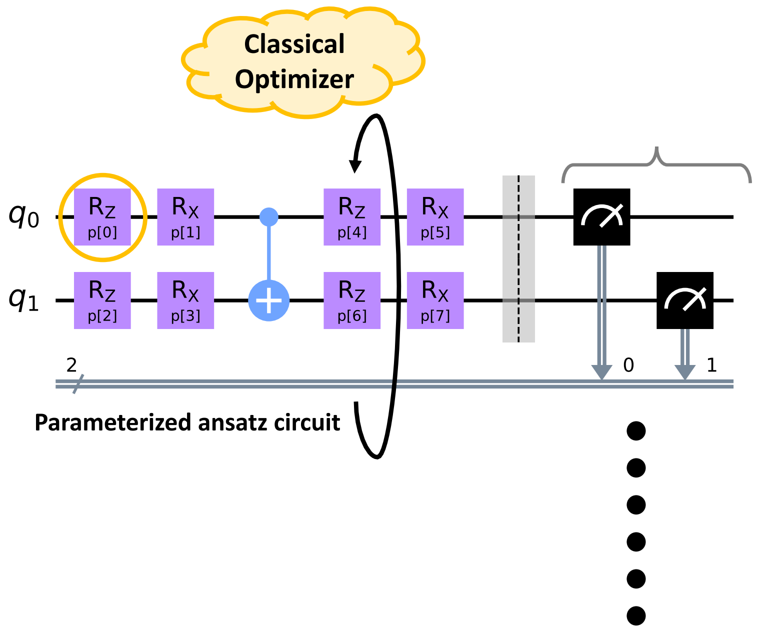
Software:

- ➢ Managing hybrid algorithms

Hardware:

