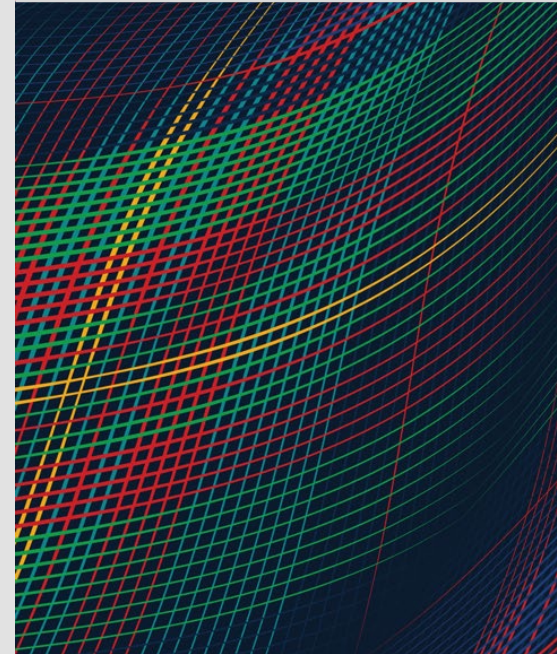


Quantum Machine Learning Workflows: What HPC Enables and What Quantum Hardware Delivers

PSC Webinar

APRIL 3, 2026

DANIEL JUSTICE
Quantum / Machine Learning Researcher



Document Markings

Copyright 2026 Carnegie Mellon University.

This material is based upon work funded and supported by the Department of War under Air Force Contract Nos. FA8702-15-D-0002, and FA870225DB003 with Carnegie Mellon University for the operation of the Software Engineering Institute, a federally funded research and development center.

The opinions, findings, conclusions, and/or recommendations contained in this material are those of the author(s) and should not be construed as an official US Government position, policy, or decision, unless designated by other documentation.

NO WARRANTY. THIS CARNEGIE MELLON UNIVERSITY AND SOFTWARE ENGINEERING INSTITUTE MATERIAL IS FURNISHED ON AN "AS-IS" BASIS. CARNEGIE MELLON UNIVERSITY MAKES NO WARRANTIES OF ANY KIND, EITHER EXPRESSED OR IMPLIED, AS TO ANY MATTER INCLUDING, BUT NOT LIMITED TO, WARRANTY OF FITNESS FOR PURPOSE OR MERCHANTABILITY, EXCLUSIVITY, OR RESULTS OBTAINED FROM USE OF THE MATERIAL. CARNEGIE MELLON UNIVERSITY DOES NOT MAKE ANY WARRANTY OF ANY KIND WITH RESPECT TO FREEDOM FROM PATENT, TRADEMARK, OR COPYRIGHT INFRINGEMENT.

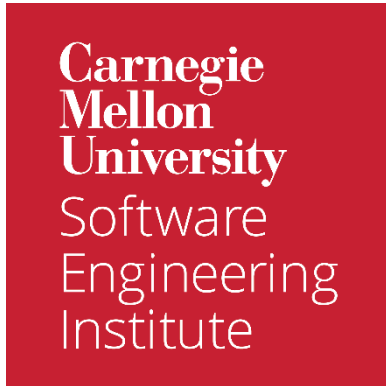
[DISTRIBUTION STATEMENT A] This material has been approved for public release and unlimited distribution. Please see Copyright notice for non-US Government use and distribution.

This material may be reproduced in its entirety, without modification, and freely distributed in written or electronic form without requesting formal permission. Permission is required for any other use. Requests for permission should be directed to the Software Engineering Institute at permission@sei.cmu.edu.

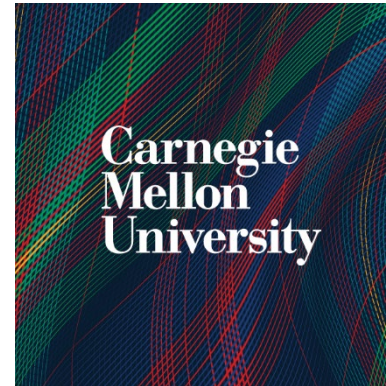
This work product was created in part using generative AI.

