Oak Ridge National Laboratory

June 2026 | QRUCH Workshop at ISC

Unleashing Quantum Acceleration: From Architectures to Applications

Travis Humble

Director, Quantum Science Center

U.S. DEPARTMENT OF ENERGY

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FOR THE US DEPARTMENT OF ENERGY

We have seen a steady rise in leadership-class computing performance for decades

OLCF-1 Phoenix

Cray X1e

2004

OLCF-2.1 Jaguar

Cray XT3

2005

OLCF-2.2 Jaguar

Cray XT4

2006

OLCF-2.3 Jaguar #1

Cray XT5

2009

OLCF-3 Titan #1

Cray XK7
First Hybrid GPU + CPU system
AMD CPUs + NVIDIA GPUs

2012

OLCF-4 Summit #1

IBM AC922
IBM CPUs + NVIDIA GPUs

2018

OLCF-5 Frontier #1

HPE Cray EX 235a
HPE Interconnect + AMD CPUs and GPUs

2022

OLCF-6 Discovery

In development
Extreme Bandwidth
ModSim + AI + workflows

2028

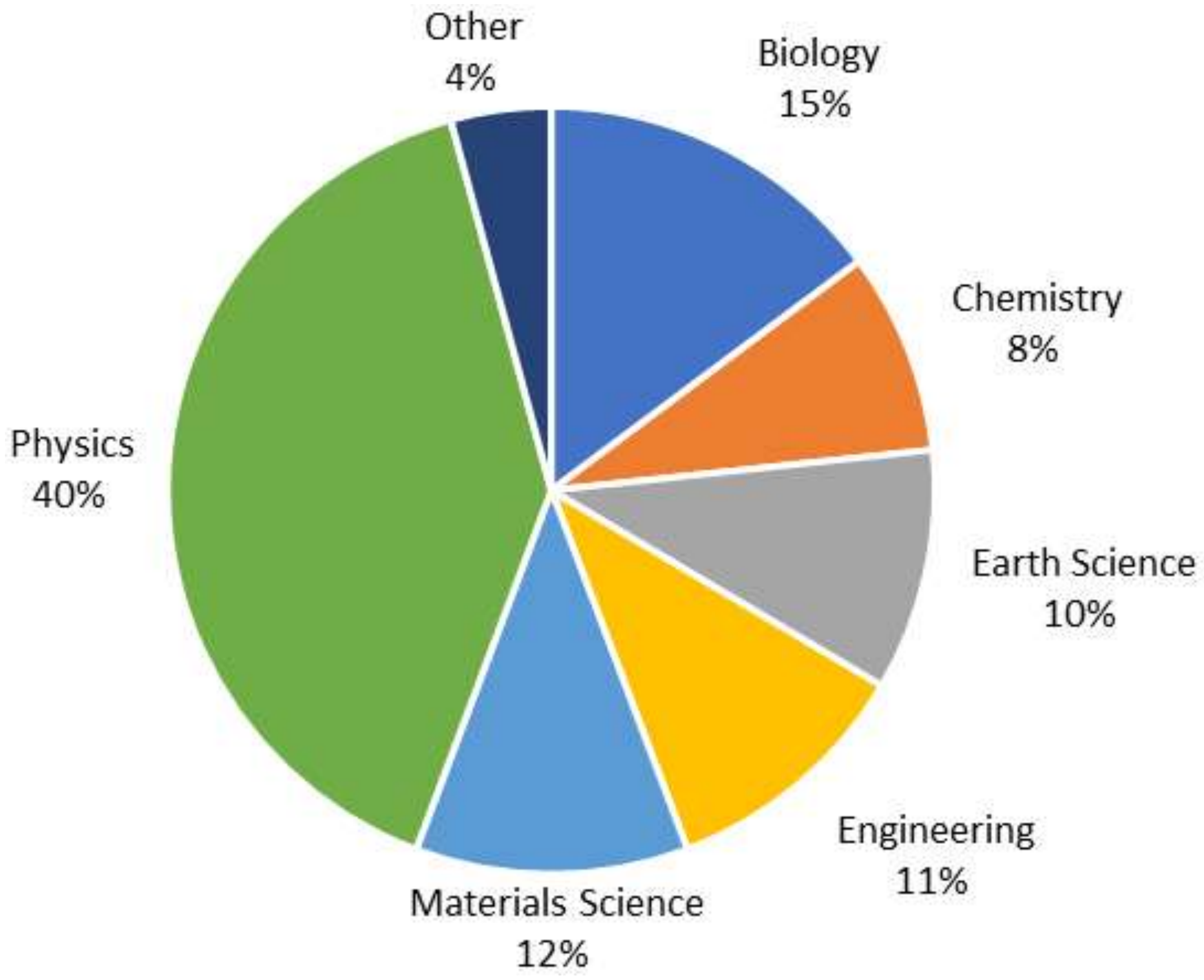
U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING

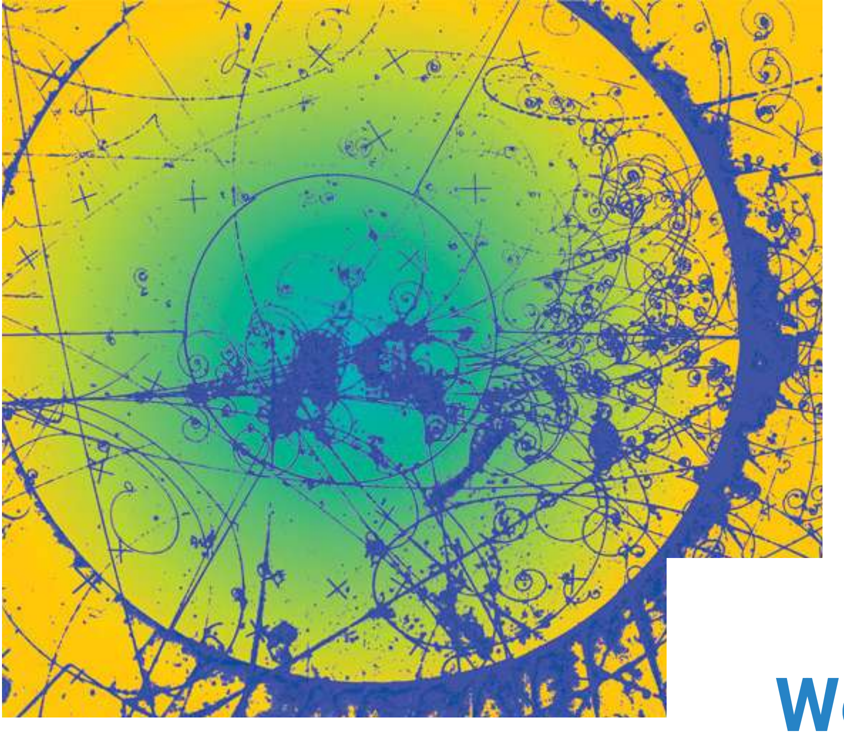
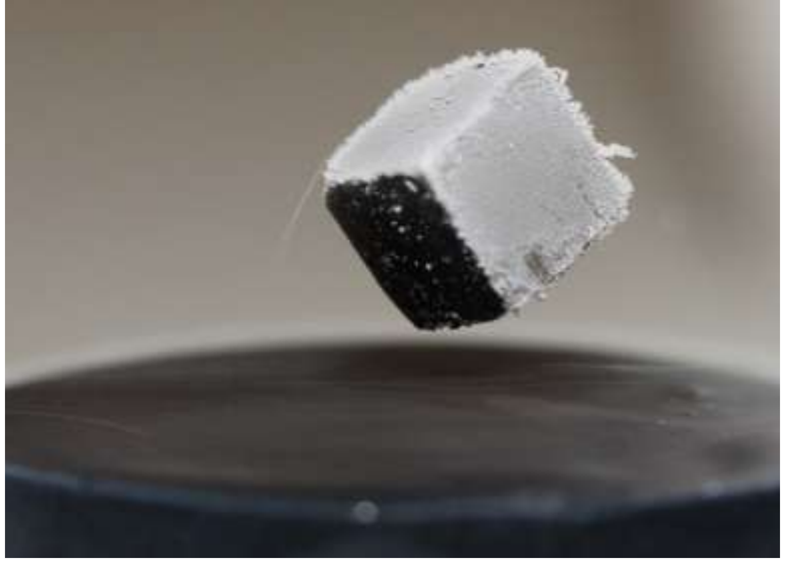
https://doeleadershipcomputing.org

2025 INCITE Allocations by Category

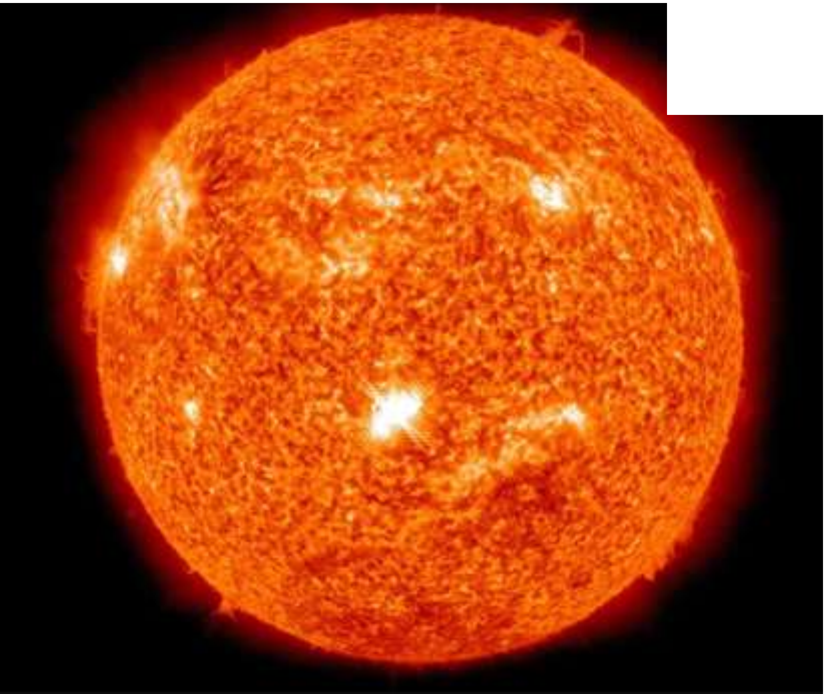
Percentage of HPC system node hours allocated across all systems

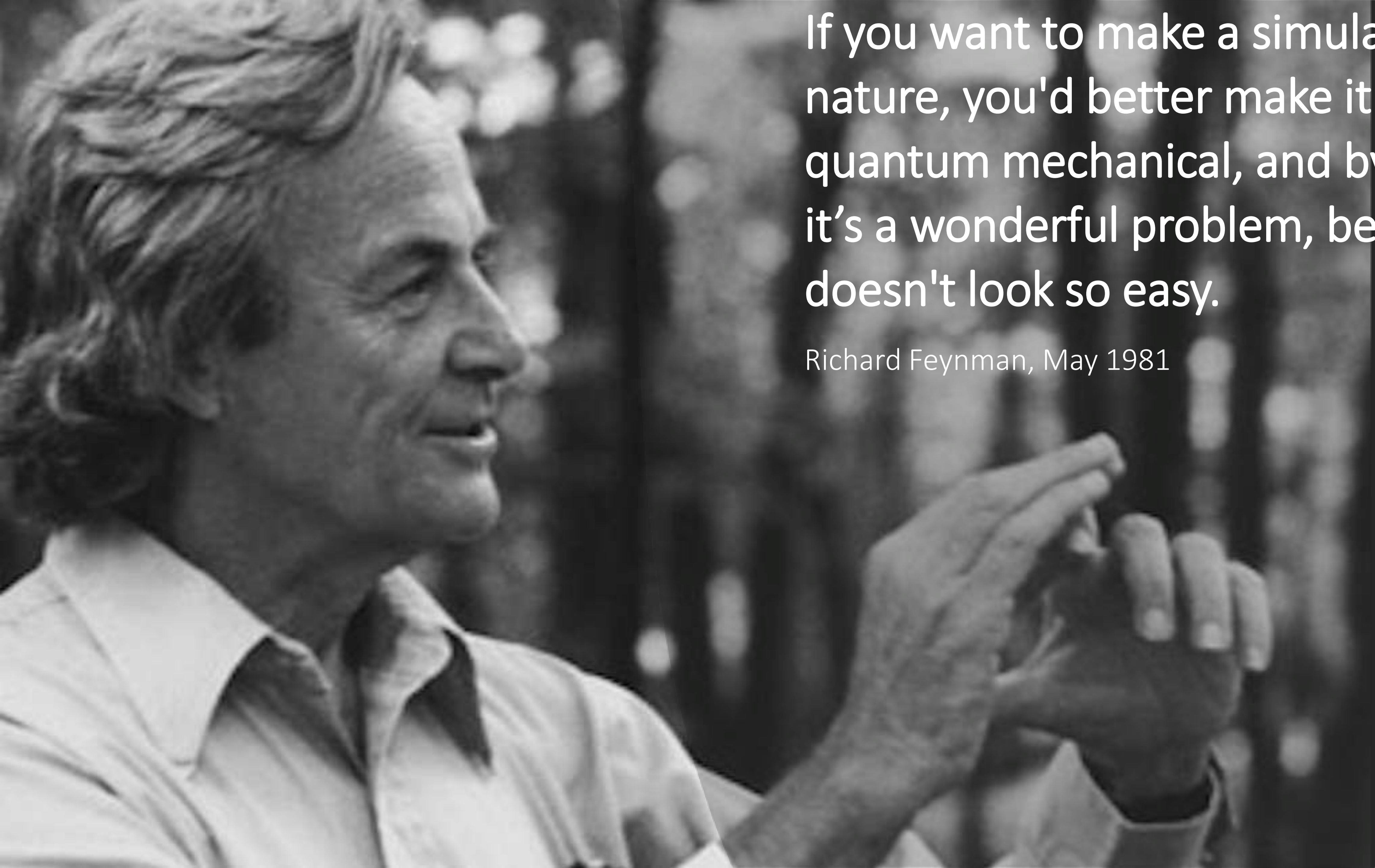
Total annual allocation is ~65M node hours




We live in a quantum universe





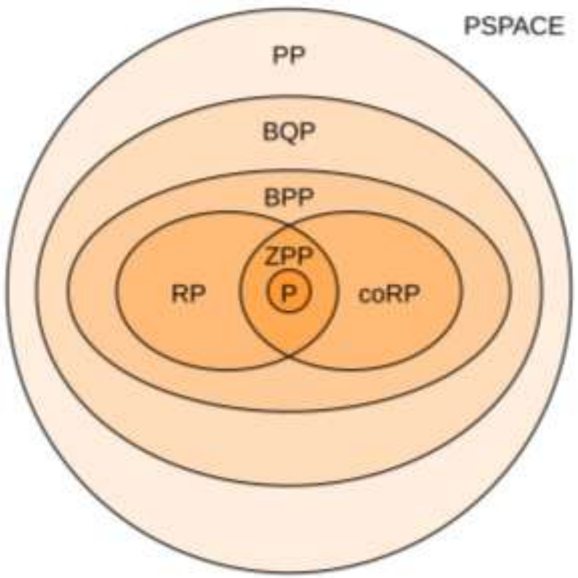
If you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it’s a wonderful problem, because it doesn't look so easy.