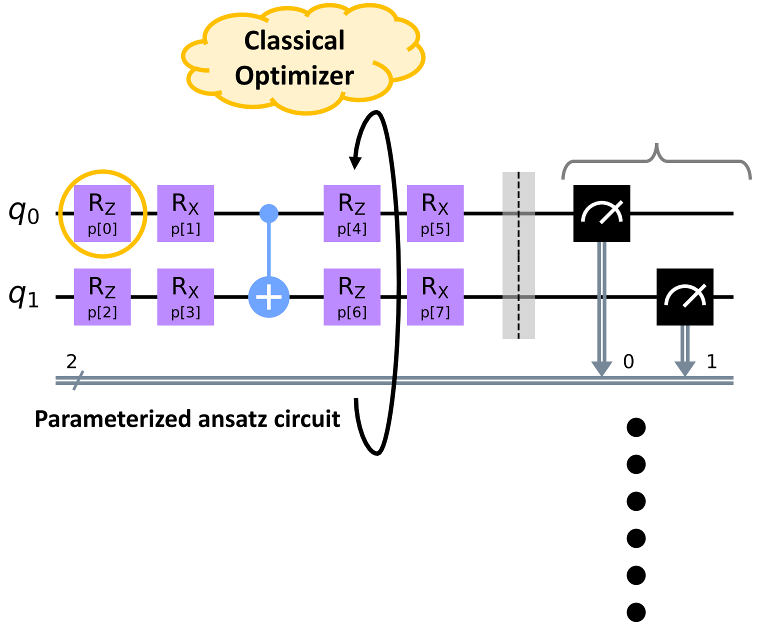
- ➢ QEC decoding
- ➢ QC interface

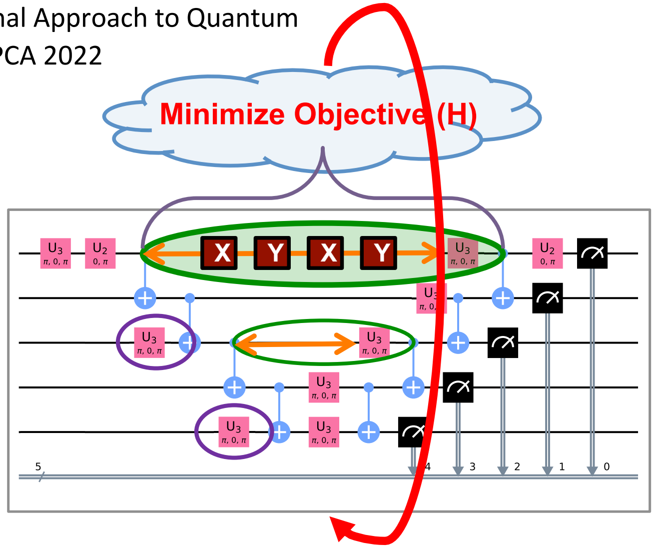
Managing hybrid quantum algorithms



Managing hybrid quantum algorithms

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





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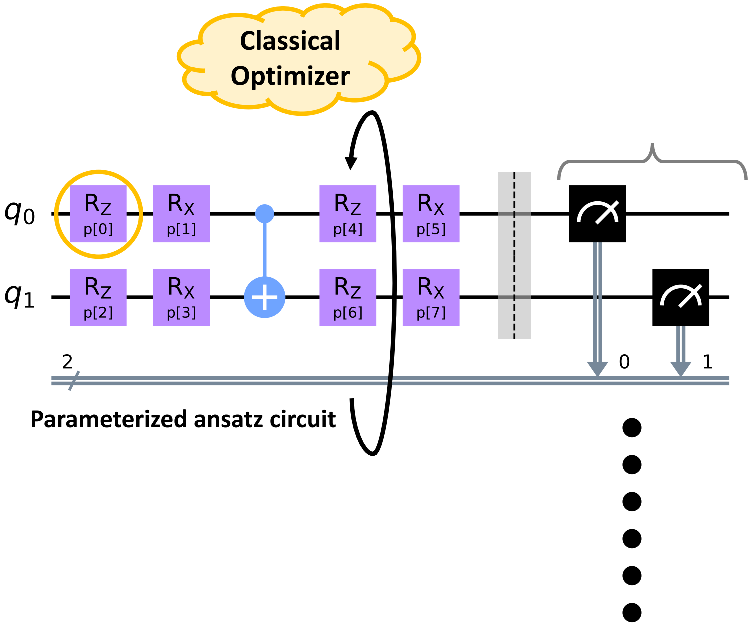
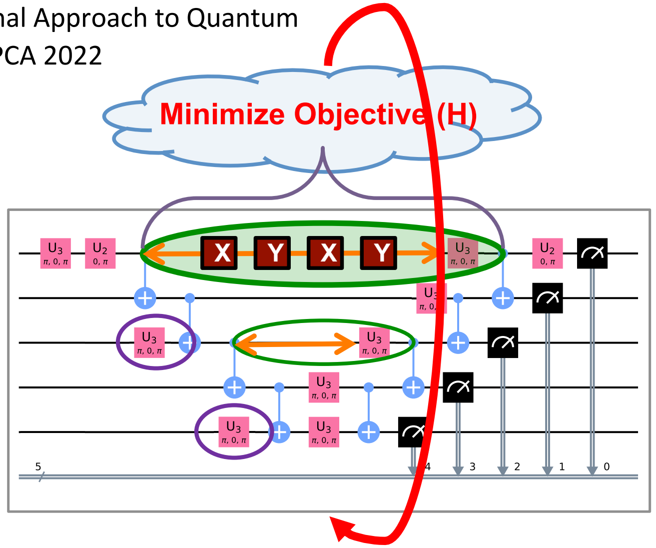
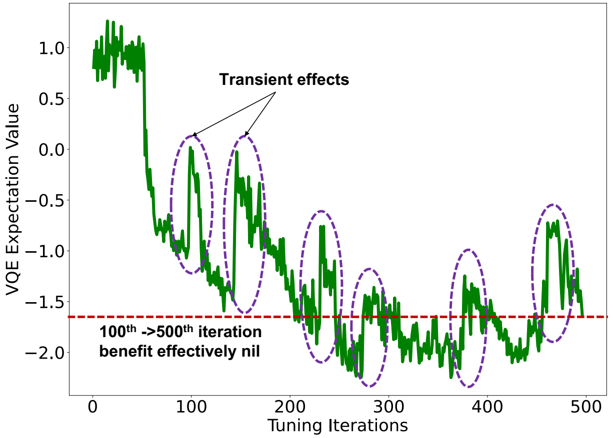
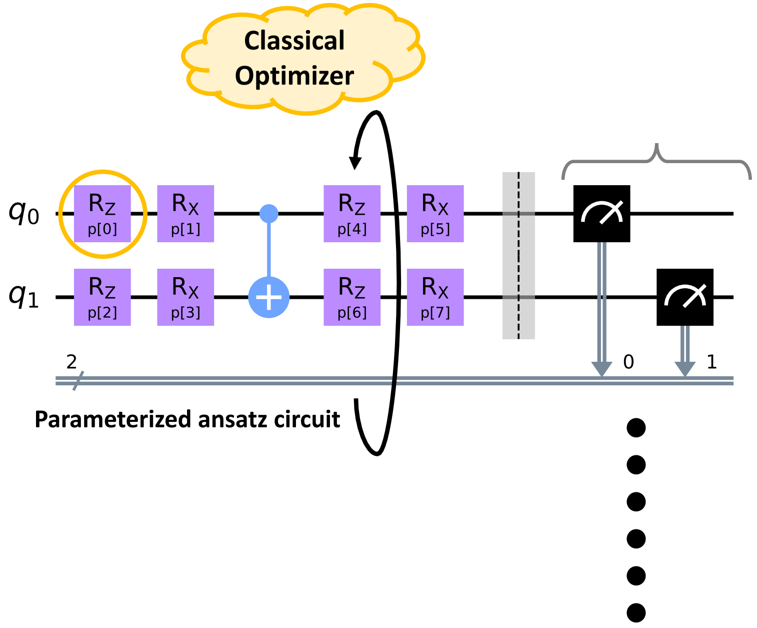






Navigating the Dynamic Noise Landscape of Variational Algorithms with QISMET. ASPLOS 2023

Managing hybrid quantum algorithms



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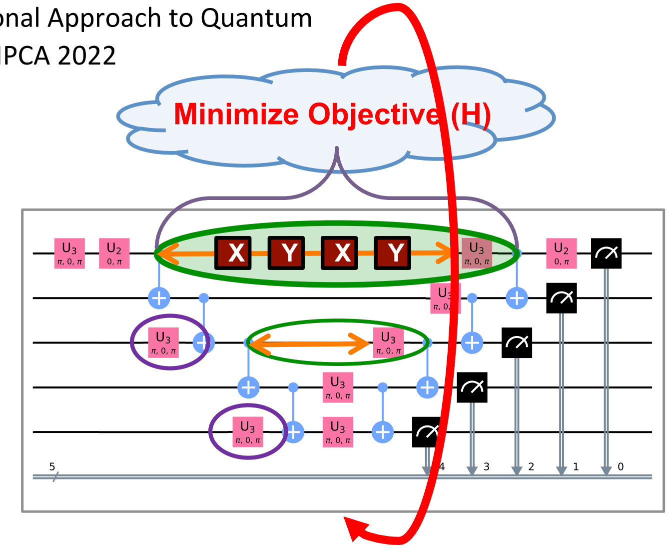
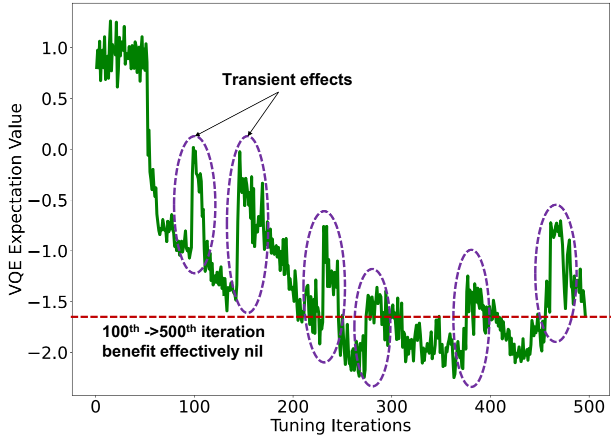
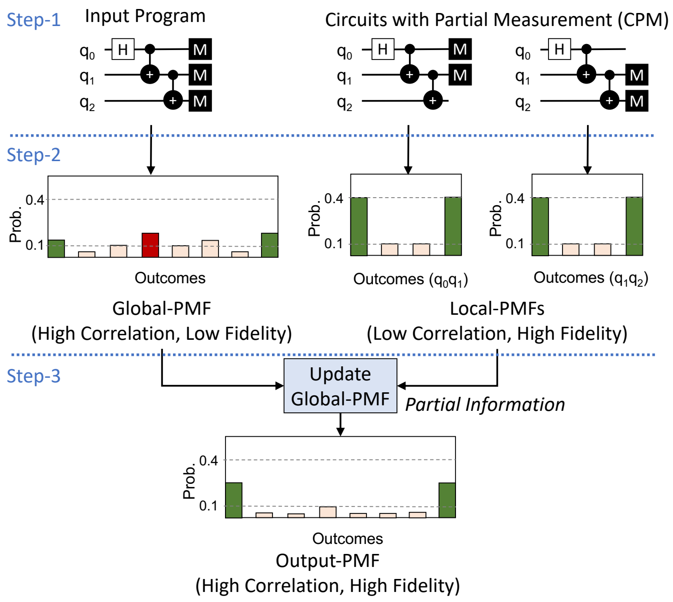