DM26-0353

Affiliations



$\langle P|Q|I \rangle$



Quantum Computing Classes

Programming Quantum Computers

CMU Course: 17-617

Quantum Machine Learning

CMU Course: 17-620

Applied Quantum Computing

CMU Course: 17-628

Quantum Computing, Cryptography and Machine Learning Lab

CMU Course: 11-860

[Rita Singh](#)

[Derek Wang](#)

[Bhiksha Raj](#)



What HPC Enables and What Quantum Hardware Delivers

The QML Approach

Scaling Limits and the Promise of QML

- Modern AI progress has been driven by scaling (data, compute, parameters)
- This scaling is becoming increasingly costly and resource-constrained
- Quantum Machine Learning is often proposed as a path beyond classical scaling limits
- HPC users are beginning to explore quantum workflows
- The gap between simulation and real hardware remains poorly understood

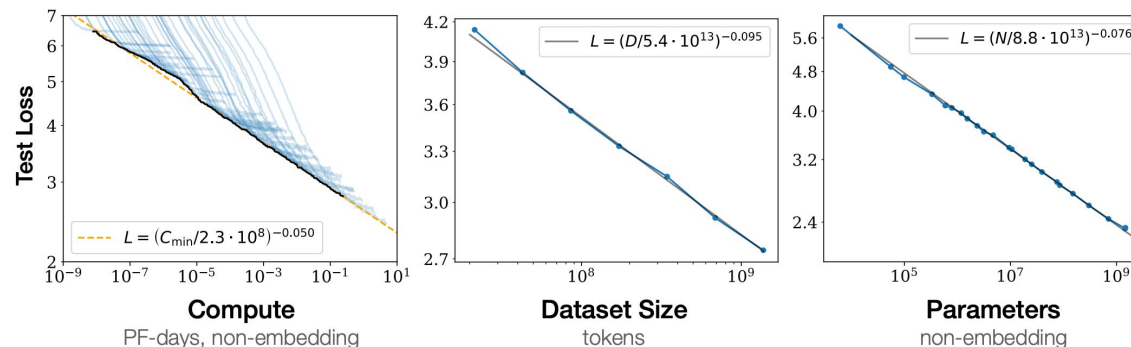
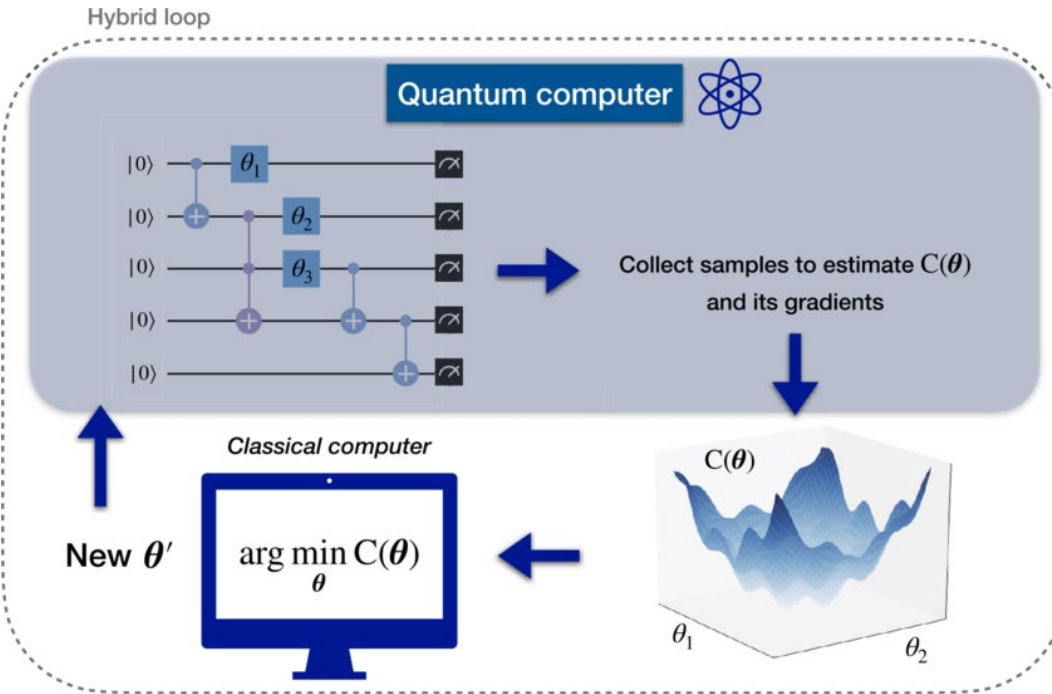