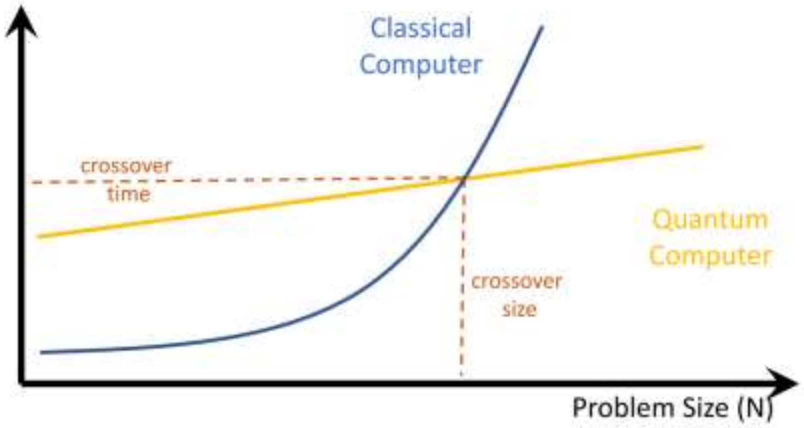
Richard Feynman, May 1981

Quantum computational models provide settings for applications

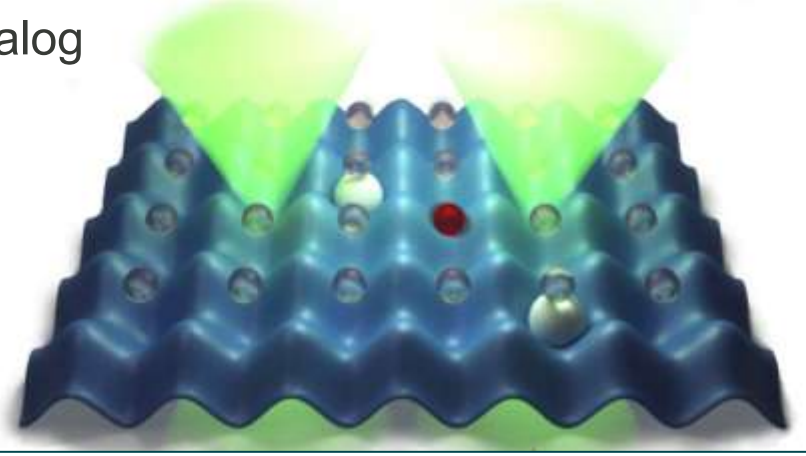
Different models present alternative methods for manipulating the quantum computation state

There is a formal equivalence between these models and the types of problems that can be solved efficiently

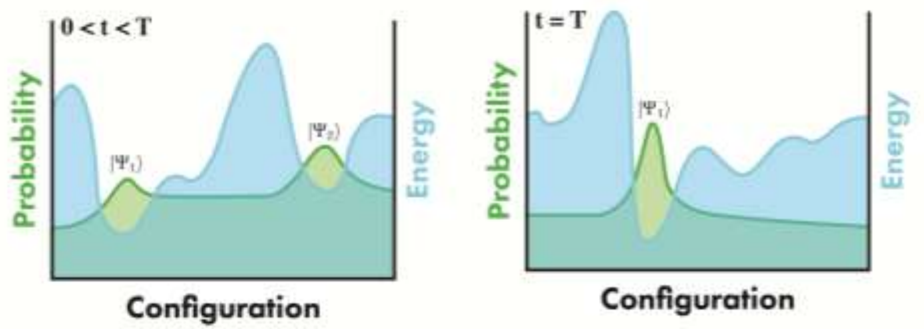




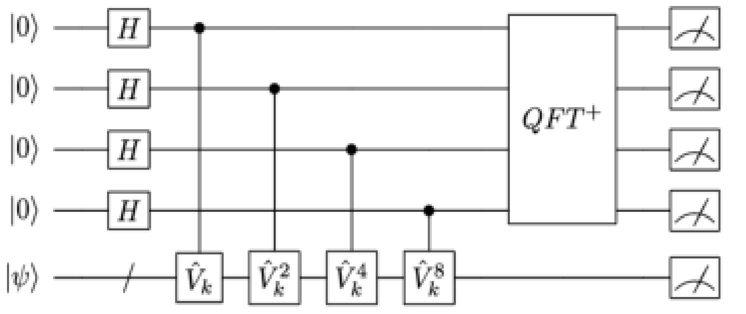
Analog



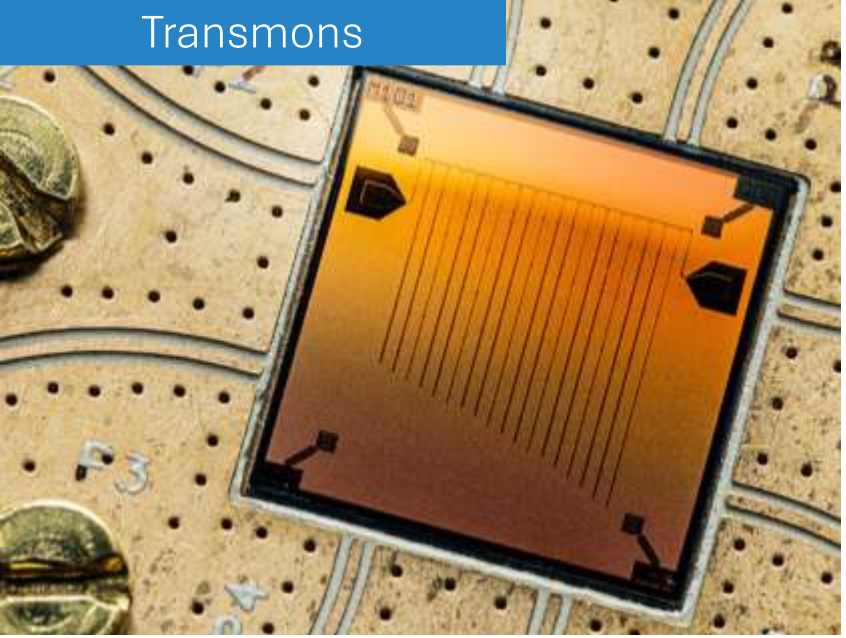
Adiabatic



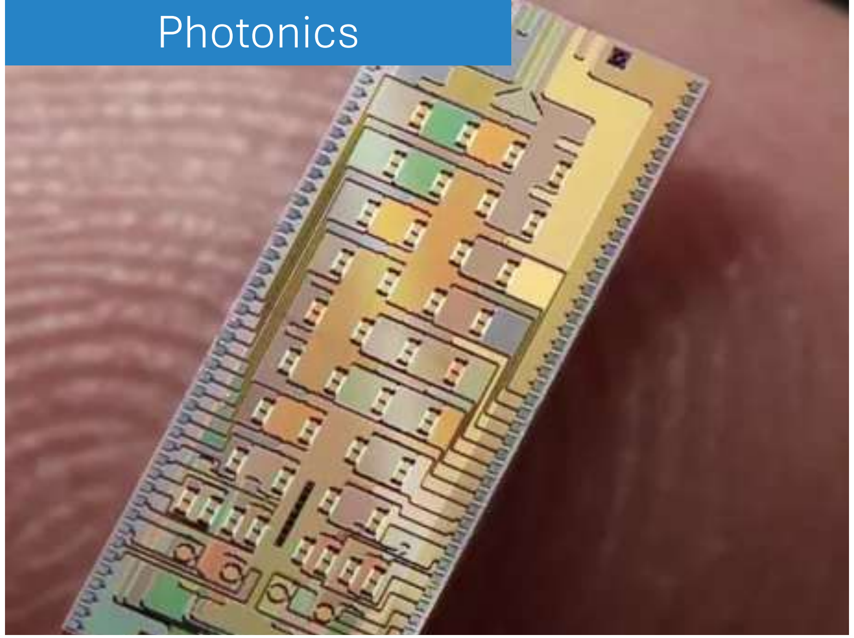
Digital



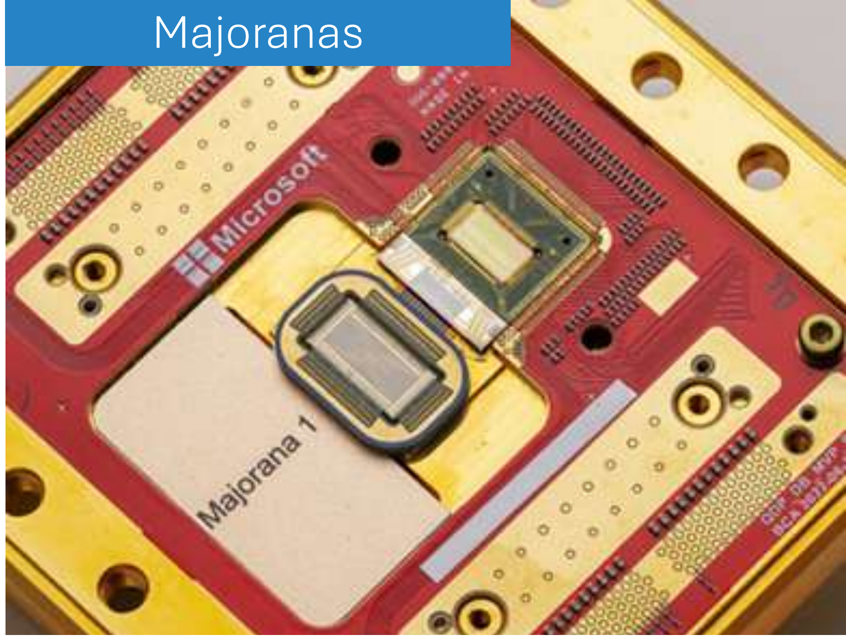
Transmons



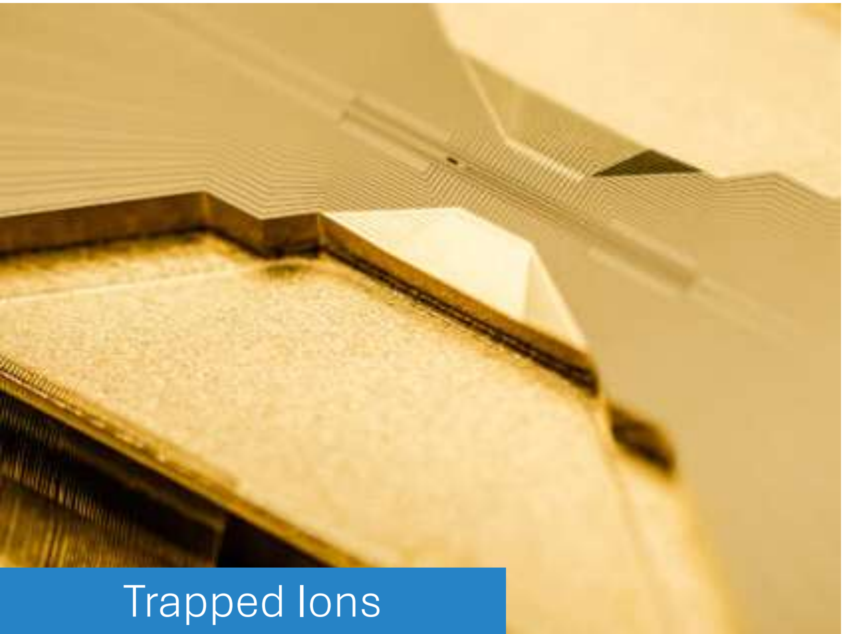
Photonics



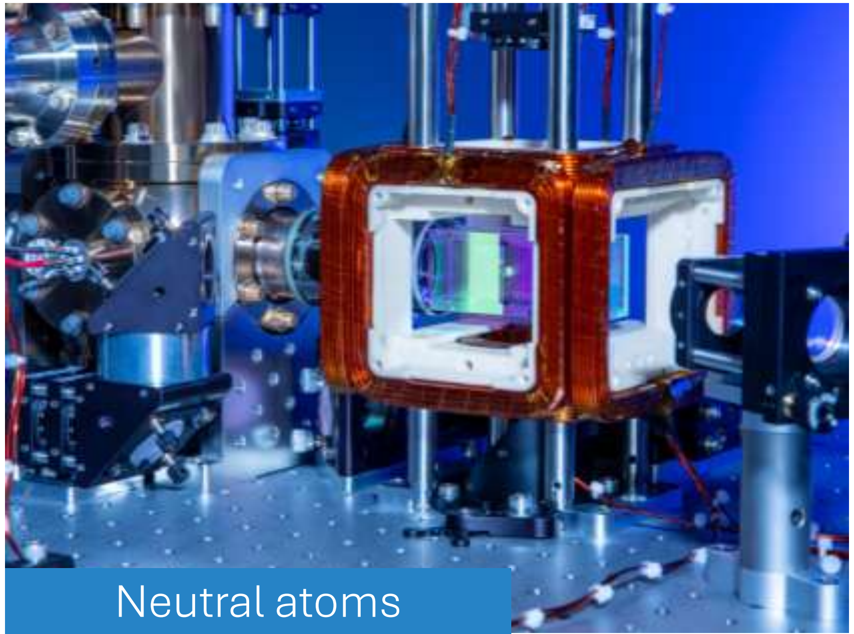
Majoranas



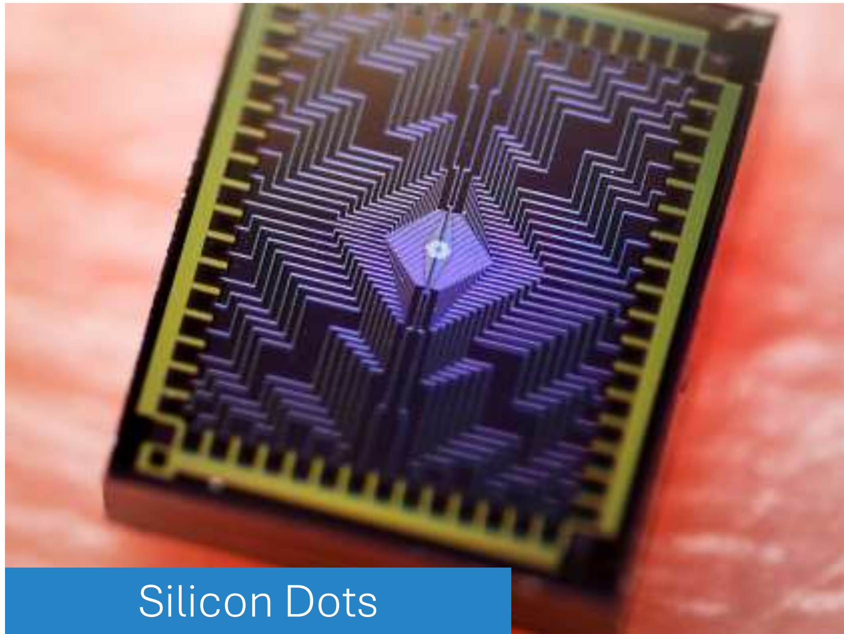
Many different modalities can realize quantum computing