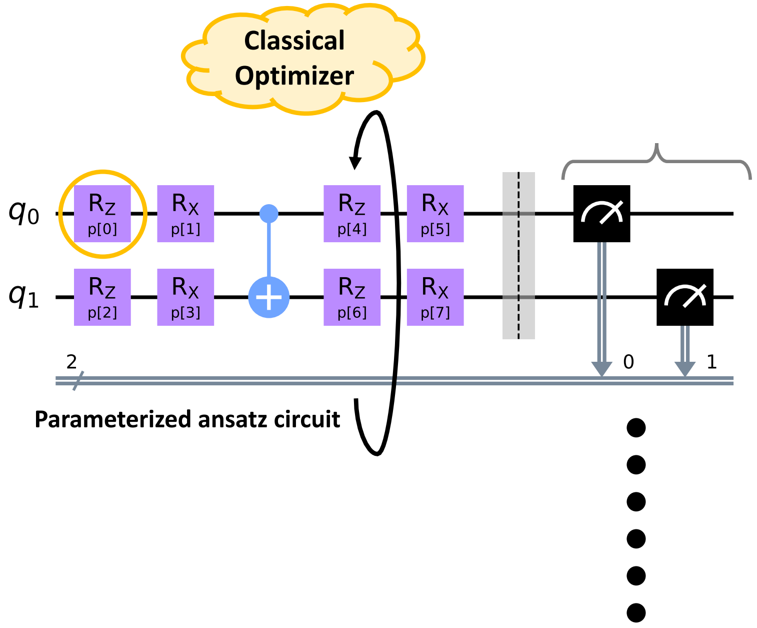


Navigating the Dynamic Noise Landscape of Variational Algorithms with QISMET. ASPLOS 2023

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



Managing hybrid quantum algorithms



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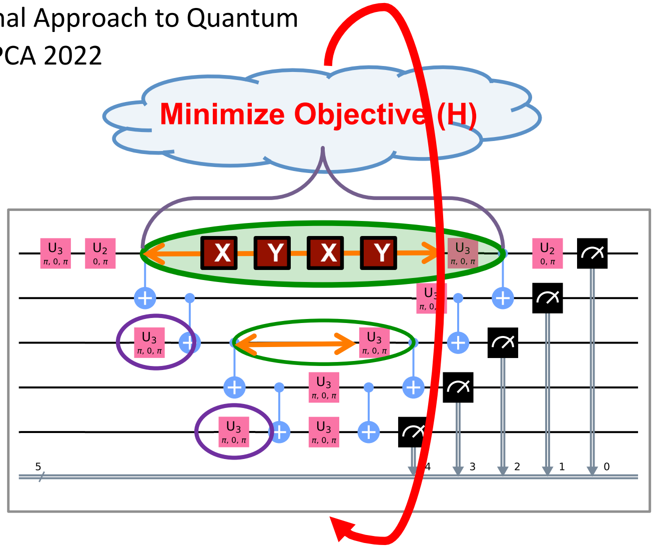

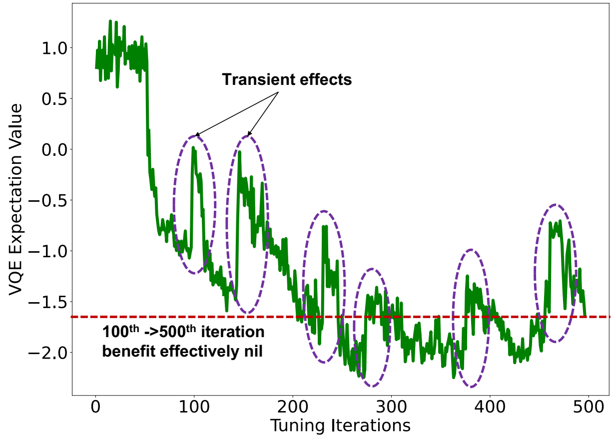

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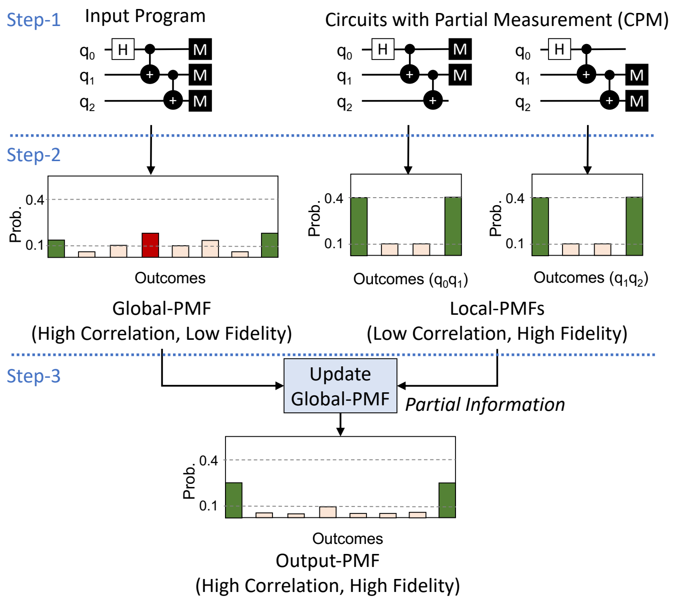
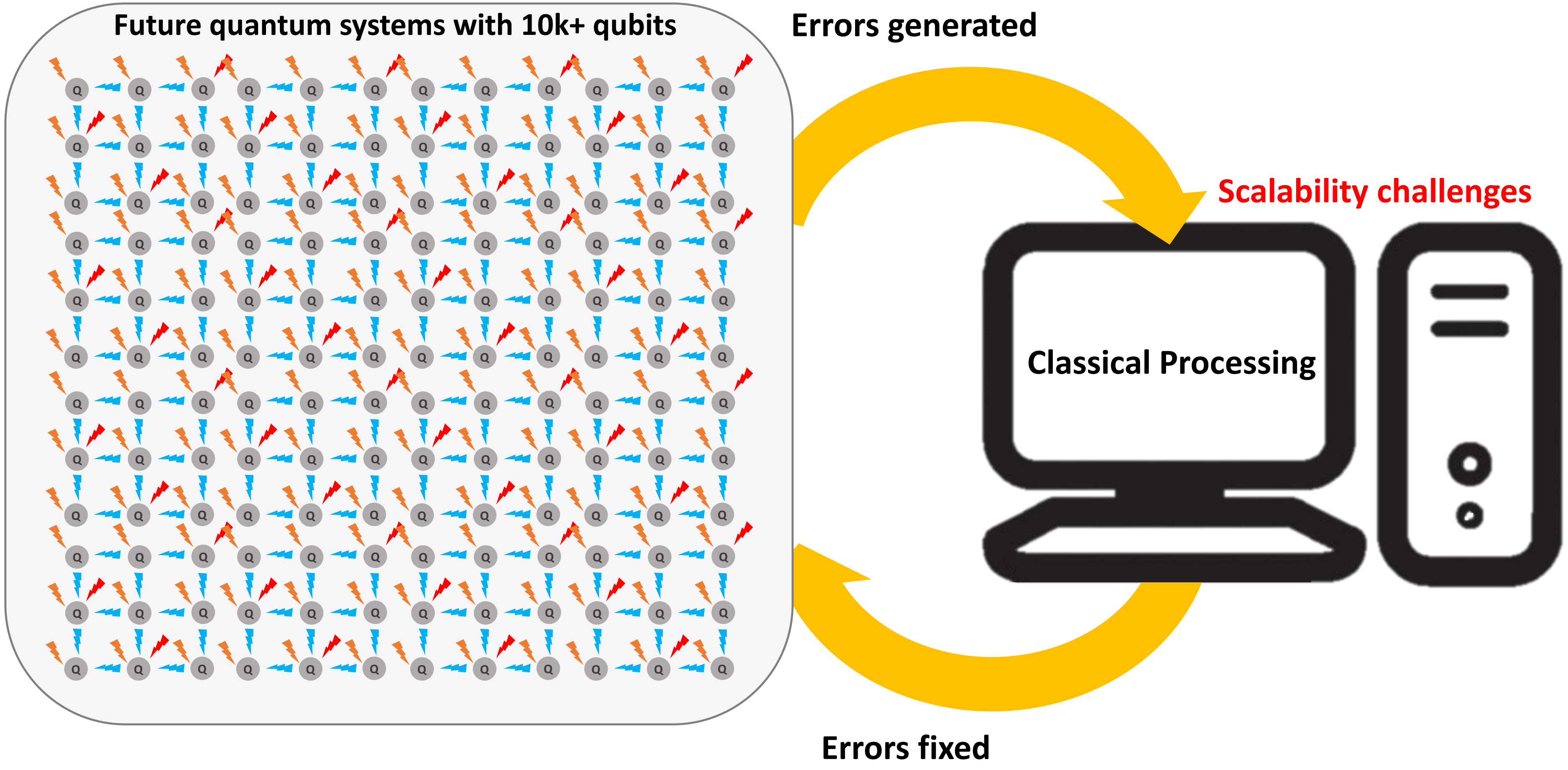