Figure 1 Language modeling performance improves smoothly as we increase the model size, dataset size, and amount of compute² used for training. For optimal performance all three factors must be scaled up in tandem. Empirical performance has a power-law relationship with each individual factor when not bottlenecked by the other two. [Kaplan, J., McCandlish, S., Henighan, T., Brown, T. B., Chess, B., Child, R., Gray, S., Radford, A., Wu, J., & Amodei, D. \(2020\). *Scaling Laws for Neural Language Models*. arXiv:2001.08361](#)

This talk focuses on what happens in practice

QML is a Hybrid Workflow



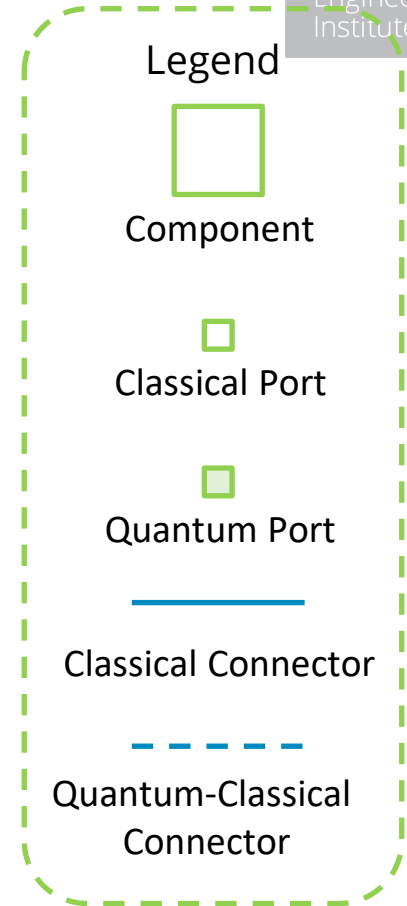
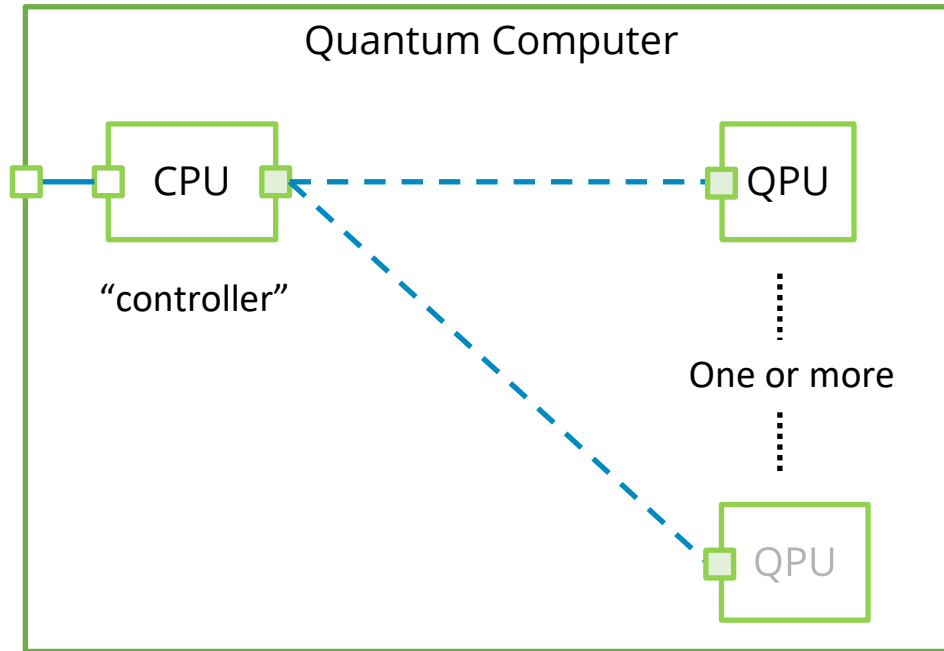
- QML models are trained through hybrid quantum-classical loops
- Quantum circuits produce probabilistic outputs (via measurement)
- Classical optimization drives parameter updates
- This loop is repeated many times during training

Compute is dominated by classical processing, while hardware access cost often sits on the QPU