Trapped Ions

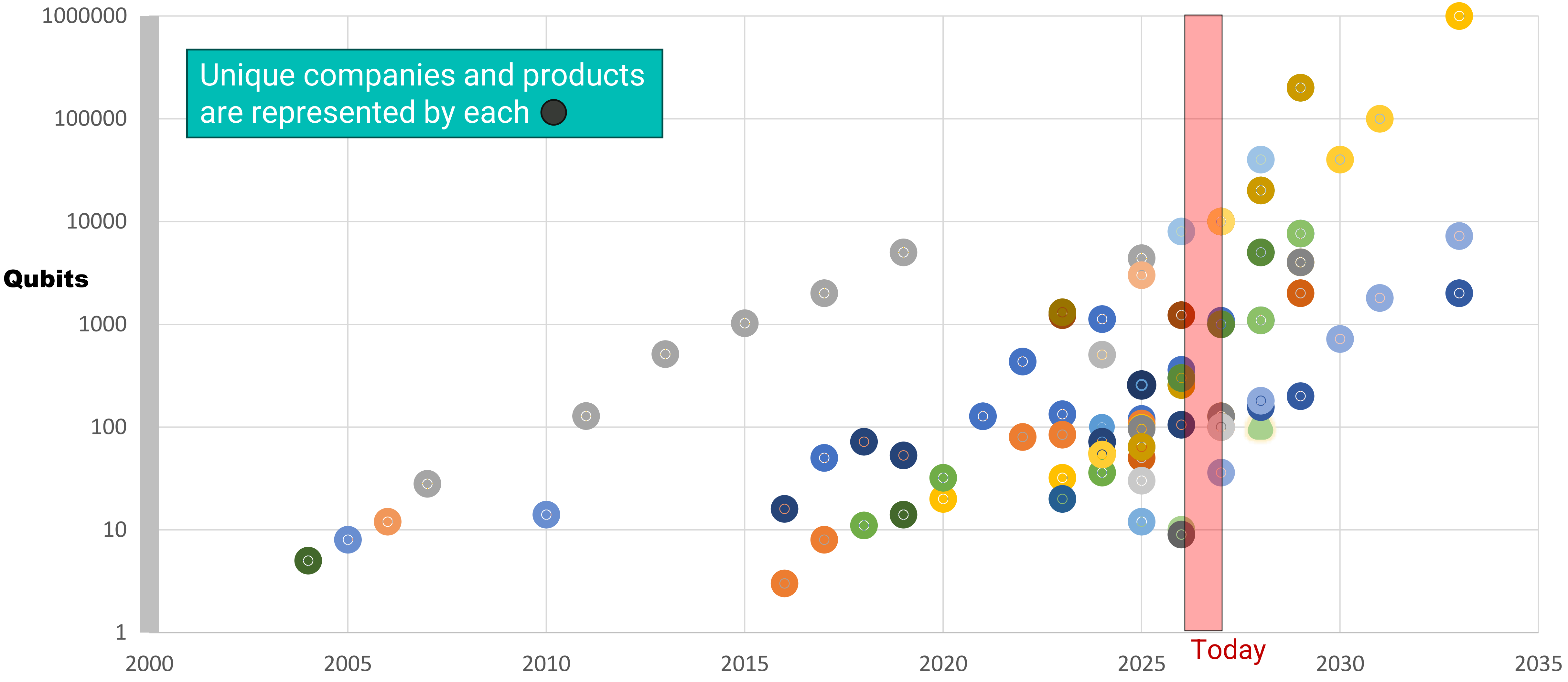


Neutral atoms



Silicon Dots

We see exponential growth in forecasted qubits



T. S. Humble, multiple sources (April 2026)

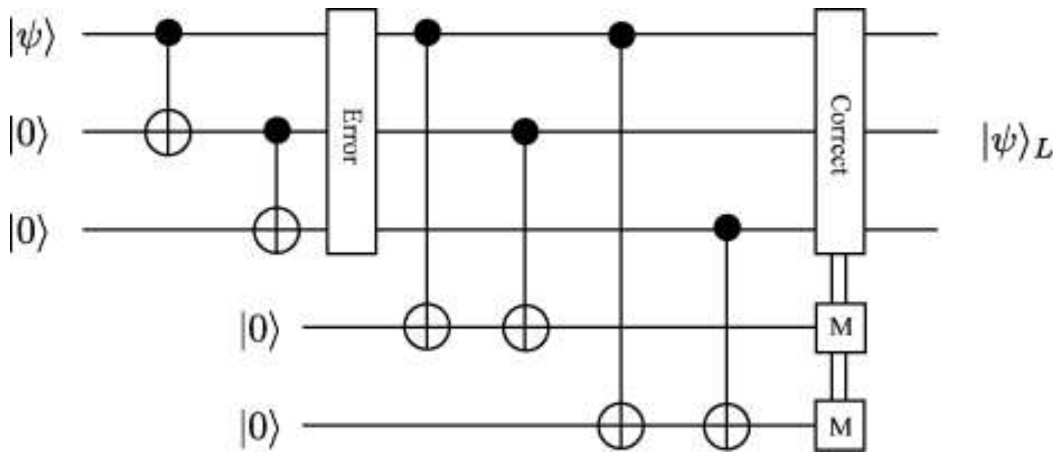
Sustained operations require fault tolerant protocols and error correction techniques

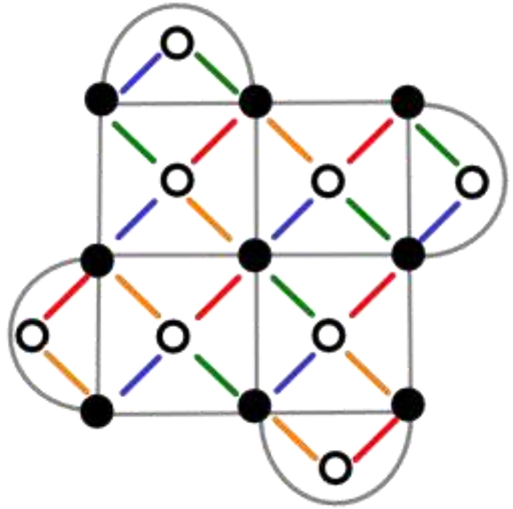
The redundant encoding of information can mitigate entropy from errors

- Familiar strategy modified for quantum information due to no-cloning theorem

Fault-tolerant device operation can be established

- Provided code is sufficiently large and error rates are sufficiently small

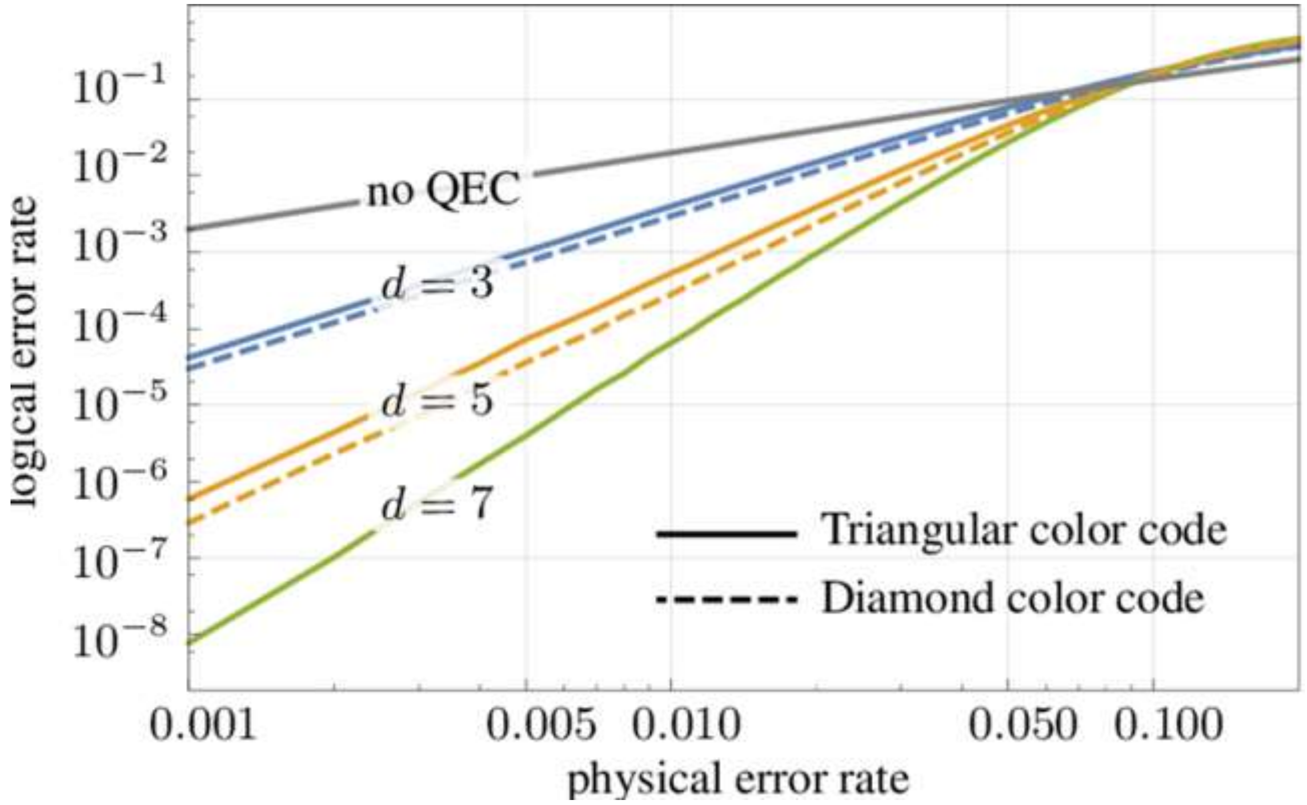




Sustained operations require fault tolerant protocols and error correction techniques

System engineering requires minimum qubit capacity and gate fidelity as well as satisfying logical constraints.

Redundant encoding also adds complexity in development and use, e.g., programming.



Litinski et al., "Combining Topological Hardware and Topological Software: Color Code Quantum Computing with Topological Superconductor Networks," Phys Rev X 7, 031048 (2017)

Logical scaling depends directly on QEC code efficiency

Information Theory

Kingdoms of QEC codes

Qubit Kingdom (316 codes)

Modular-qudit Kingdom (38 codes)

Galois-qudit Kingdom (47 codes)

Bosonic Kingdom (68 codes)

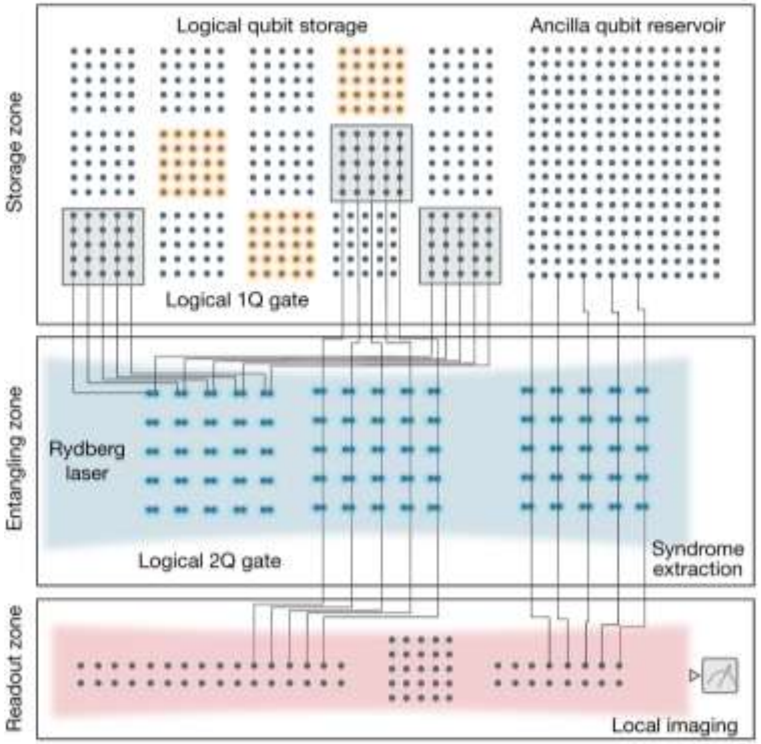
Spin Kingdom (14 codes)

Group quantum Kingdom (48 codes)

Homogeneous-space quantum Kingdom (4 codes)

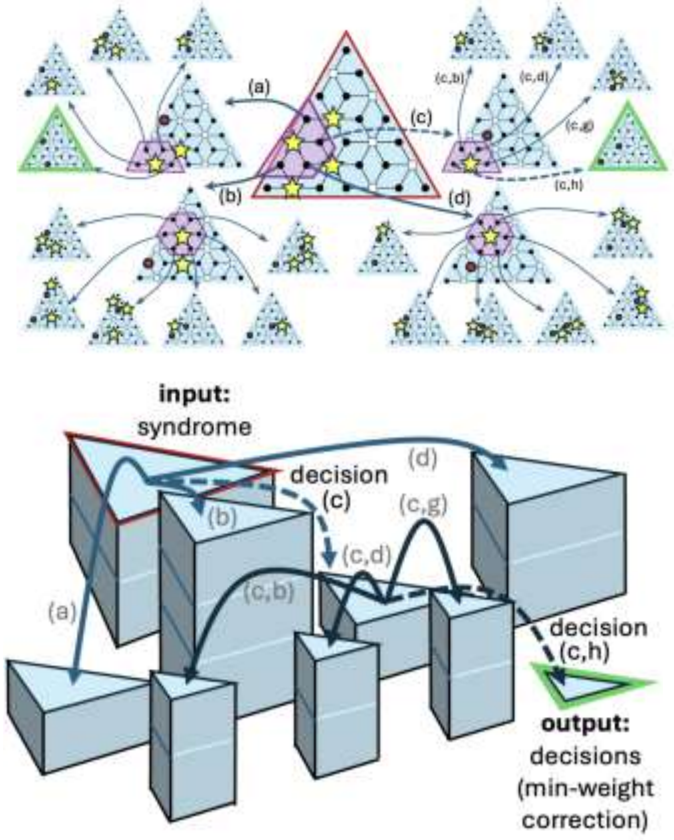
www.errorcorrectionzoo.org

Hardware Design



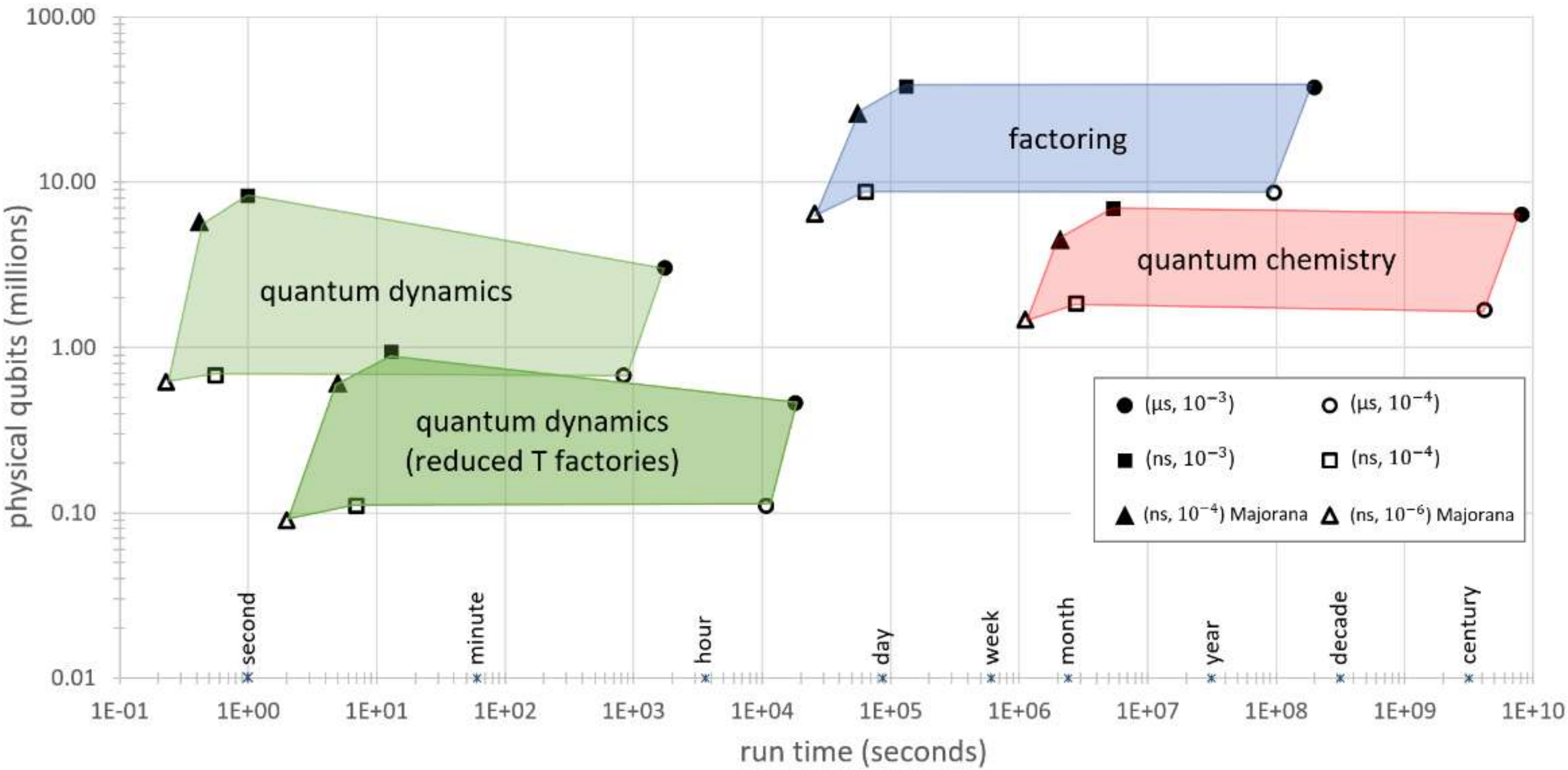
D. Bluvstein et al., “Logical quantum processor based on reconfigurable atom arrays,” Nature 626, 48 (2024)