Increased tuning parameters and additional features makes optimizer and related classical processing efficiency critical. Non-trivial HW/SW resources.

Decoding for quantum error correction



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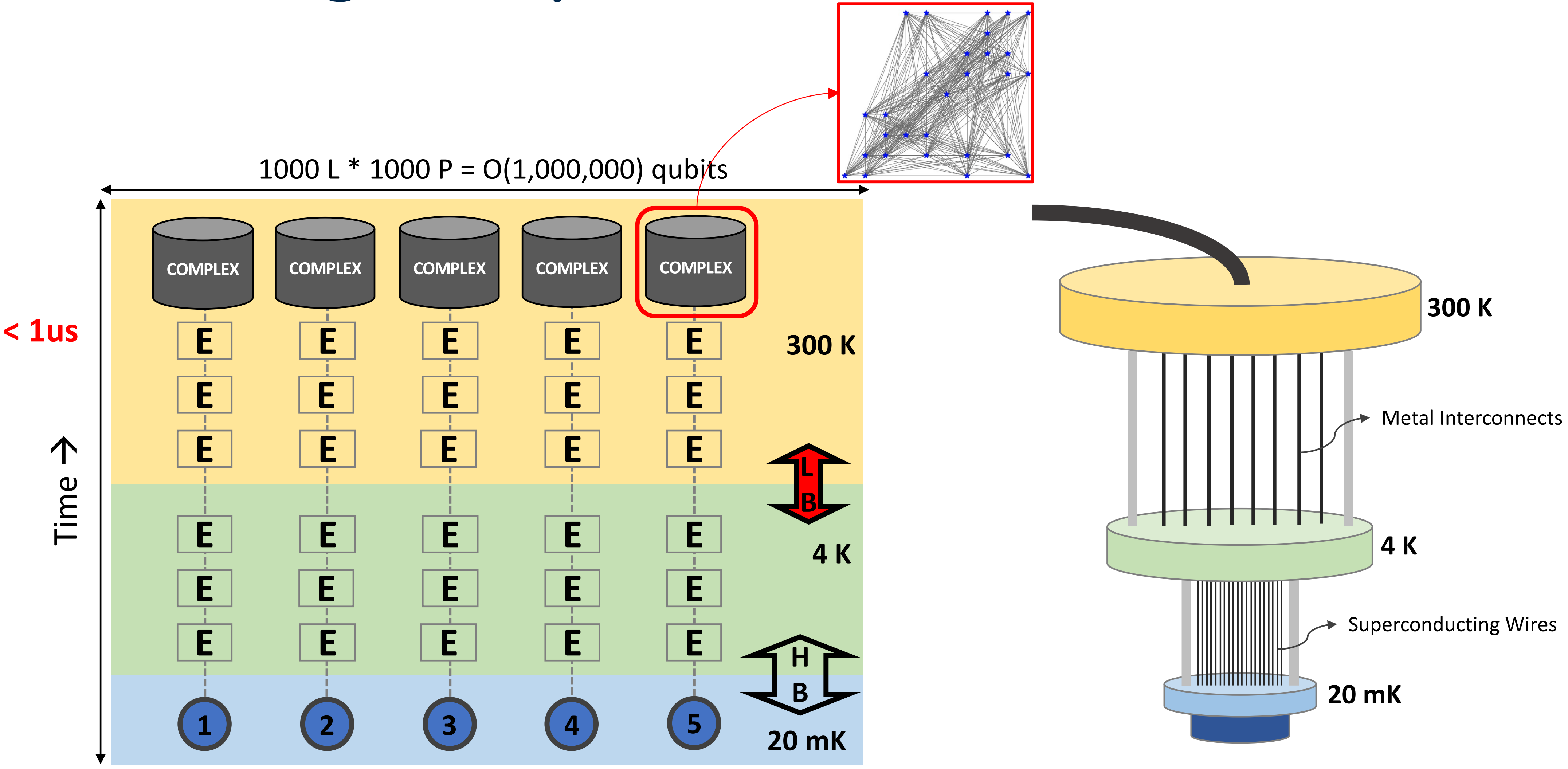