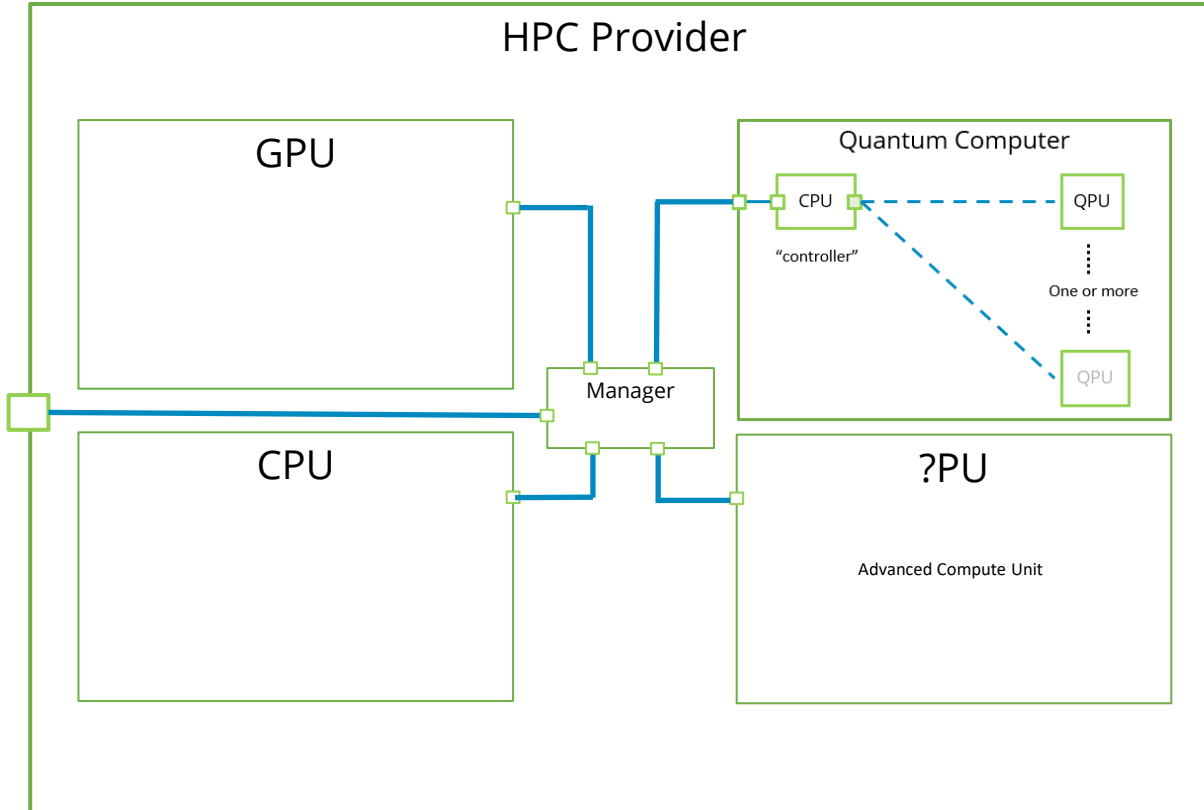
[Torta, Pietro & Casati, Rebecca & Bruni, Stefano & Mandarino, Antonio & Prati, Enrico. \(2025\). Quantum computing for space applications: a selective review and perspectives. EPJ Quantum Technology. 12. 10.1140/epjqt/s40507-025-00369-8.](#)

Quantum Computer – Basic Architecture

A quantum computer requires a classical computer (CPU) to act as a controller. Literature often calls this a *quantum controller*. This is the same model as how GPUs are currently deployed in that they are controlled via a CPU usually over PCI (embedded or external).