Decoder Design

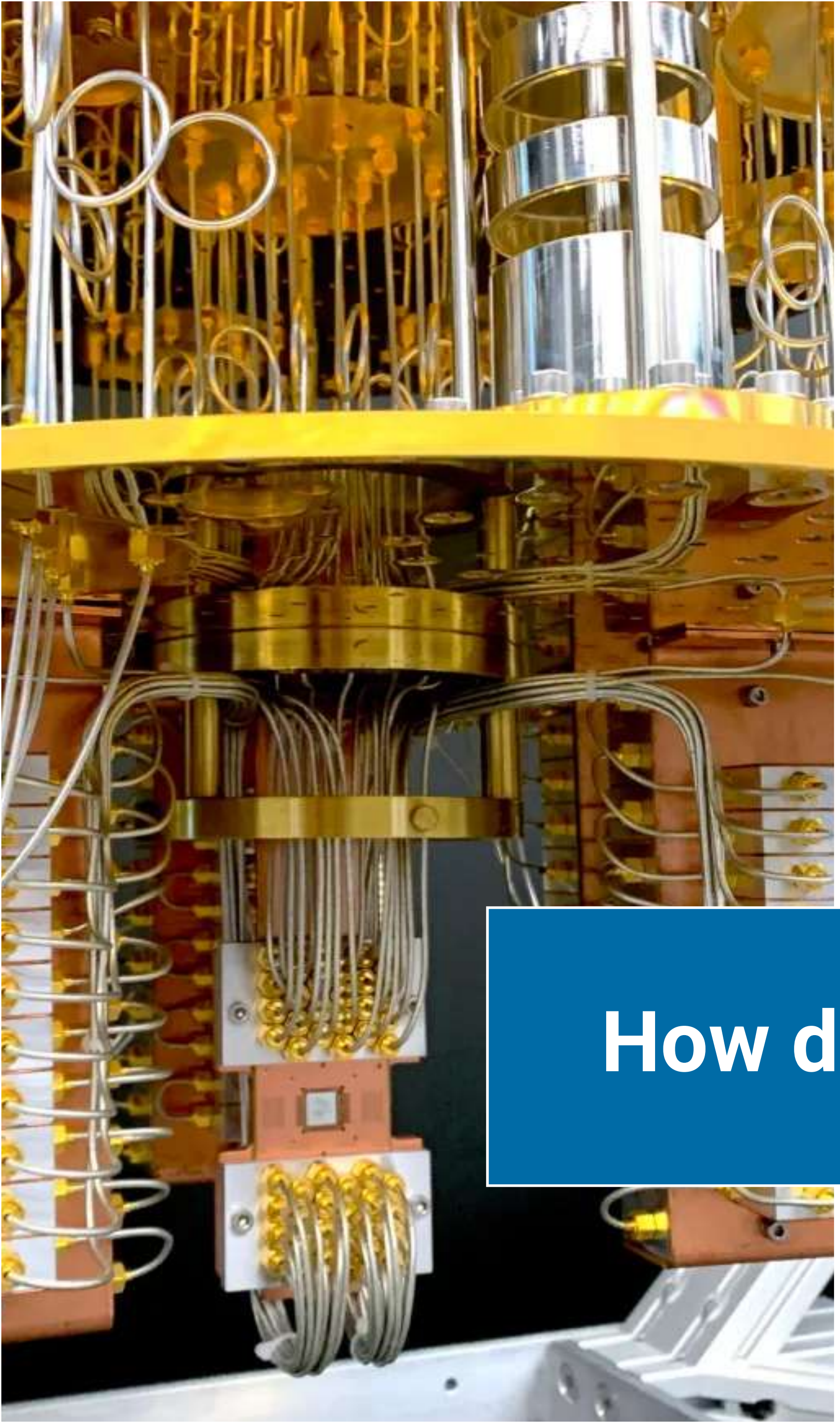


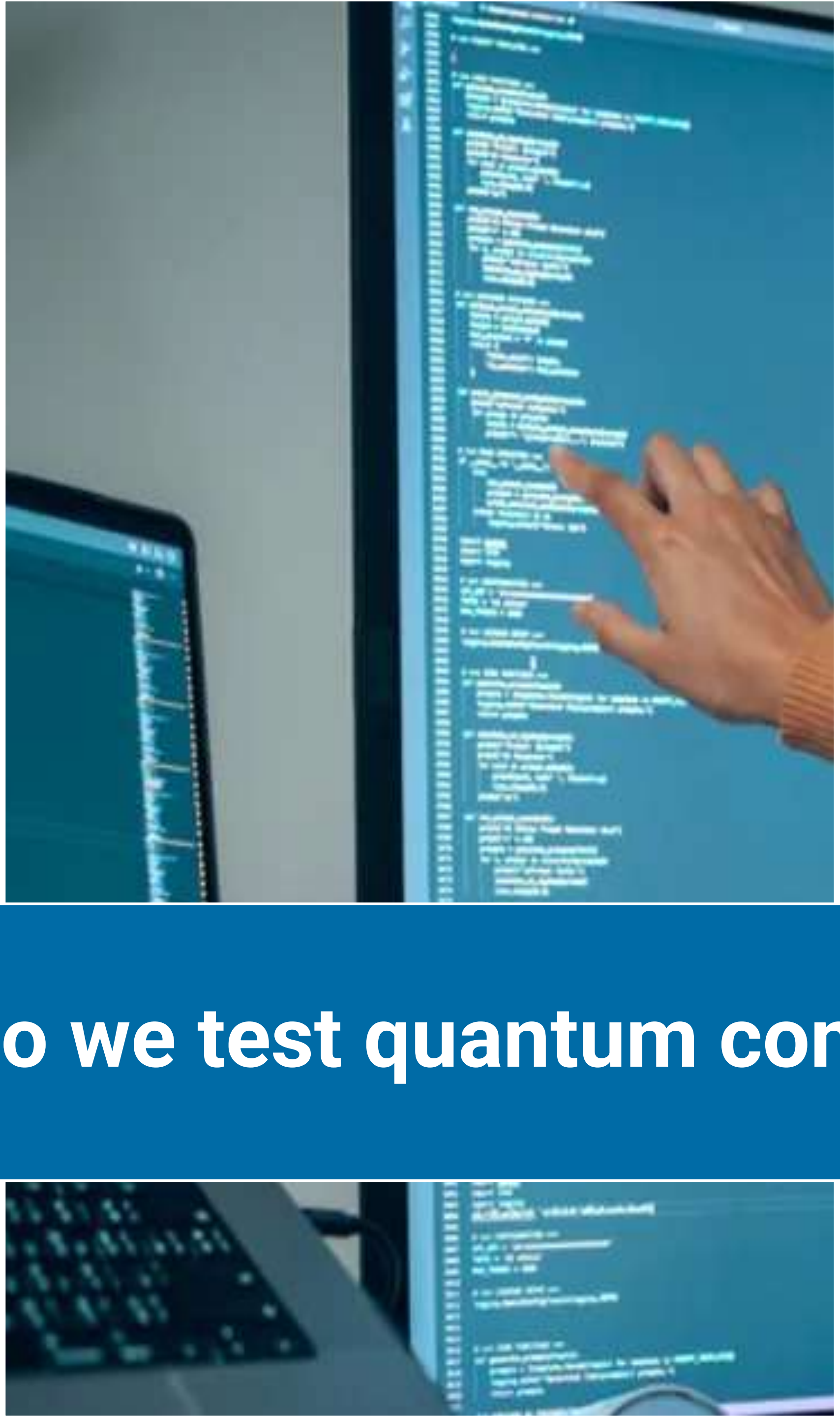
K. R. Ott et al., “Decision-tree decoders for general quantum LDPC codes,” arXiv:2502.16408 (2025)

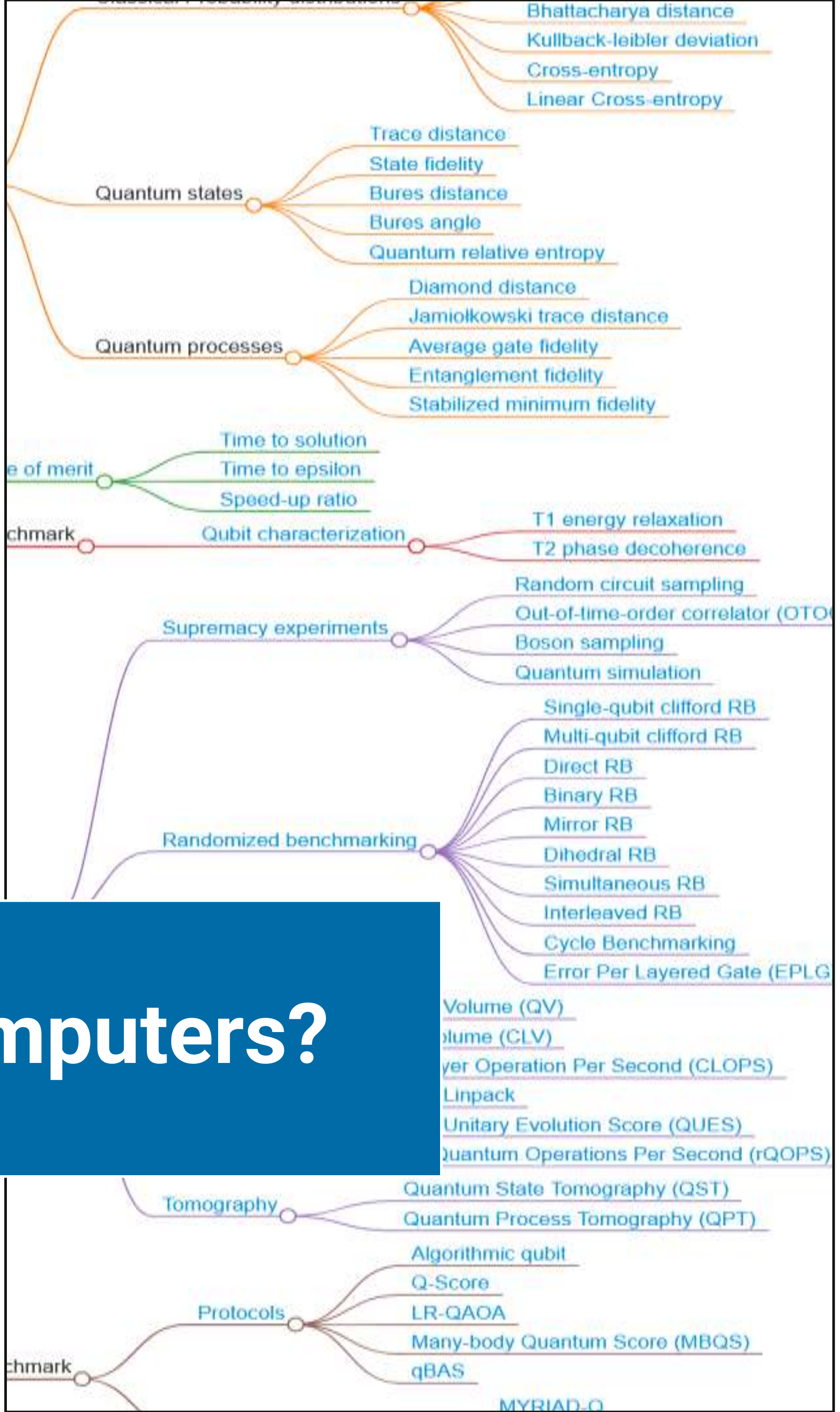
We see exponential demands for (forecasted) resources



M. E. Beverland et al., “Assessing requirements to scale to practical quantum advantage”, arxiv:2211.07629 (2022)

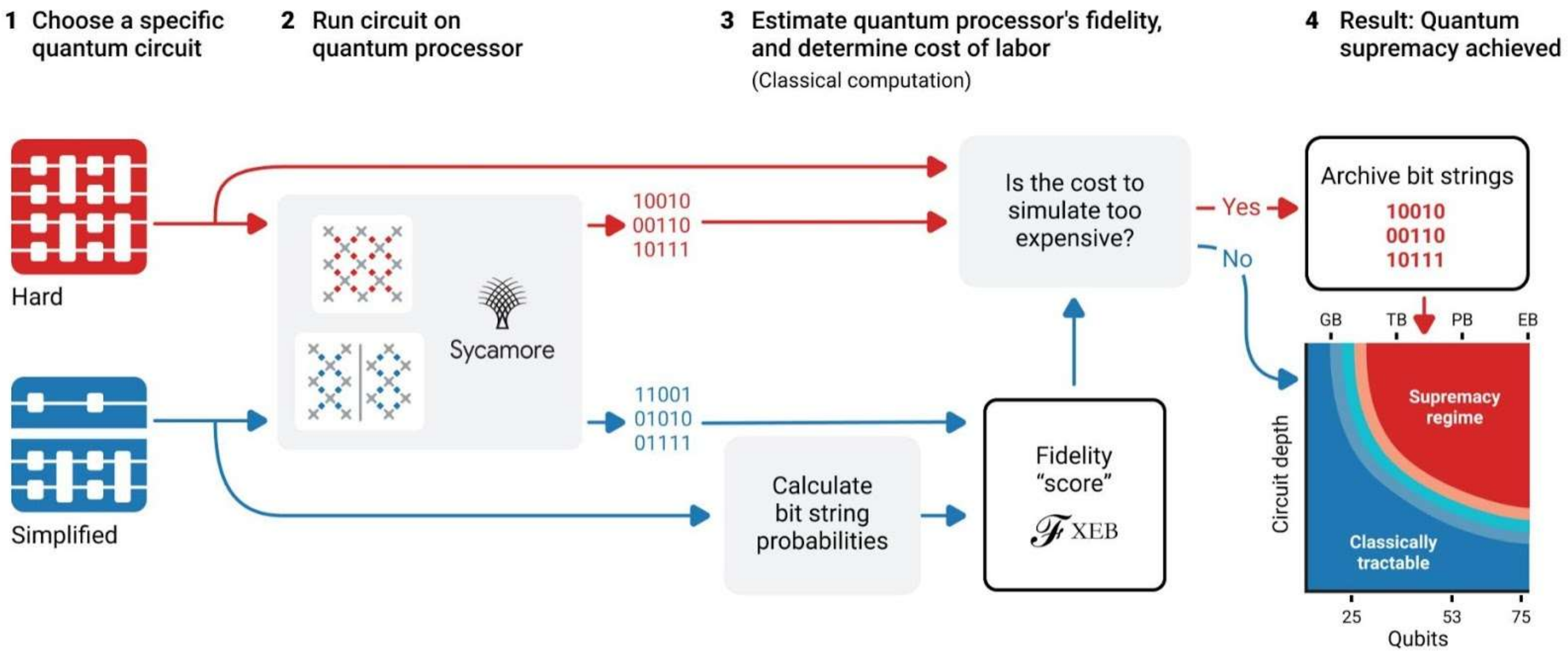






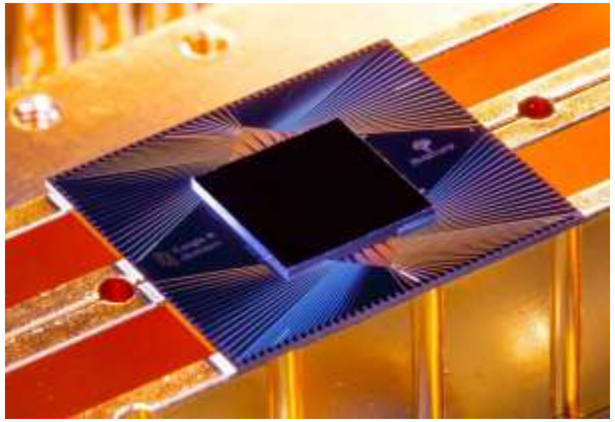
How do we test quantum computers?