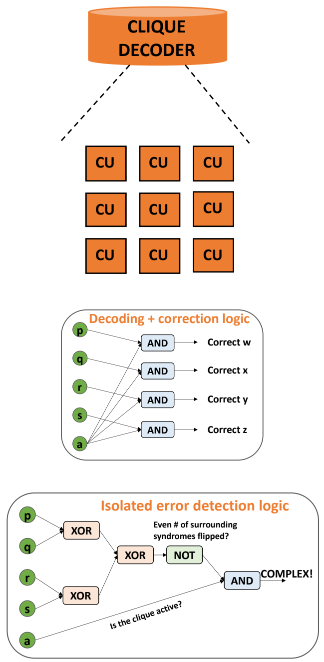
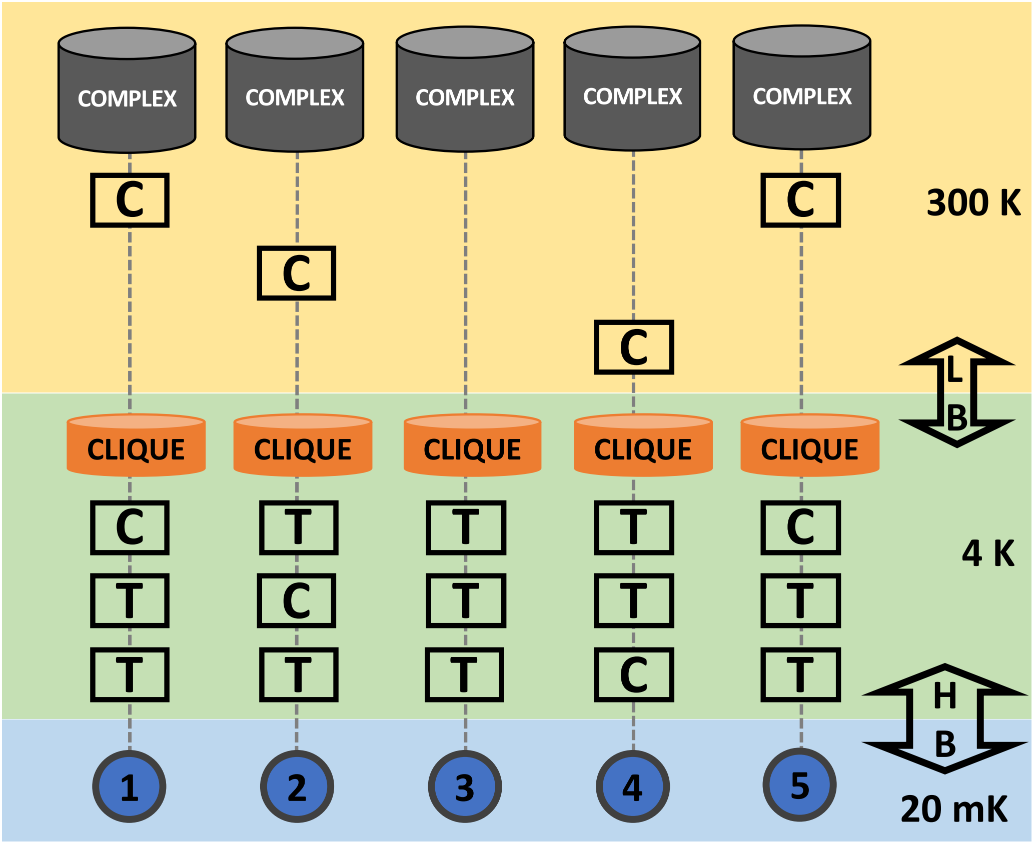
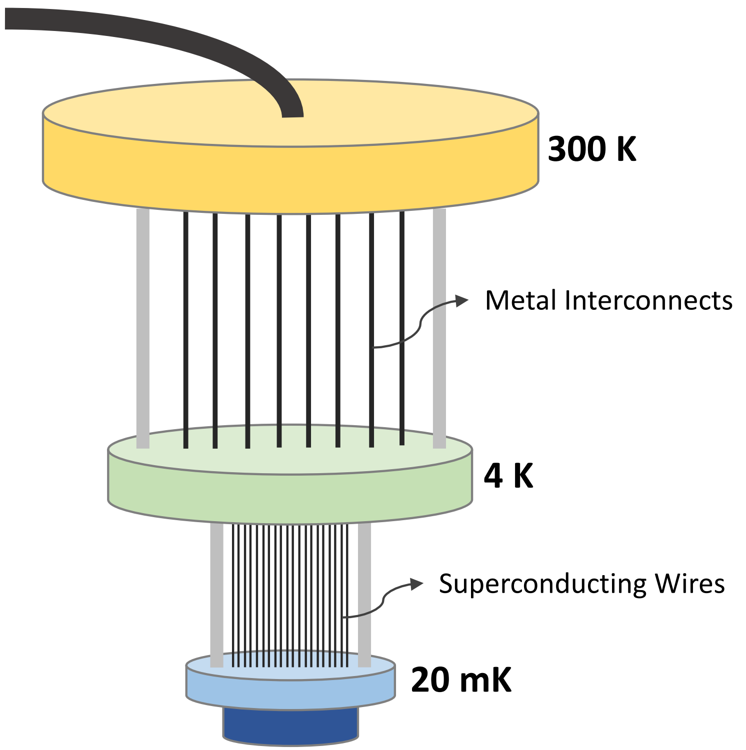


Decoding for quantum error correction



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





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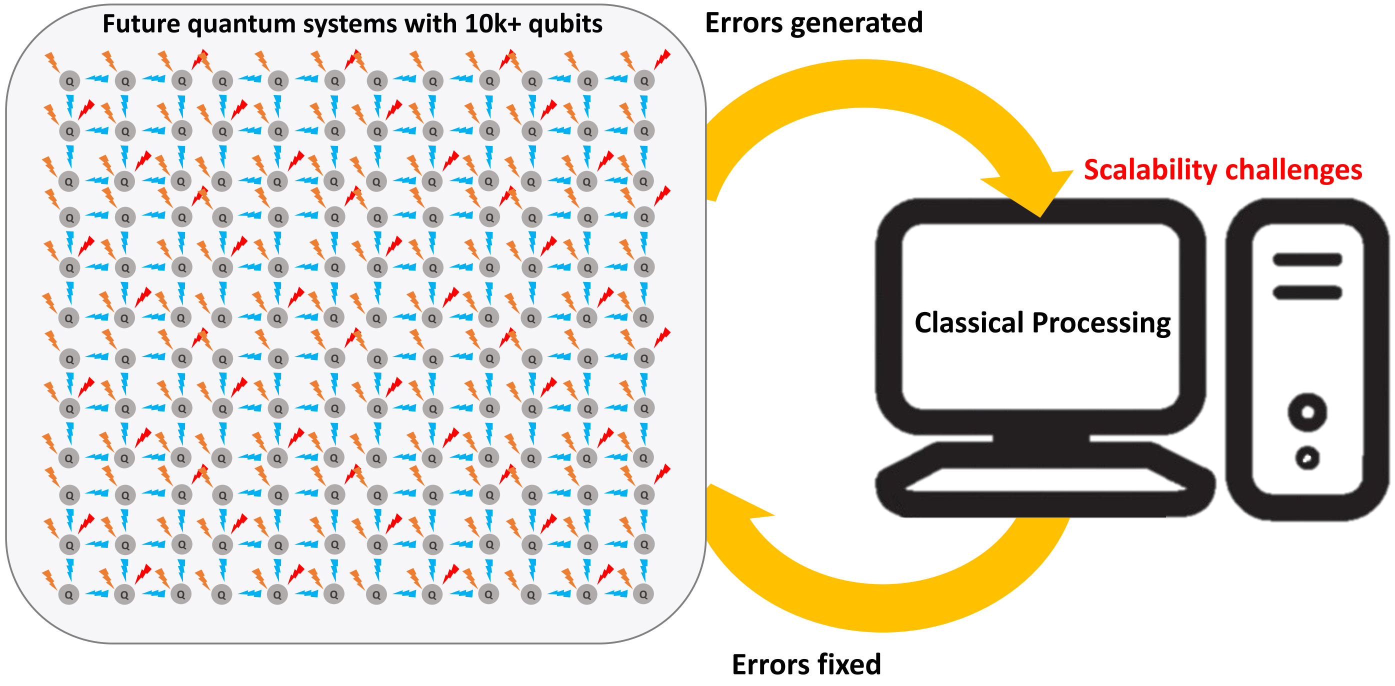