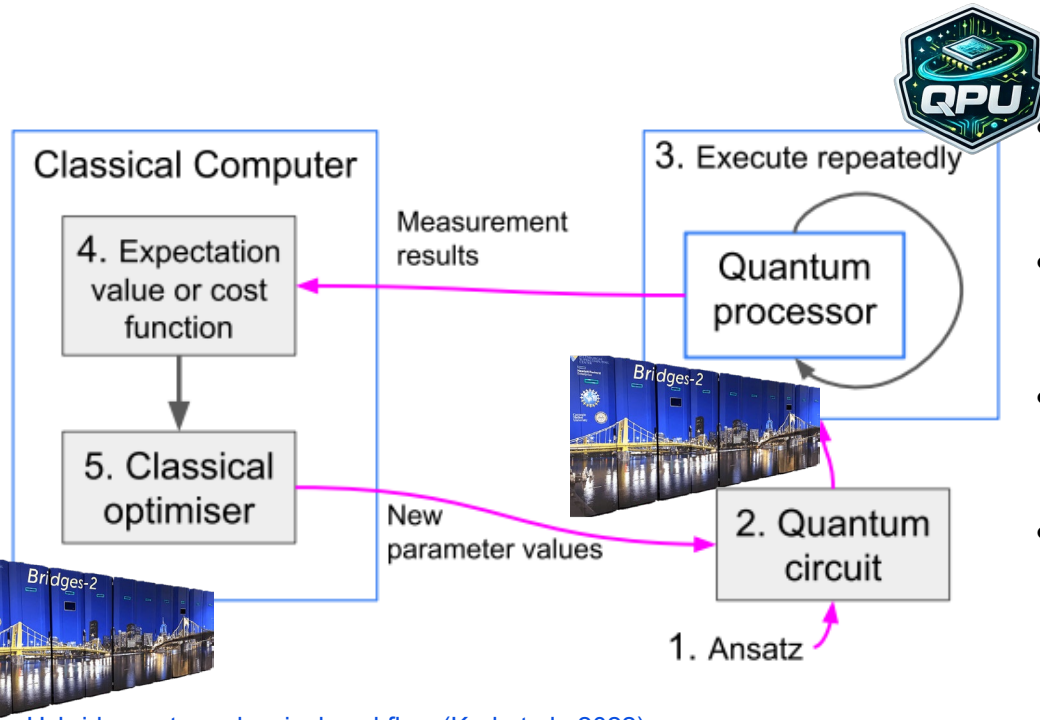


Quantum-Classical Hybrid Compute



Quantum computers will be used to solve large, complex problems where other types of compute may be preferred first.

Where HPC Fits



[Hybrid quantum-classical workflow \(Krol et al., 2022\)](#)

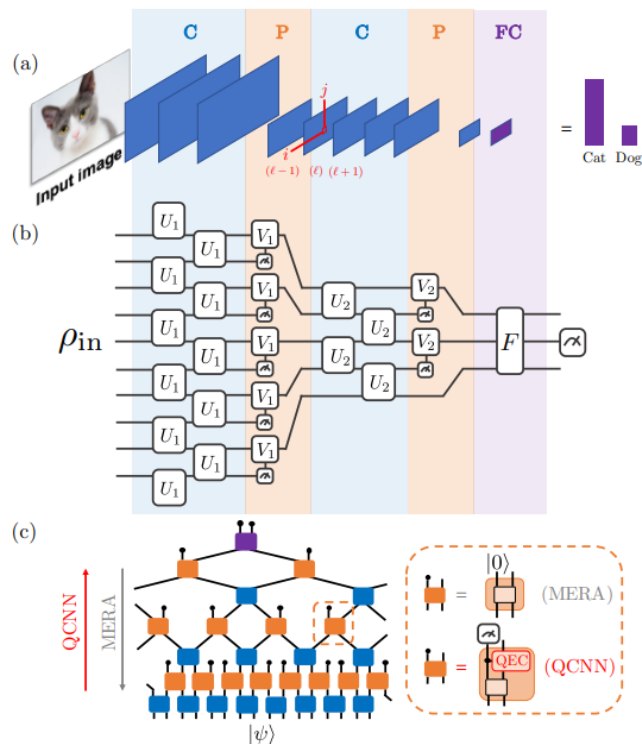
- Simulation of quantum circuits at scale (statevector, GPU)
- Parameter optimization across many iterations
- Large-scale experiment orchestration and sweeps
- Data preprocessing and batching

HPC enables training and scaling, while QPUs provide limited, high-cost evaluations