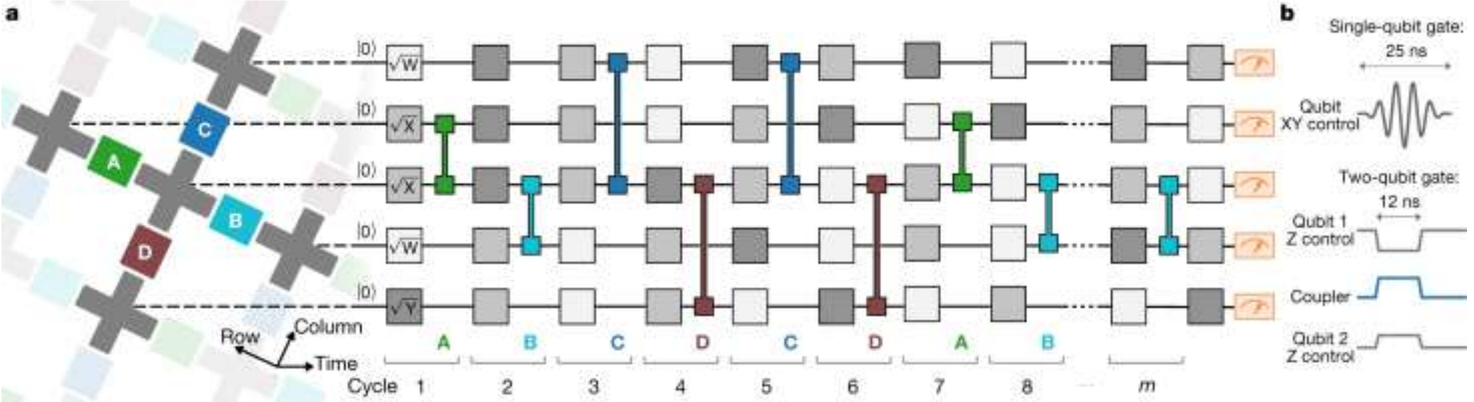
A first test for crossover was the performance of random circuit sampling, quantum supremacy

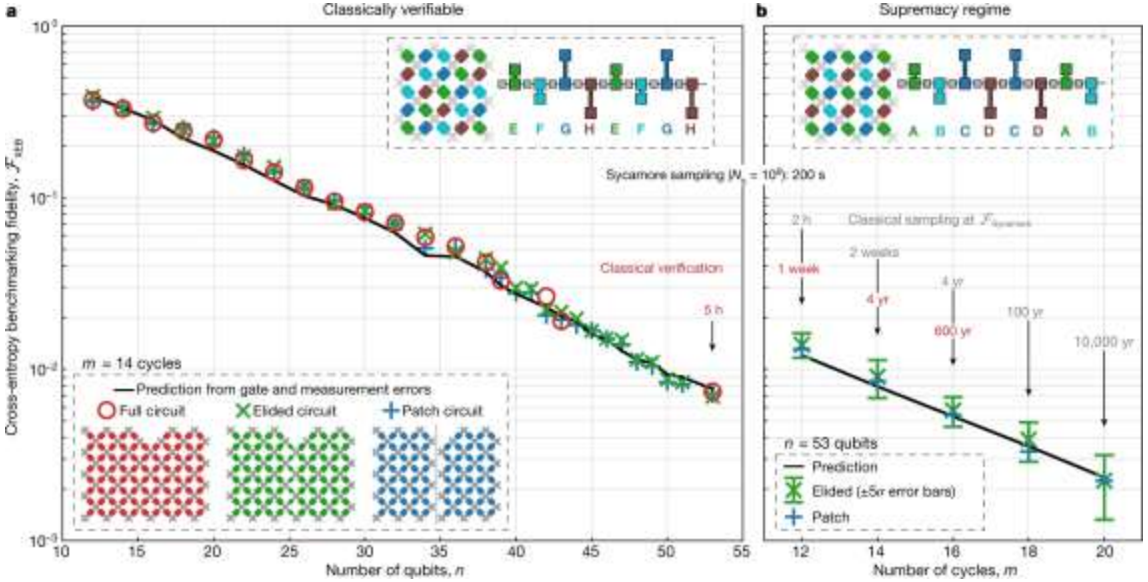


F. Arute et al. "Quantum supremacy using a programmable superconducting processor," Nature 574, 505-510 (2019)

This established a new computational frontier for how quantum processors outperform modern HPC





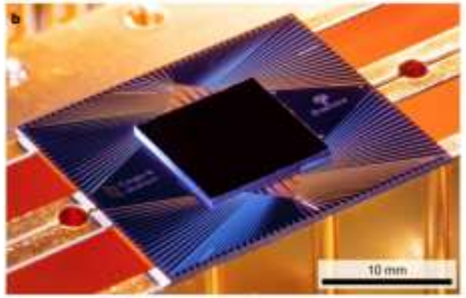


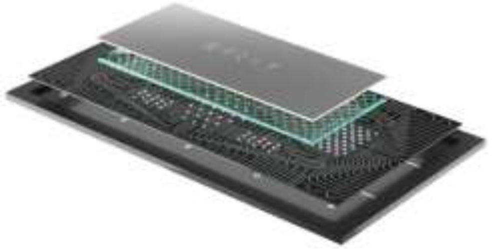
F. Arute et al. “Quantum supremacy using a programmable superconducting processor,” Nature 574, 505-510 (2019)

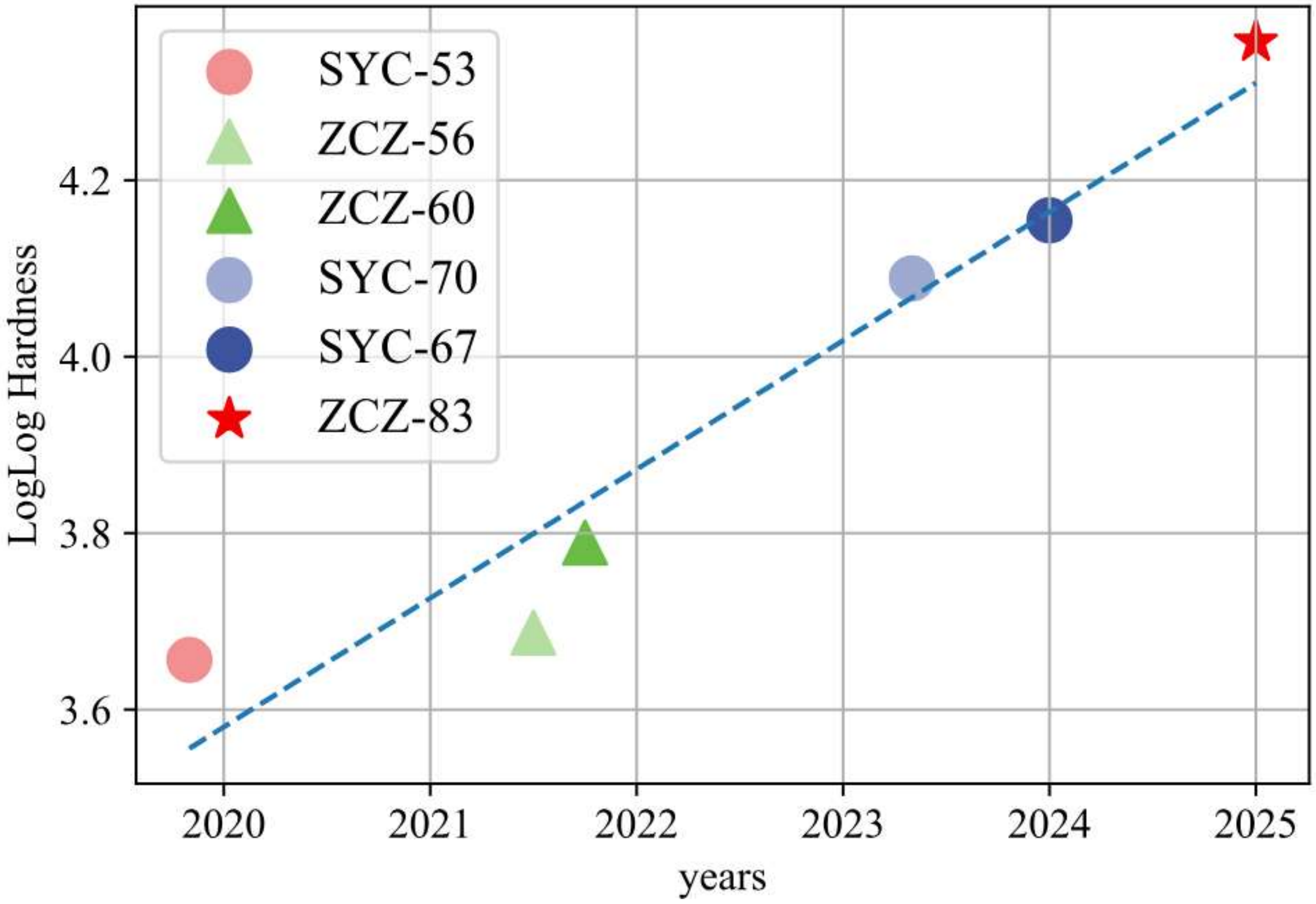
Quantum computing performance systems is rising quickly

The dotted line illustrates a pattern of **doubly exponential growth** for the classical complexity of the random circuit sampling problem solved.

SYC and ZCZ denote the Sycamore and Zuchongzhi processors.







D. Gao et al., “Establishing a New Benchmark in Quantum Computational Advantage with 105-qubit Zuchongzhi 3.0 Processor,” Phys. Rev. Lett. 134, 090601 (2025)

Quantum computing performance now exceeds the limits of HPC

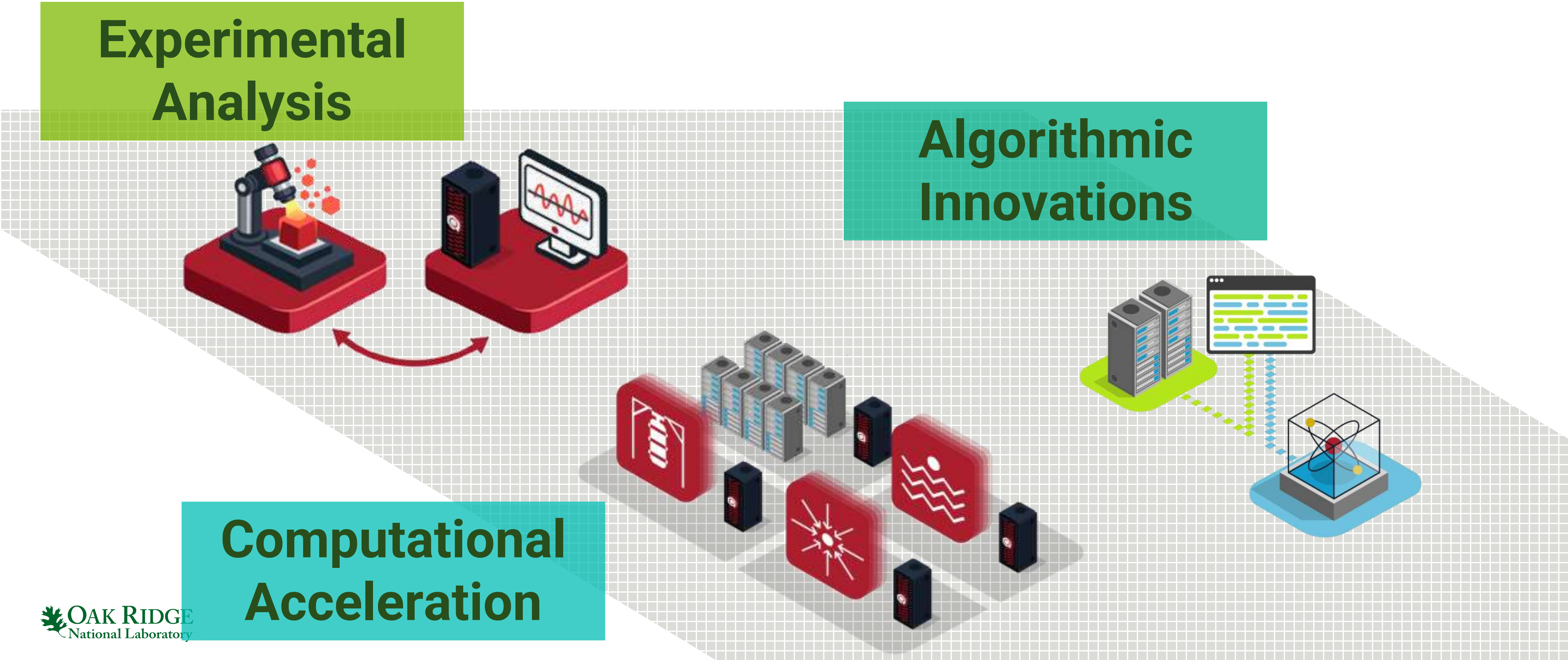
TABLE I. Estimated classical computational cost for different experiments. The Frontier supercomputer boasts a theoretical peak performance of 1.685×10^{18} FLOPS. In our estimations, we presume a 20% FLOP efficiency and convert the machine FLOPS to single-precision complex FLOPS. We provide two scenarios: one with 9.2 PB of memory (the actual memory of Frontier) and another with 762.2 PB (combining Frontier's actual memory with all storage, which is an impractical situation).

		Memory constraint: 9.2 PB			Memory constraint: 762.2 PB		
Experiment	Fidelity	1 amplitude (FLOP)	1×10^6 noisy samples (FLOP)	Run-time on Frontier	1 amplitude (FLOP)	1×10^6 noisy samples (FLOP)	Run-time on Frontier
Sycamore-53-20	2.2×10^{-3}	7.2×10^{18}	6.5×10^{16}	1.6 s	5.9×10^{18}	6.1×10^{16}	1.5 s
Zuchongzhi-56-20	6.6×10^{-4}	9.3×10^{19}	2.2×10^{17}	5.3 s	1.0×10^{20}	1.5×10^{17}	3.6 s
Zuchongzhi-60-24	3.7×10^{-4}	3.2×10^{21}	1.6×10^{19}	384.0 s	3.0×10^{21}	2.3×10^{18}	55.2 s
Sycamore-70-24	1.7×10^{-3}	1.7×10^{25}	8.2×10^{25}	62.1 yr	3.2×10^{24}	1.4×10^{24}	1.1 yr
Sycamore-67-32	1.5×10^{-3}	8.2×10^{28}	4.7×10^{27}	3.6×10^3 yr	1.3×10^{26}	9.6×10^{24}	7.2 yr
Zuchongzhi-83-32	2.3×10^{-4}	5.1×10^{31}	7.7×10^{33}	5.9×10^9 yr	1.3×10^{29}	6.9×10^{31}	5.2×10^7 yr

D. Gao et al., "Establishing a New Benchmark in Quantum Computational Advantage with 105-qubit Zuchongzhi 3.0 Processor," Phys. Rev. Lett. 134, 090601 (2025)

How will we use quantum computers?

Tightly coupling quantum computers with scientific capabilities creates hybrid workflows that transcend conventional methods



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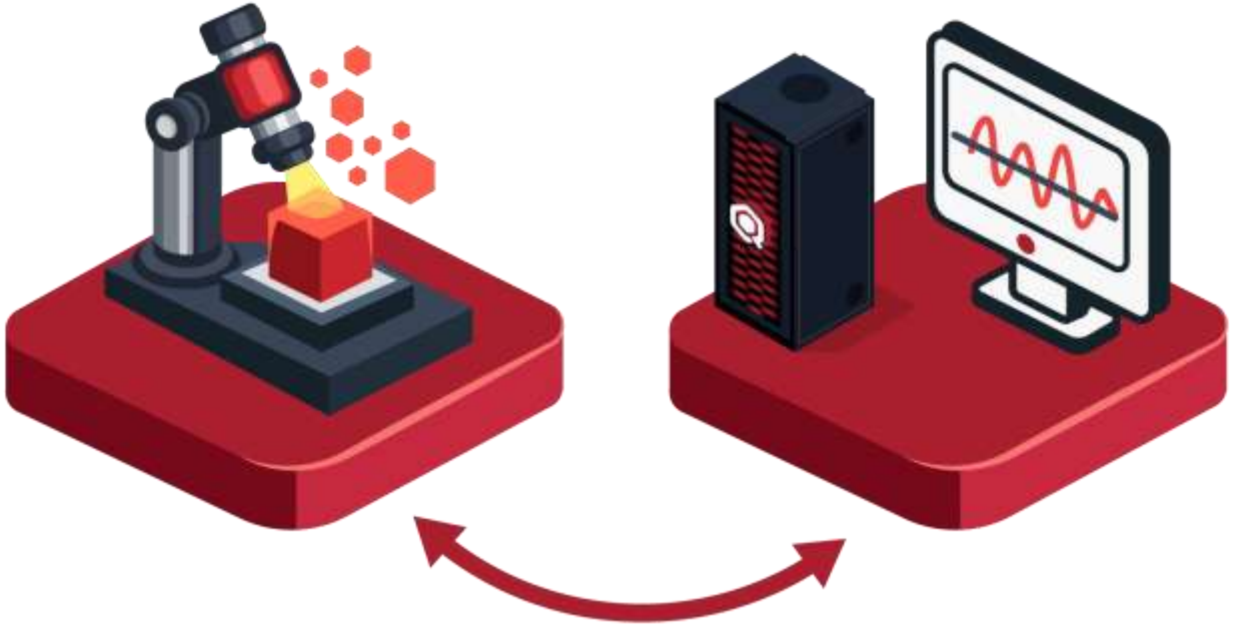
Quantum twins couple theoretical models with experimental data to offer new platforms for simulating measurements



New experimental setups may be too costly or time consuming to implement

A high-fidelity material model on a quantum computer can be used to test new measurements ideas

Concurrent measurements across different parameter regimes are enabled by quantum predictive power