Opportunities:

- *Efficient decoders for exotic codes.*
- *Latency reduction in decoding.*
- *Bandwidth reduction at quantum-classical interface.*
- *ASICs/HPC/GPUs?*

Quantum-classical research directions

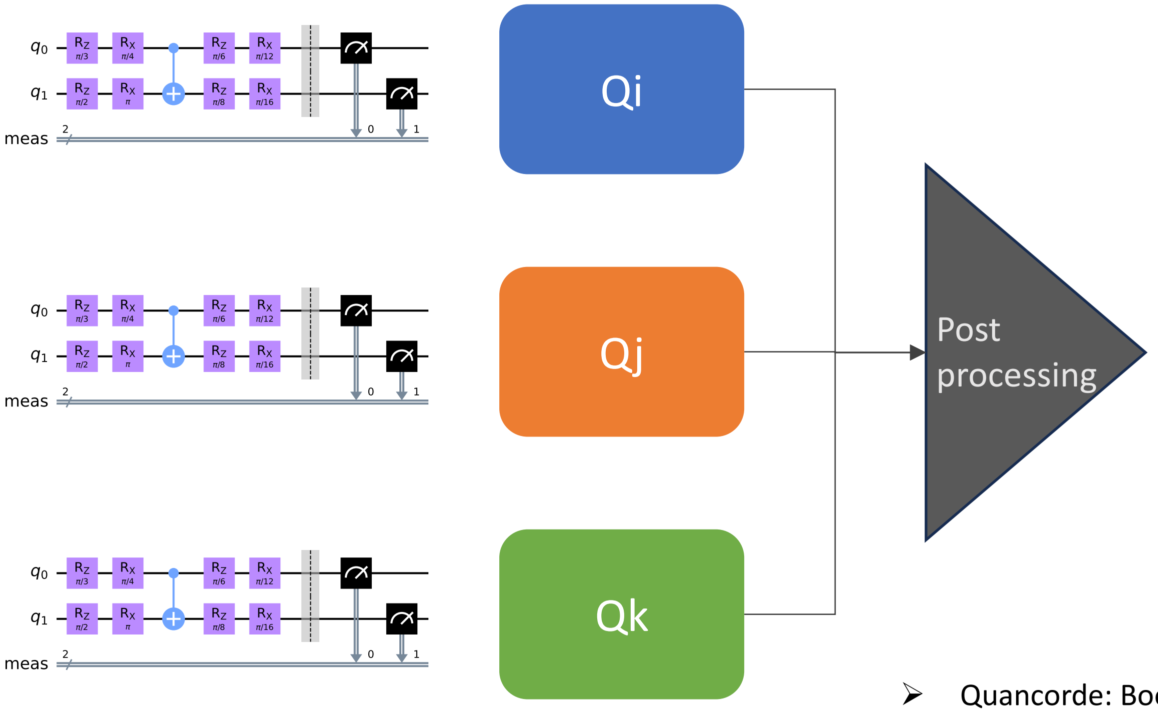
Quantum Compute

Post-processing

Software:
- Ensemble methods
- Statistical techniques

Hardware:
- Readout optimization

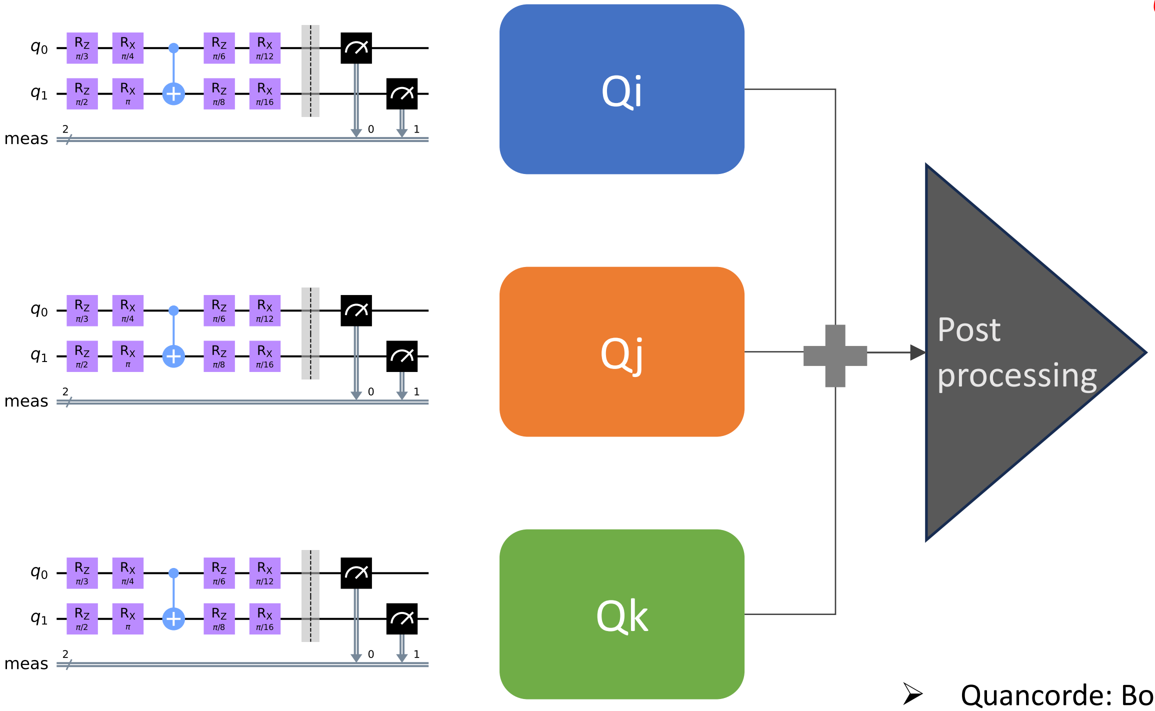
Resource ensemble methods



Boosting fidelity / functionality beyond the capability of any single device.