What HPC Enables and What Quantum Hardware Delivers

The Case Study

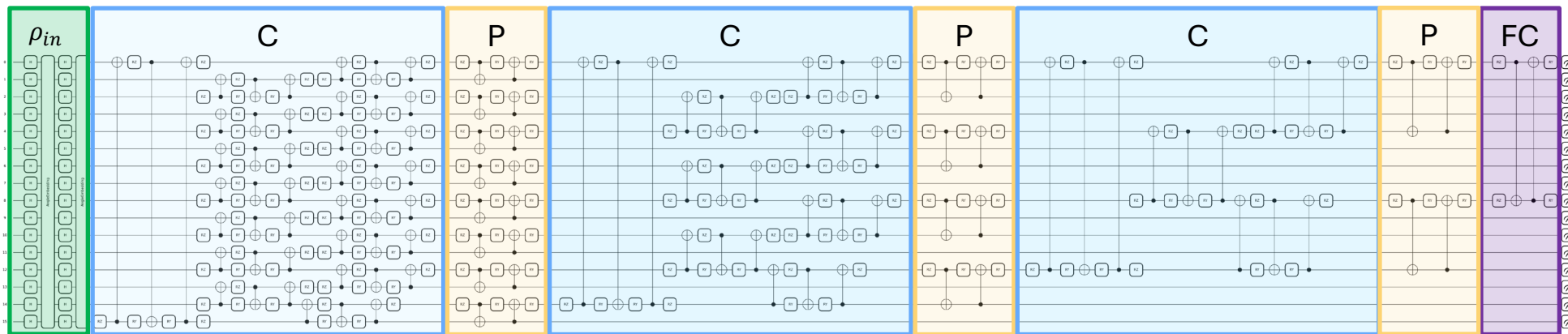
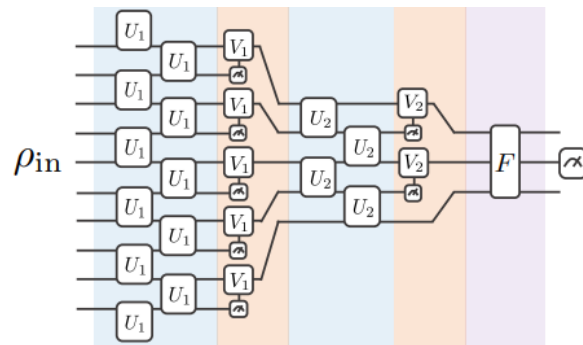
Case Study: QCNN Deployment



- Model: QCNN (image classification)
- Environments:
 - Simulator
 - QPUs (Braket)
- Same circuit across multiple hardware

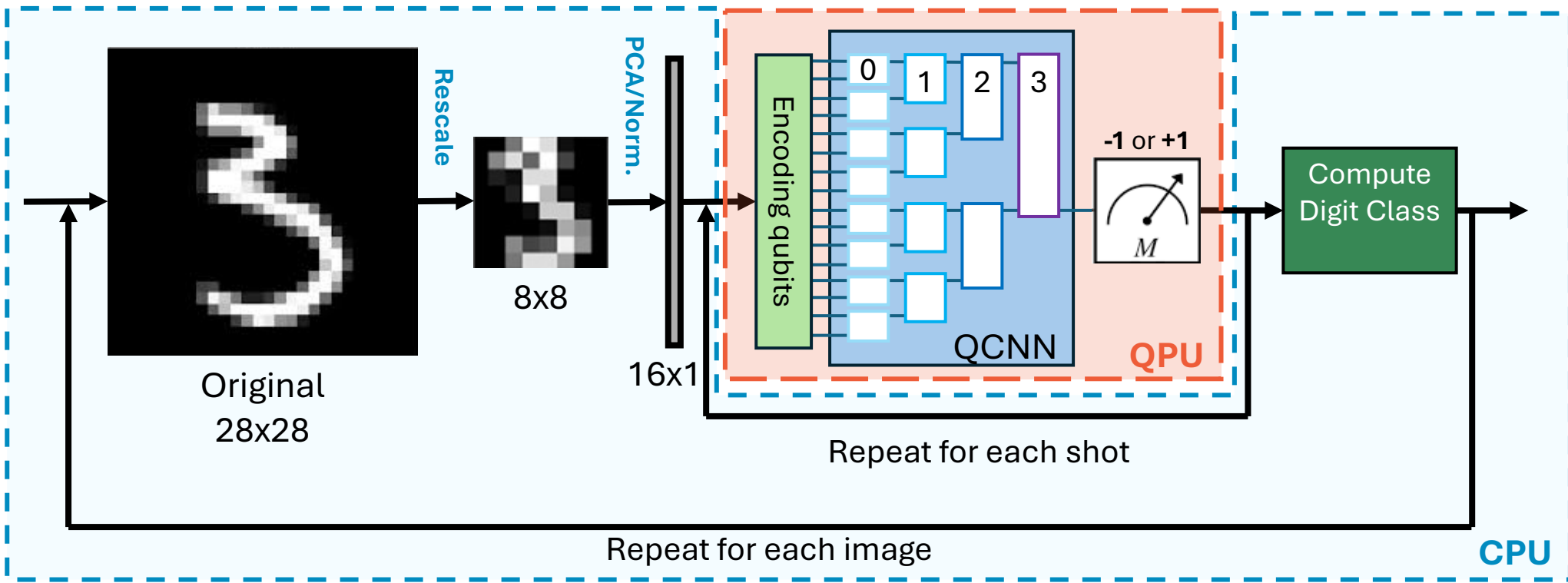
[QCNN architecture \(Cong et al., 2018\)](#)