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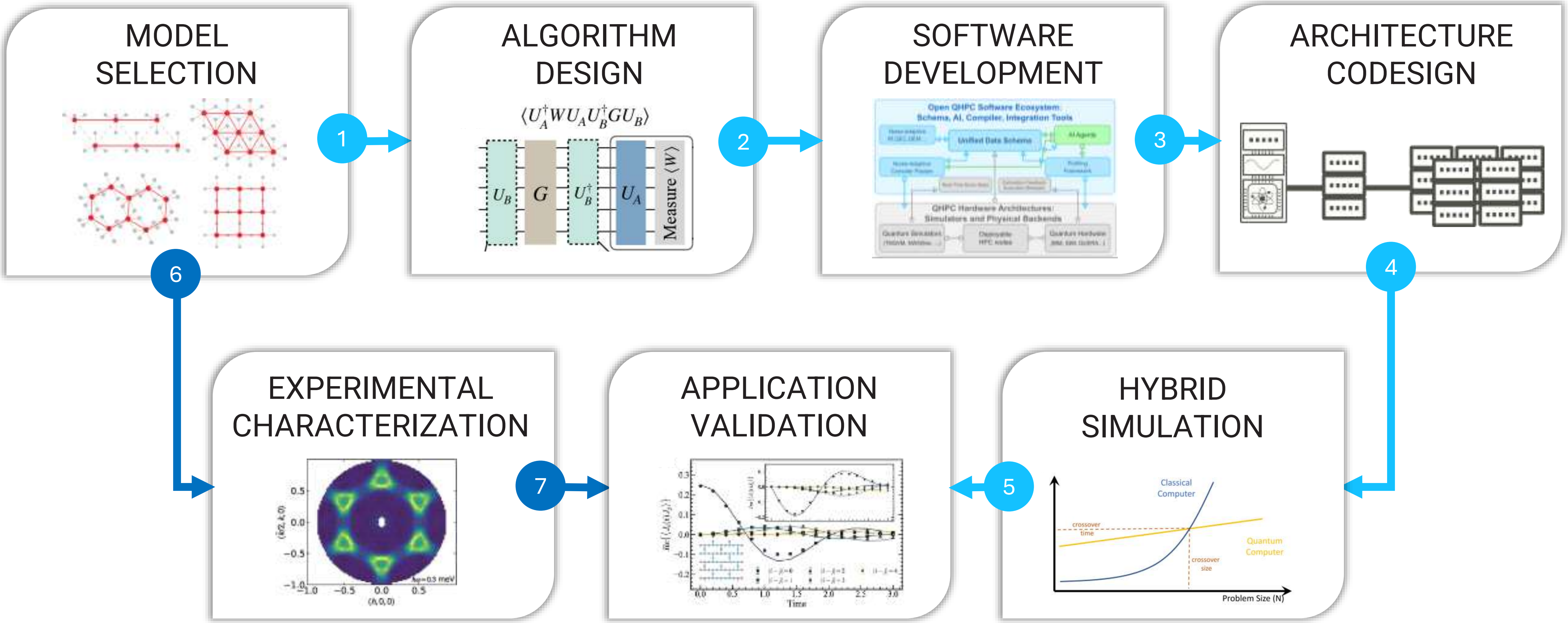
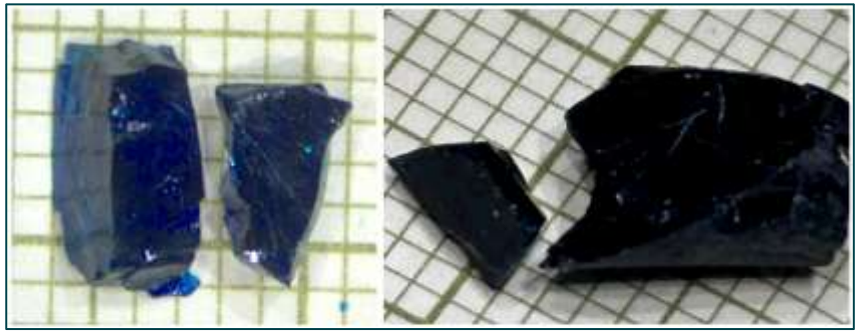
The *quantum simulation workflow* validates theoretical models for materials against experimental cauterization



We are measuring and modeling materials to guide quantum simulations towards new scientific discoveries



Quantum spin liquids are a phase of matter where magnetic spins do not freeze into a fixed pattern, even at absolute zero temperature, due to strong quantum correlations

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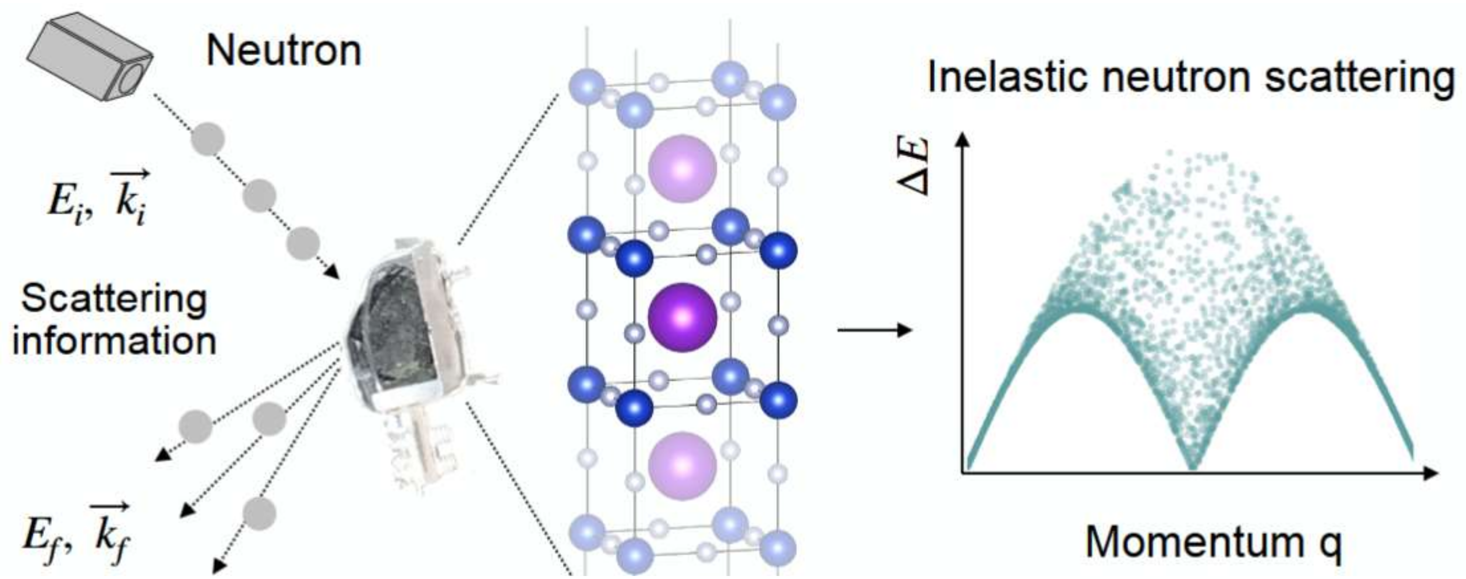
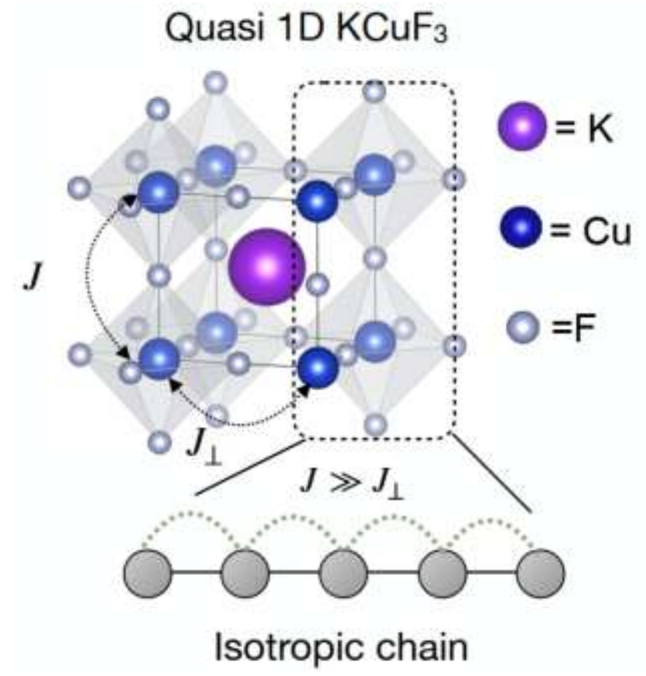
Y.-T. Lee et al., "Benchmarking quantum simulation with neutron scattering experiments," (2026)

Neutrons scatter off magnetic ions in a material, exchanging both energy and momentum with its spins





The measured signal can be used to compute **two-point dynamical correlation functions** that capture how local excitations propagate through the system in space and time.

Y.-T. Lee et al., "Benchmarking quantum simulation with neutron-scattering experiments," arxiv:2603.15608 (2026)

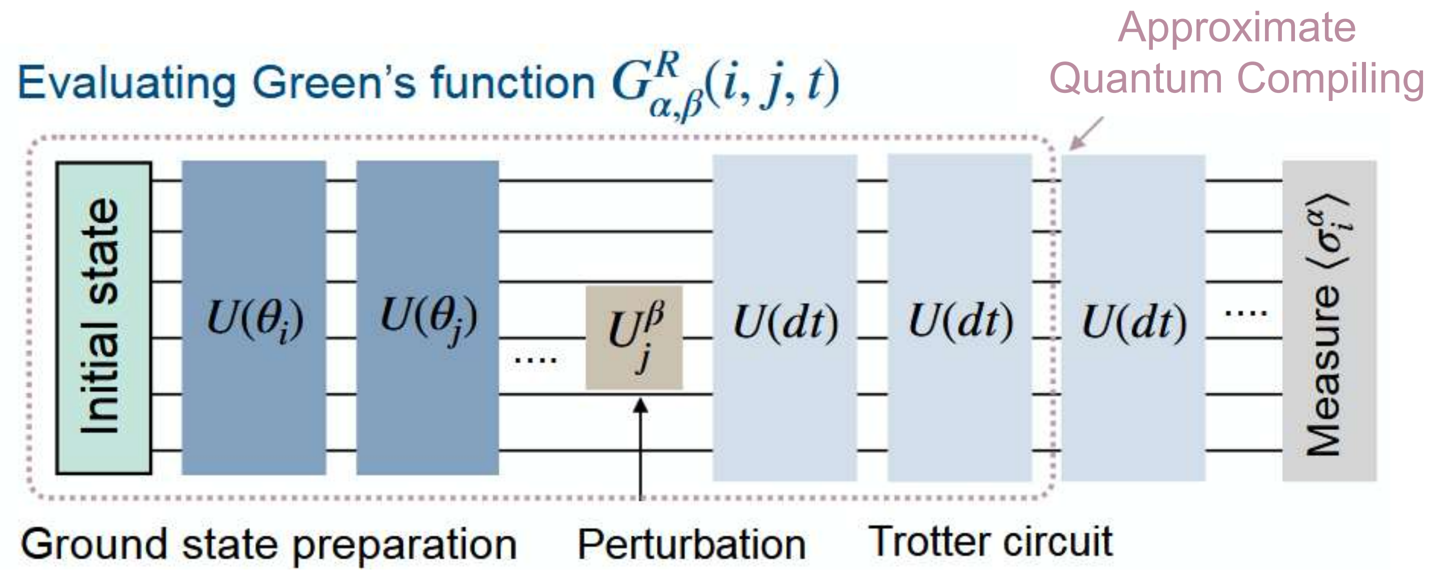
Quantum simulation calculate the dynamic structure factor underlying the inelastic neutron scattering spectra

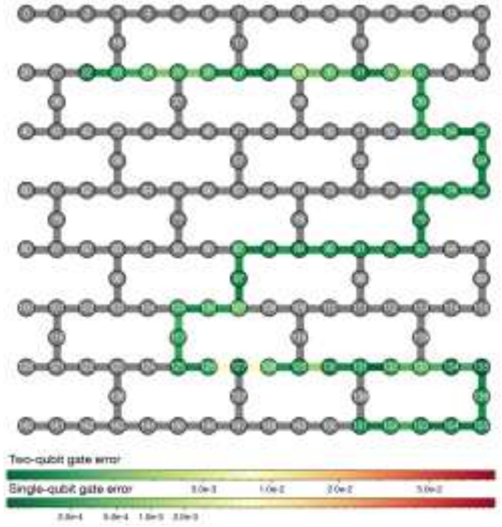
$$I(\mathbf{q},\omega) = (\gamma r_0)^2 \frac{k_f}{k_i} \left|\frac{g}{2}F(\mathbf{q})\right|^2 \sum_{\alpha,\beta=x,y,z} (\delta_{\alpha\beta} - \hat{q}_\alpha \hat{q}_\beta)\, S^{\alpha,\beta}(\mathbf{q},\omega)$$

$$H_{\mathrm{NN}} = 2J \sum_{i=1}^{N-1} \left(S_i^Z S_{i+1}^Z + \epsilon(S_i^X S_{i+1}^X + S_i^Y S_{i+1}^Y)\right)$$

$$S_{\alpha,\beta}(q,\omega) = -\frac{1}{\pi}[1 + n_B(\omega)]\, Im[G^R_{\alpha,\beta}(q,\omega)]$$

$$G^R_{\alpha,\beta}(i,j,t) = -\frac{i}{2}\langle S_i^\alpha(t) S_j^\beta - S_j^\beta S_i^\alpha(t)\rangle_0$$





50-qubit chain on the IBM Heron processor ibm_boston

Y.-T. Lee et al., "Benchmarking quantum simulation with neutron-scattering experiments," arxiv:2603.15608 (2026)

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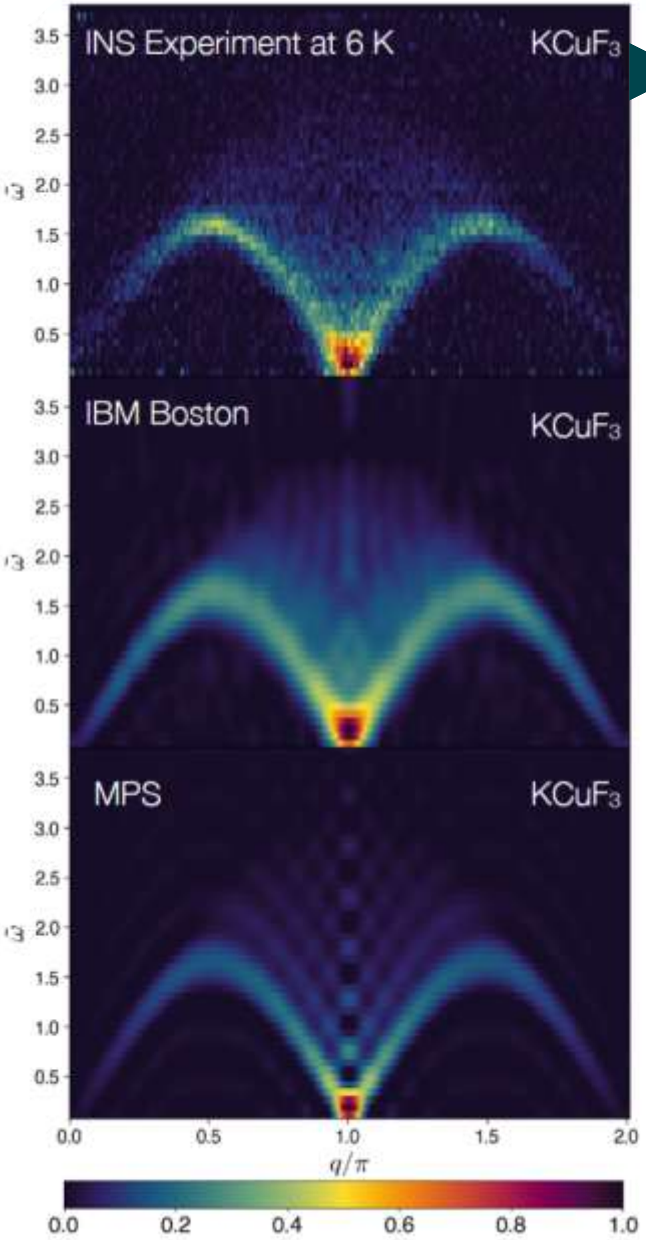
Quantum simulation calculates inelastic neutron scattering spectrum

Simulated results using a 1D model give very good agreement.

Numerical methods give similar accuracy, but do not scale in dimensionality.