- ➢ Quancorde: Boosting fidelity with Quantum Canary Ordered Diverse Ensembles. ICRC 2023.
- ➢ EQC : Ensembled Quantum Computing for Variational Quantum Algorithms. ISCA 2022.
- ➢ CutQC: Using Small Quantum Computers for Large Quantum Circuit Evaluations. ASPLOS 2021.
- ➢ Ensemble of Diverse Mappings. MICRO 2019.
- ➢ Zero noise extrapolation (many papers).
- ➢ Probabilistic error cancellation. Nature Physics 2023.

Resource ensemble methods



Opportunities:

- *Reducing classical post-processing overheads.*
- *Reducing quantum execution overheads.*
- *(Classically simulable) noise modeling.*
- *Full-stack resource management framework to manage ensemble methods.*

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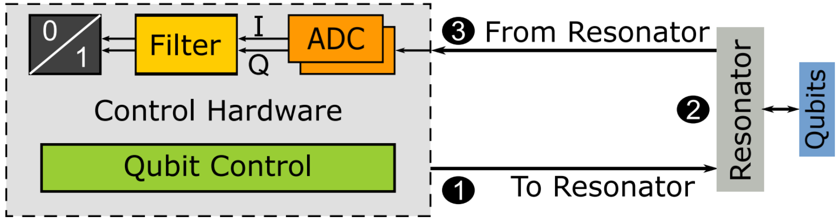
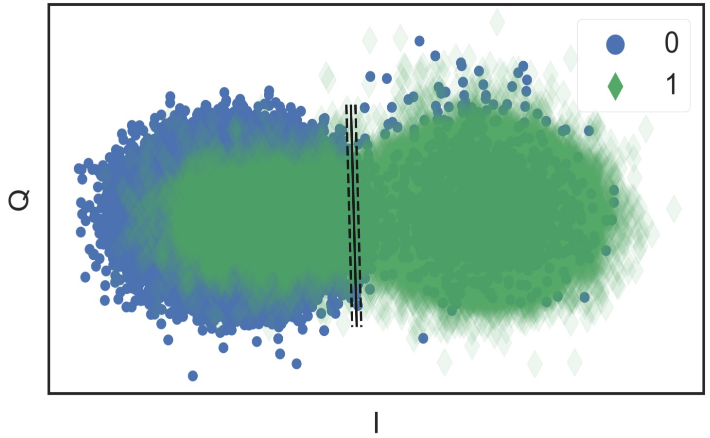
Readout optimization

Scaling Qubit Readout with Hardware Efficient
Machine Learning Architectures. ISCA 2023





Readout optimization

Deep Neural Network Discrimination of Multiplexed Superconducting Qubit States. 2022.

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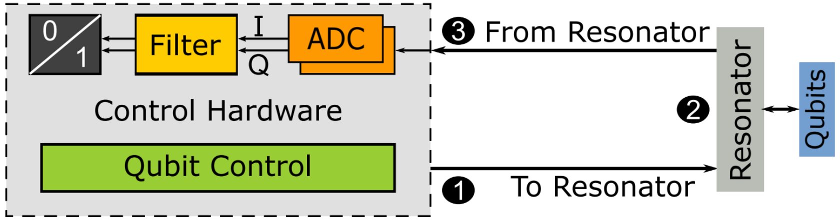