QCNN Circuit Implementation



Experiment Architecture

Preprocessing Encoding Inference Measurement Postprocessing



CPU

Real To Simulation Challenges

- Increased Inferencing Times
- Varying Quantum Architectures
- Varying quality of qubits
- Increase in cost of compute
- Decrease in accuracy

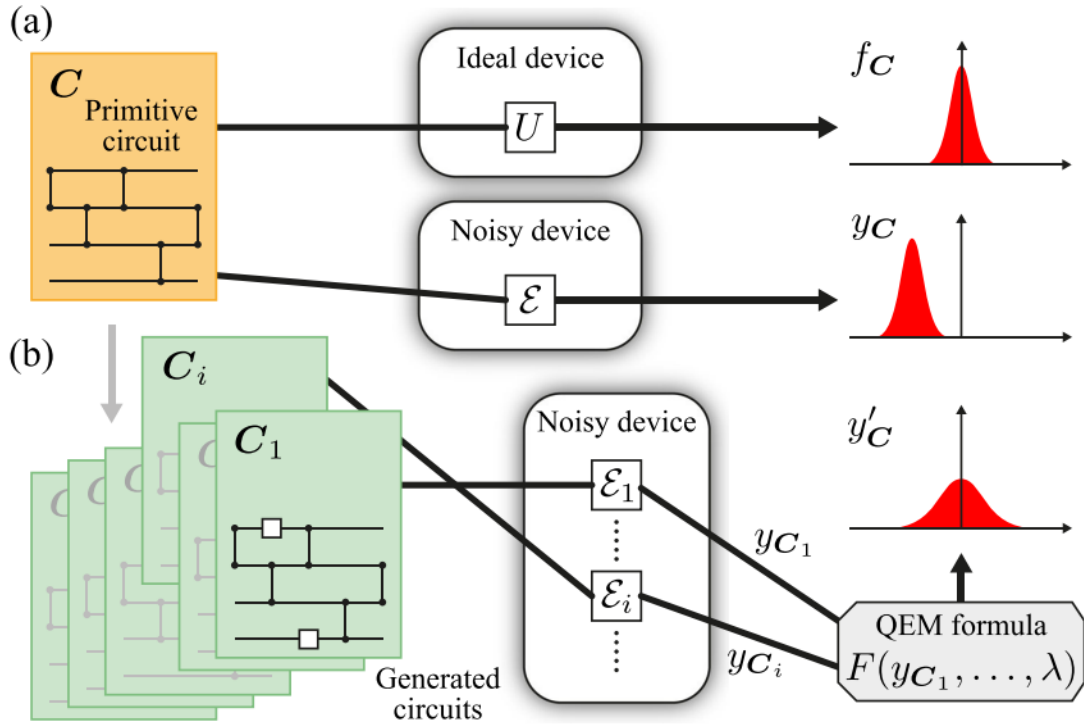
QPU	Vendor	Size of QPU (qubits)	Average Inference Time (sec.)	Cost/Inference (USD)
Pennylane Simulator	Xanadu	~32	0.147	---
Ankaa-3	Rigetti	82	0.495	\$0.76
Emerald	IQM	54	1.294	\$1.12
Garnet	IQM	20	1.166	\$1.04
Forte Enterprise 1	IONQ	36	371.405	\$41.26

QPU	Per Inference Charge (USD)	Per Shot Charge (USD)	Cost @ 48 inferences, 512 shots each	Cost @ 48 inferences, 1024 shots each
Rigetti Ankaa-3	\$0.30	\$0.0009	\$36.52	\$58.64
IQM Emerald	\$0.30	\$0.0016	\$53.72	\$93.04
IQM Garnet	\$0.30	\$0.00145	\$50.04	\$85.67
IonQ Forte Enterprise 1	\$0.30	\$0.08	\$1980.48	\$3946.56