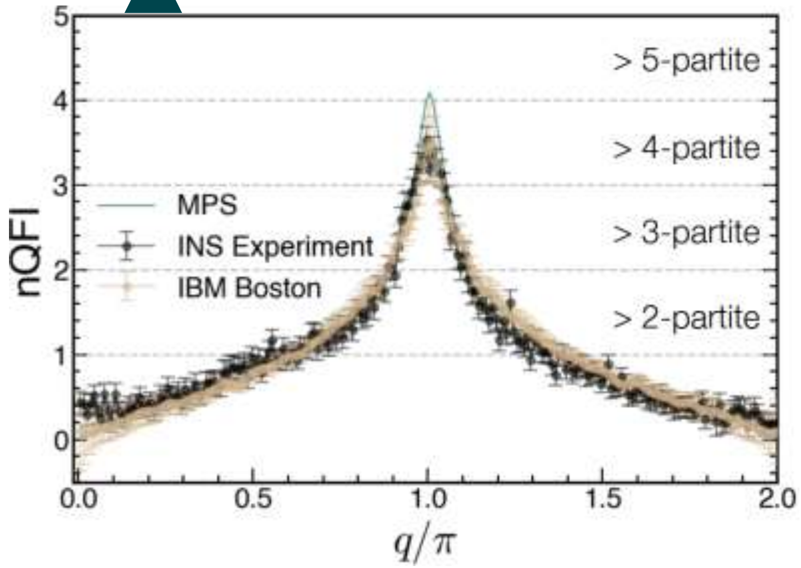
Zero temperature suffices for this model material, but thermodynamics will be important.

Spatial and temporal resolutions are driven by circuit width and depth.



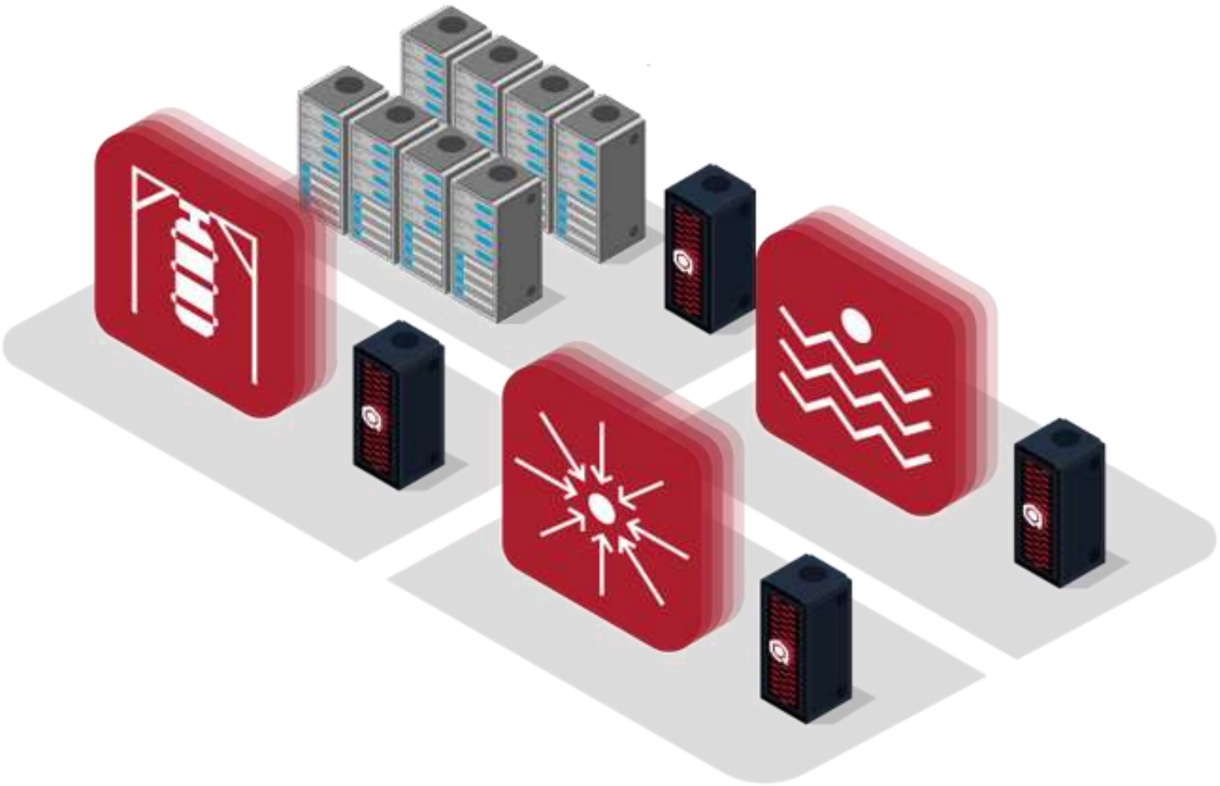
Measured, simulated, and numerical spectra for $KCuF_3$ under a 1D XX model assumption.

Quantum Fisher Information validates entanglement in the probed quantum state



Y.-T. Lee et al., "Benchmarking quantum simulation with neutron-scattering experiments," arxiv:2603.15608 (2026)

Hybrid computing platforms couple emerging technologies to accelerate quantum simulation campaigns



Quantum computing is one of many technologies supporting computation

Hybrid platform development drives new designs for better integration

Performance and efficiency are essential measures of system utility

But adoption is the final test of value

Converging quantum computing with HPC and AI creates a post-exascale computing paradigm

How will these three technological platforms integrate to advance computation?

Quantum computing must scale up to match the sophistication HPC and AI.

HPC and AI are likely pivotal results for operating large-scale quantum computers, circuit/program design

QC-AI-HPC yields a model of hierarchical computation built from heterogeneous architectures.

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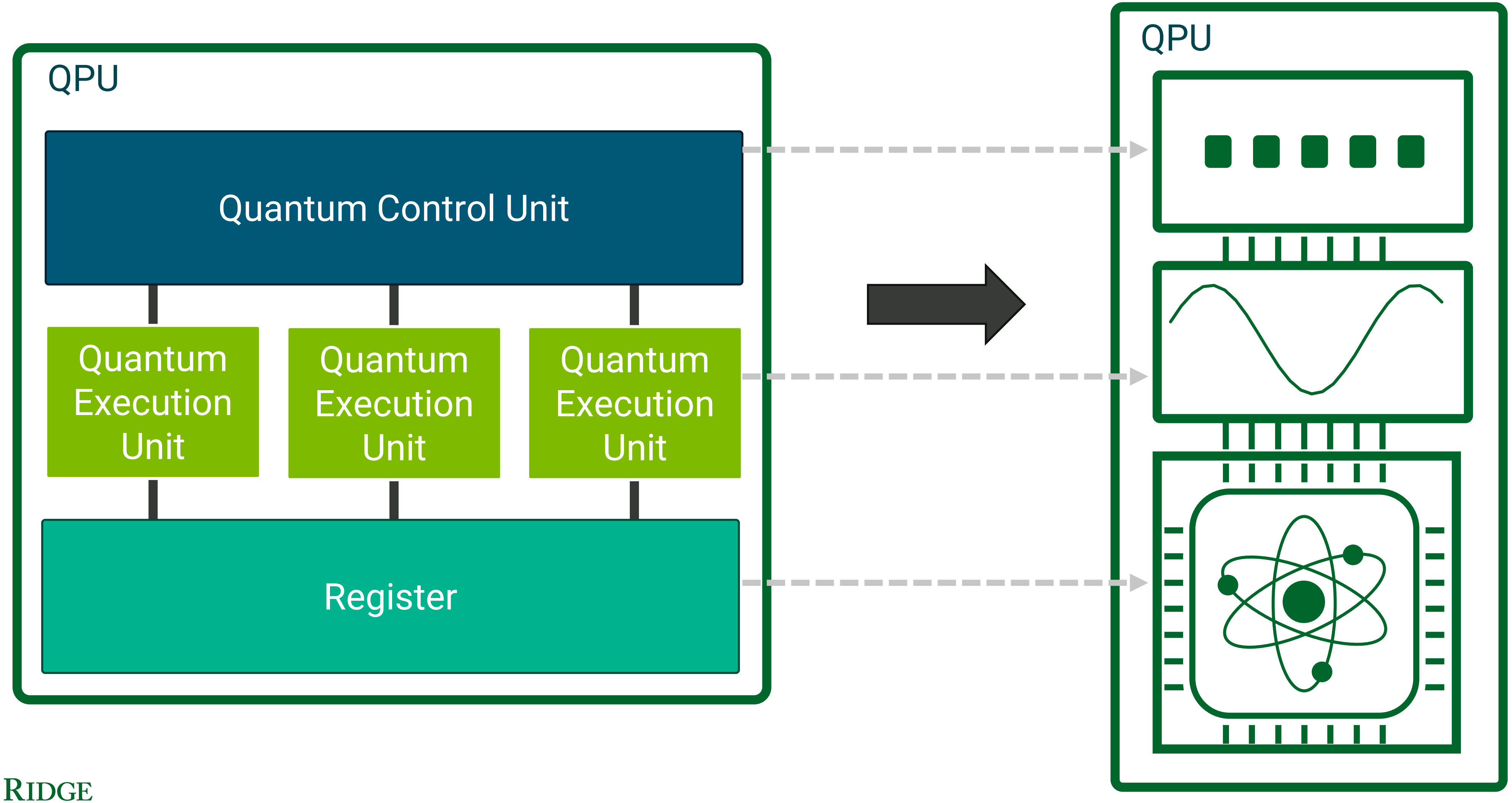
The quantum processing unit (QPU) is a fundamental logical concept for integrating quantum computing



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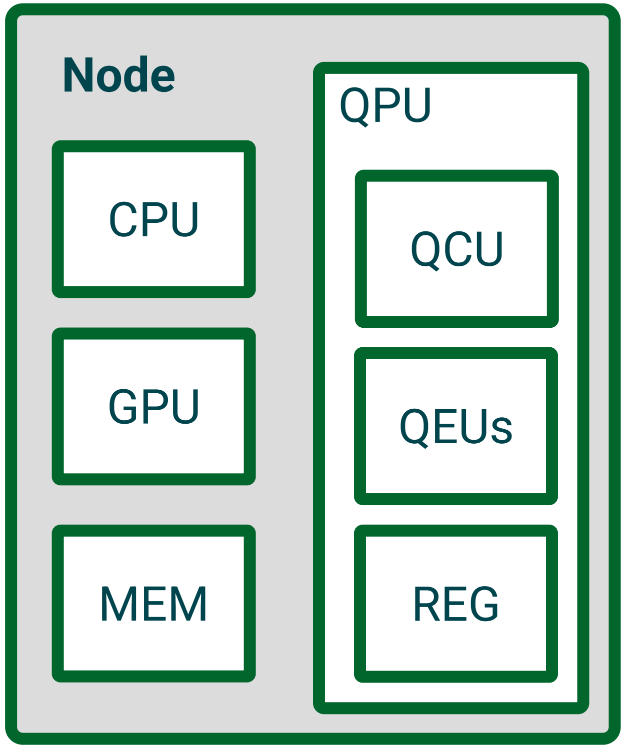
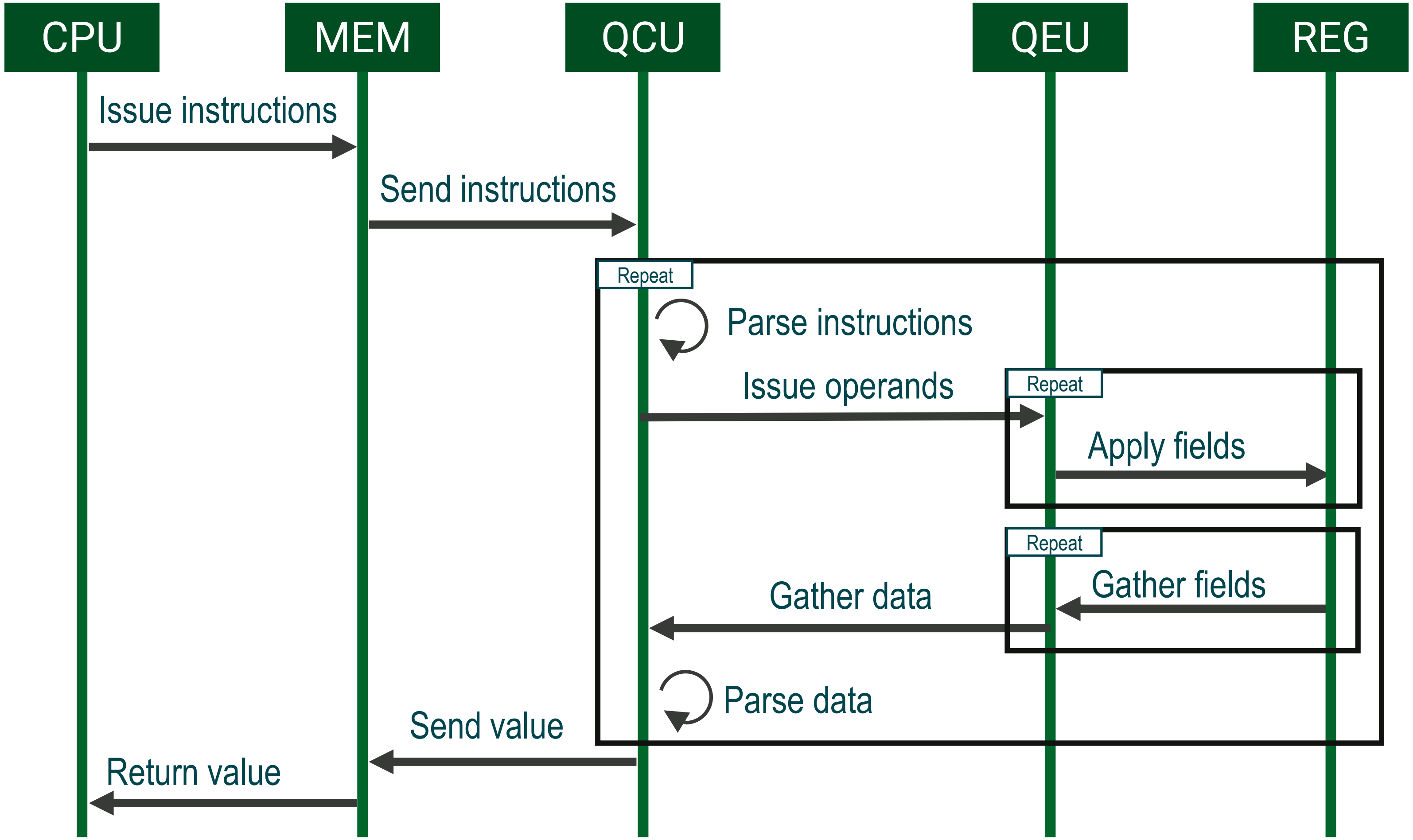
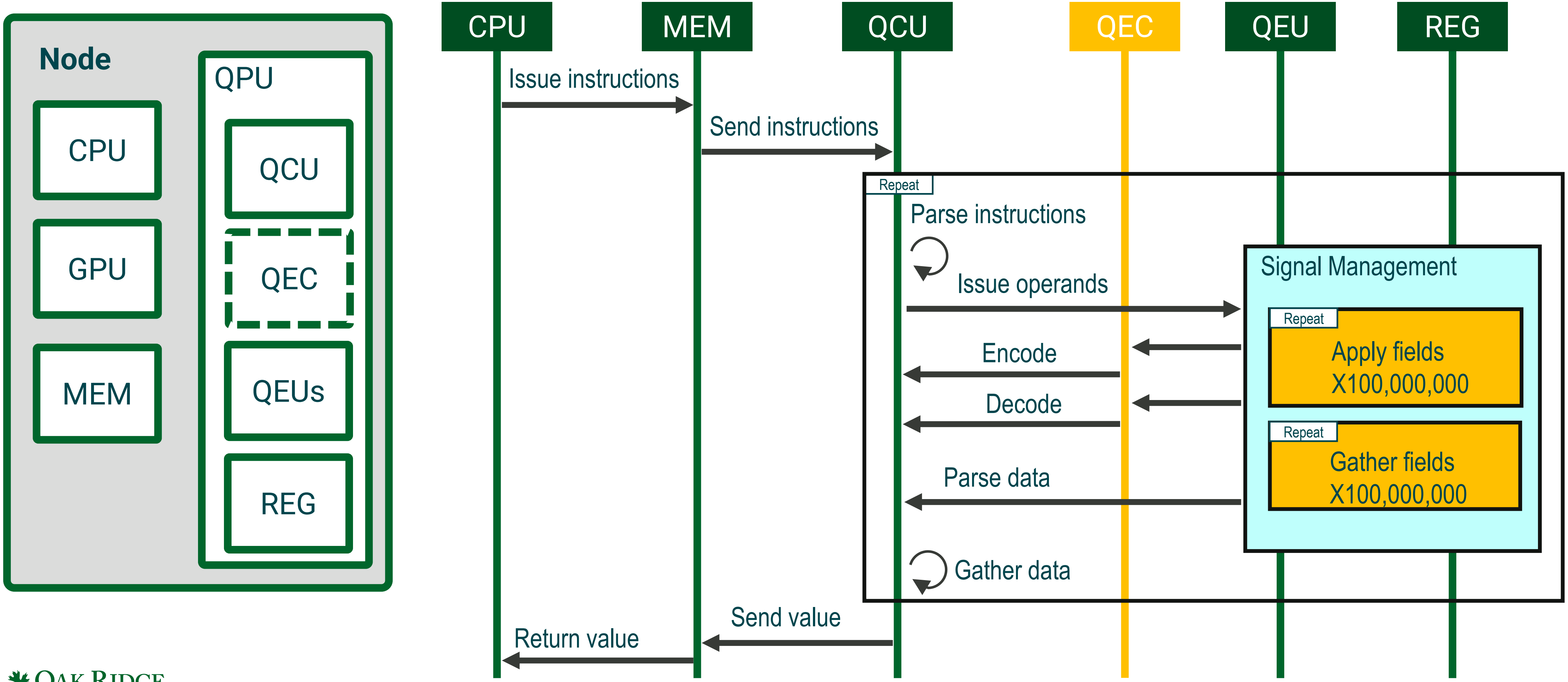
Integration with conventional CPU systems requires a hybrid execution model with different clock cycles