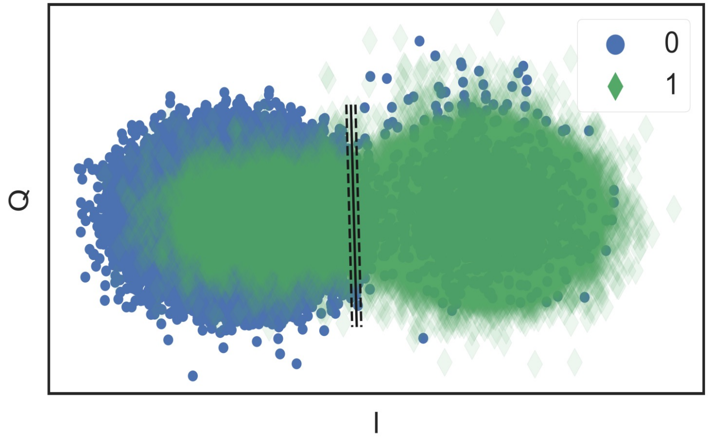

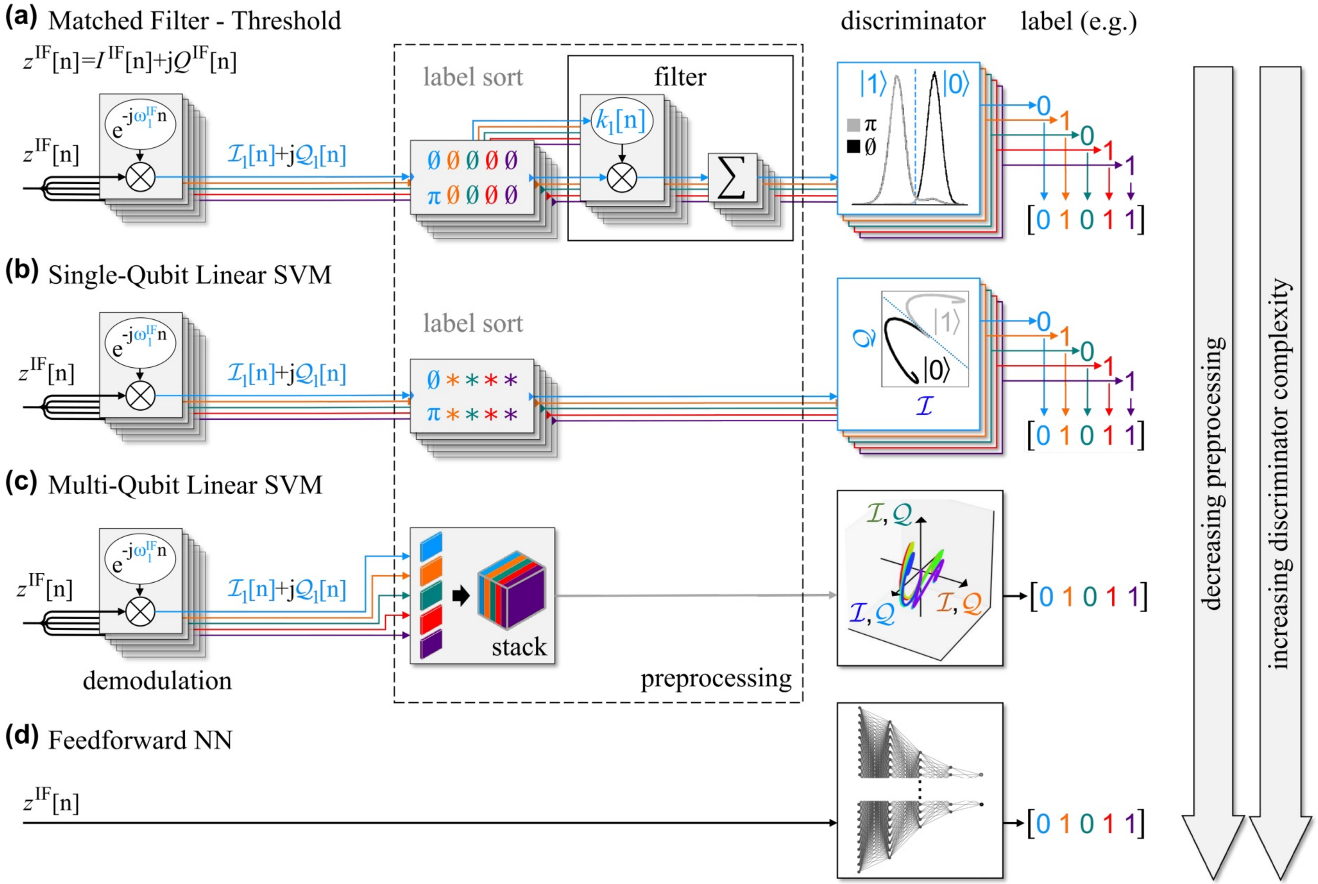

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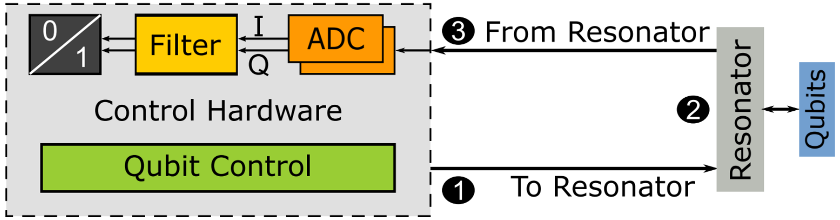

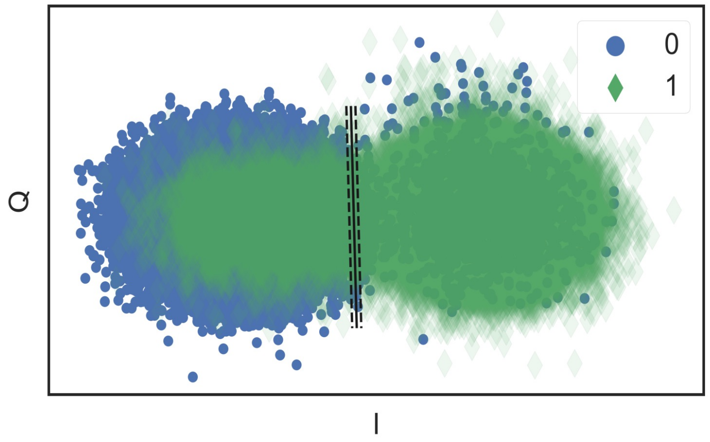

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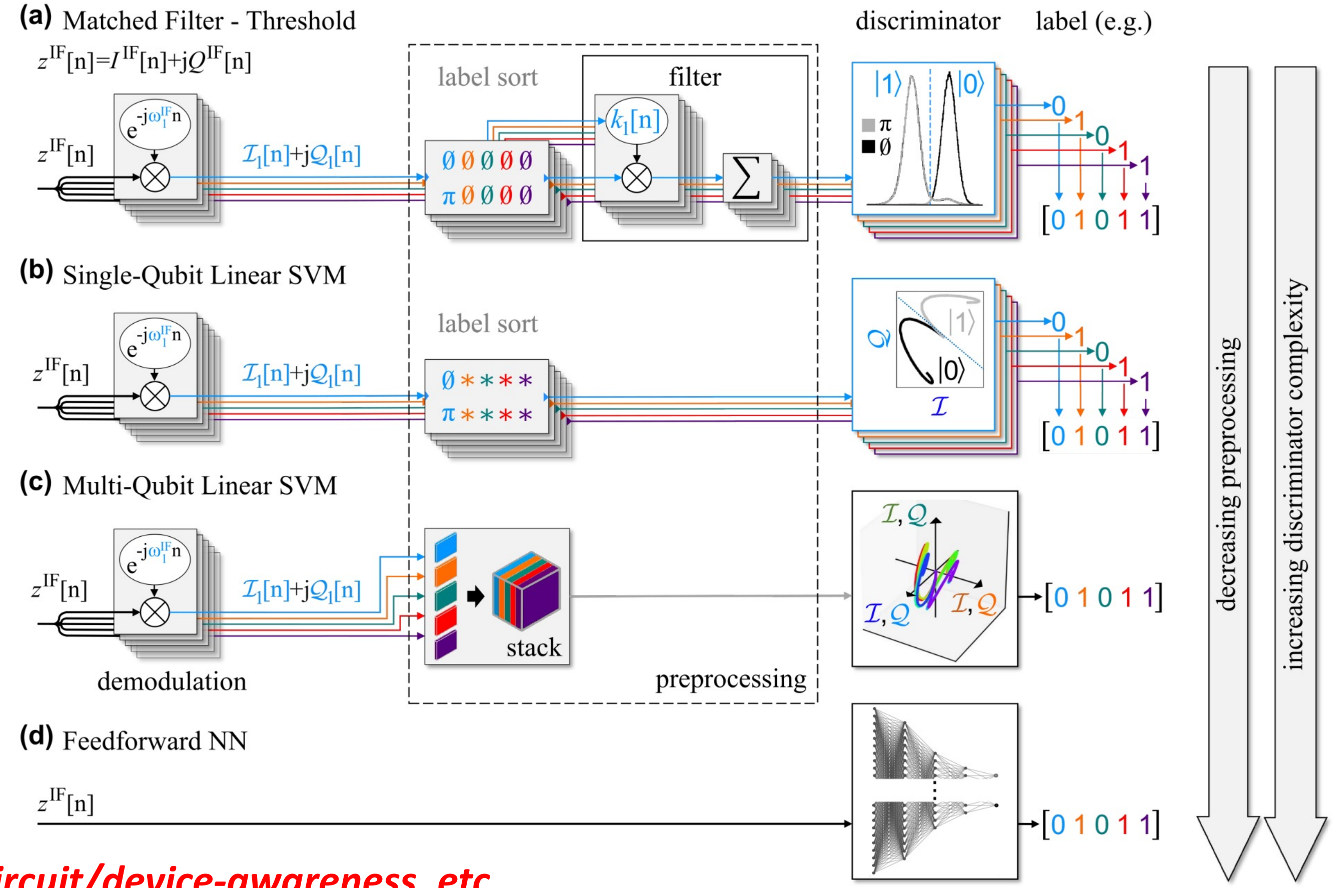

Need for high accuracy, low latency, low overheads, circuit/device-awareness, etc.

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