What HPC Enables and What Quantum Hardware Delivers

The Sim2Real Challenge

Why Performance Degrades on Hardware



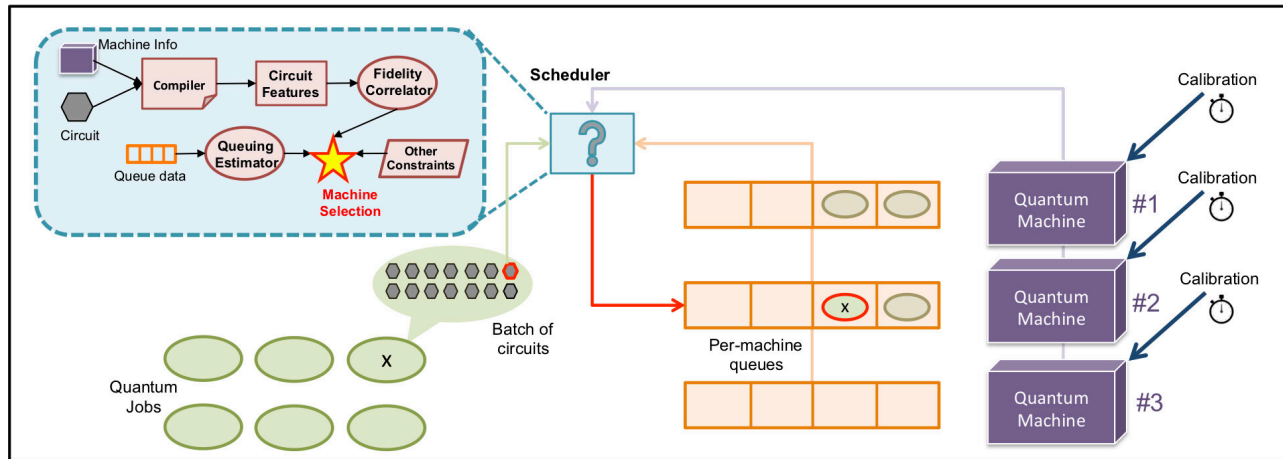
- Errors accumulate with circuit depth and gate count
- Noise scales with the number of operations in the circuit
- Error mitigation reduces but does not eliminate degradation
- Measurement noise and finite sampling introduce additional variance

[Qin, D., Chen, Y., & Li, Y. \(2023\). Error statistics and scalability of quantum error mitigation formulas. npj Quantum Information, 9, 35.](#)

Errors scale with circuit complexity, causing learned behavior to break down on hardware

Operational Constraints in QPU Deployment

- Queue times and shared access introduce significant latency
- Throughput is limited by shot-based execution
- Cost scales with number of circuit evaluations
- Results depend on device calibration and availability



Even simple workloads become slow and expensive to run.

What HPC Enables and What Quantum Hardware Delivers

The Experimental Progression

A Practical Progression for QML Development

Laptop

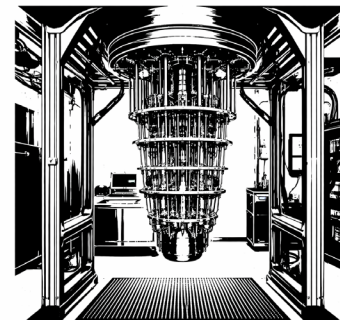
- Small Circuits
- Debugging
- Fast Iteration
- Proof of Concept

HPC

- Large simulations
- Optimization loops
- Parameter sweeps
- Concept Validation

QPU

- Real device behavior
- Noise effects
- Final testing



Scale understanding before deploying to hardware

Practical Guidance for HPC Users

Use HPC for:

- Training QML models in simulation
- Exploring circuit architectures and hyperparameters
- Running large-scale parameter sweeps
- Orchestrating hybrid optimization loops

Use QPUs for:

- Validating behavior on real hardware
- Studying noise and hardware effects
- Small-scale experiments and benchmarks
- Testing assumptions, not building models

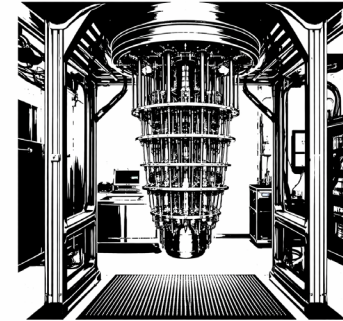
Train on HPC. Validate on QPU.

What HPC Enables and What Quantum Hardware Delivers

The Last Slide

Key Takeaways

- Classical computation dominates QML workflows today
- Quantum hardware introduces noise, latency, and instability
- Simulation and hardware results can diverge significantly
- HPC is essential for developing and scaling QML systems



QML today is a systems problem, not just a quantum problem