Integration with conventional CPU systems requires a hybrid execution model with different clock cycles



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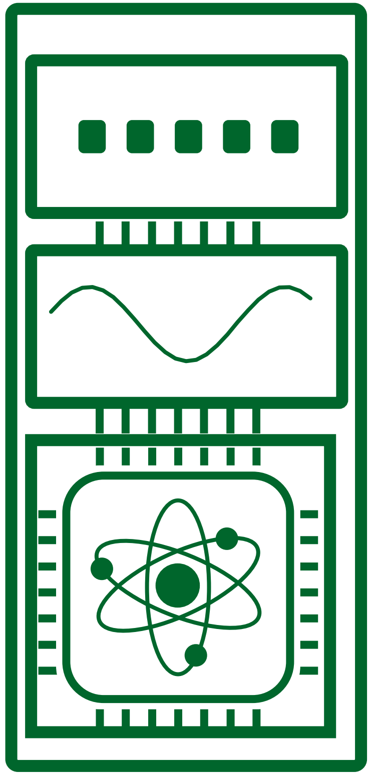
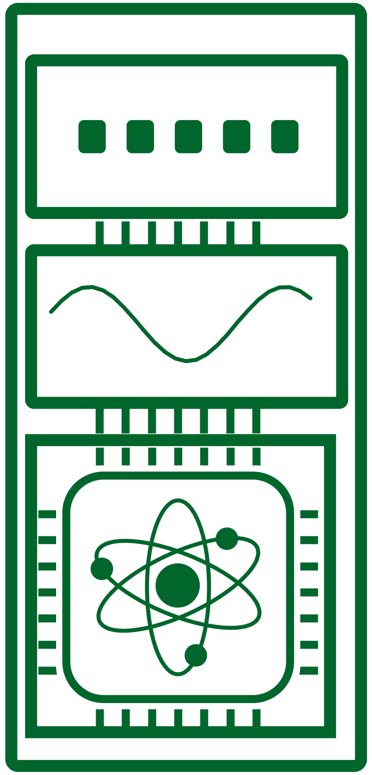
Integrating QPUs creates a hierarchical model for QHPC



Integrating QPUs creates a hierarchical model for QHPC

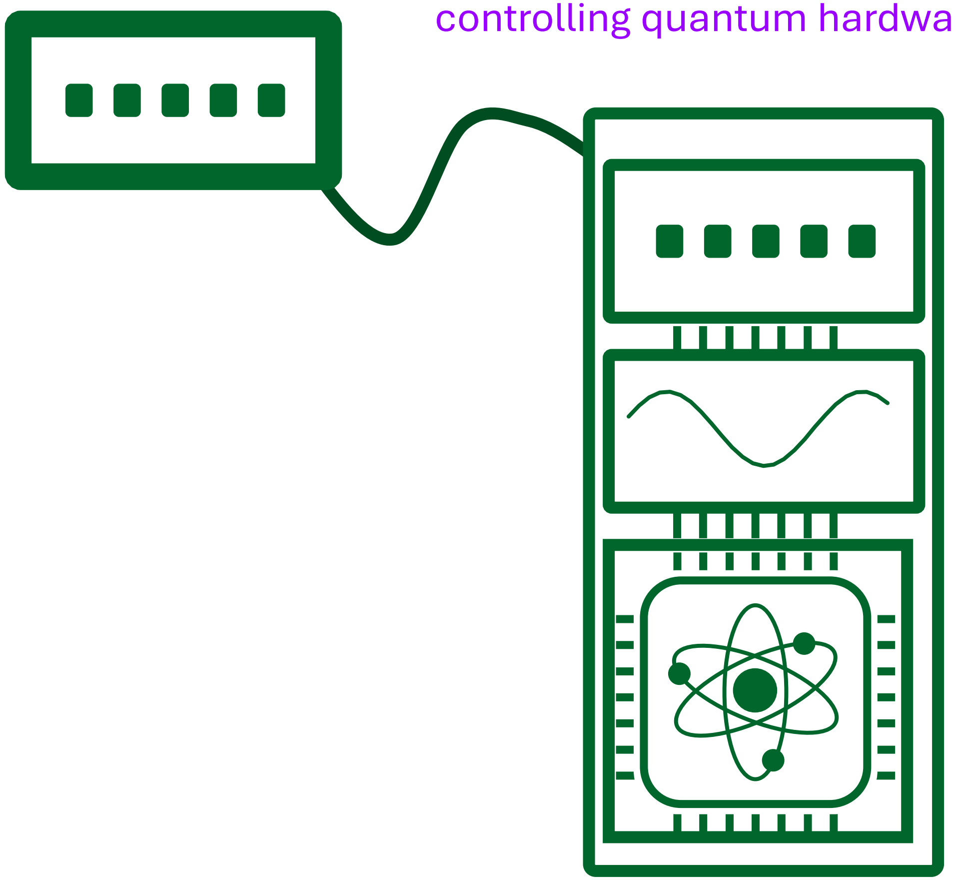
Micro-architecture integration
of low-latency HPC resource for
controlling quantum hardware



Integrating QPUs creates a hierarchical model for QHPC

Meso-architecture integration of localized HPC resources for supplementing quantum computing performance

Micro-architecture integration of low-latency HPC resource for controlling quantum hardware



Integrating QPUs creates a hierarchical model for QHPC

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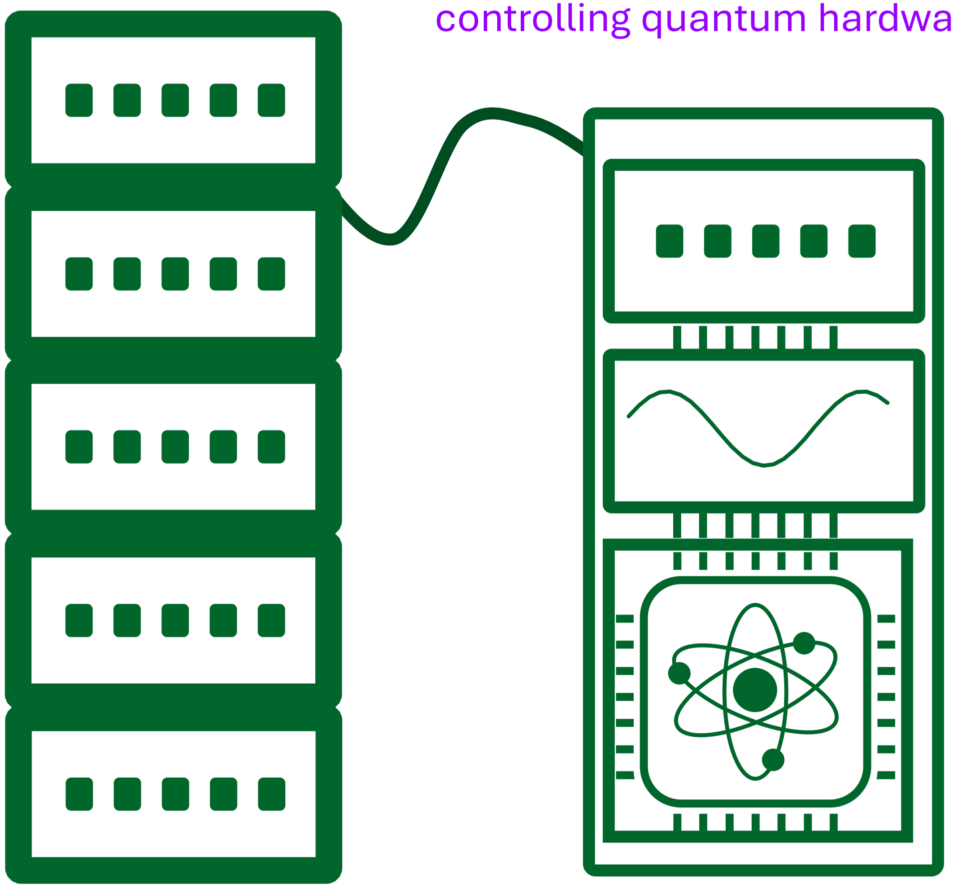

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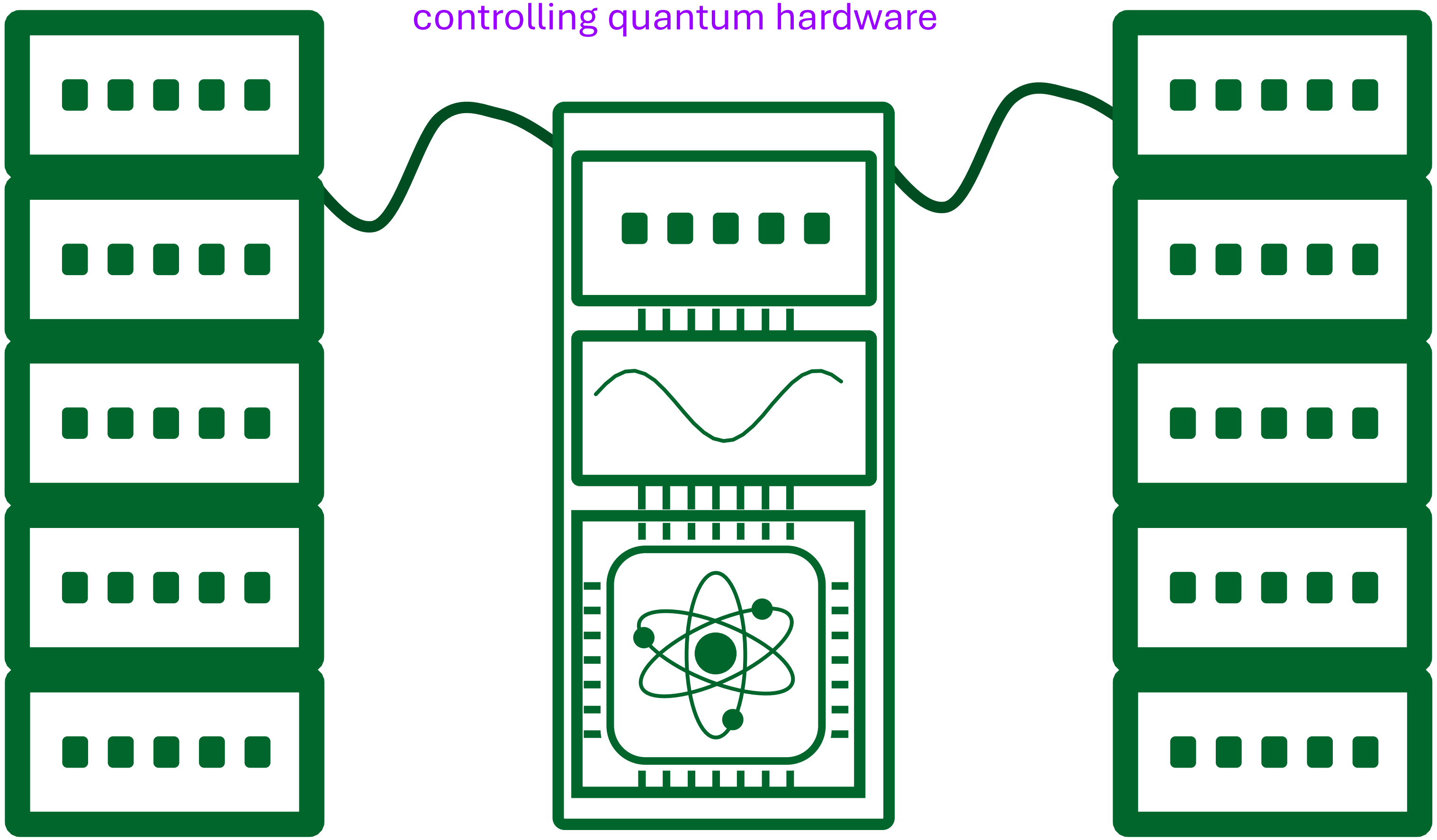

Macro-architecture integration of system resources including quantum computers

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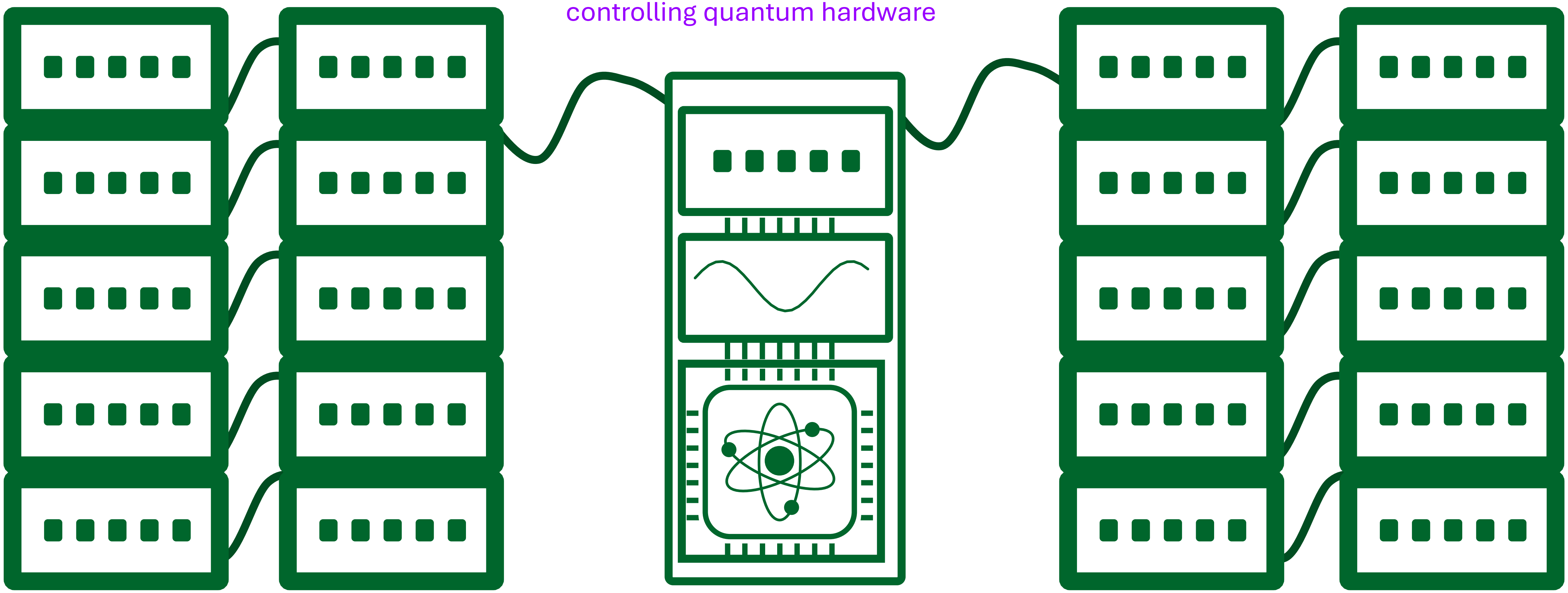

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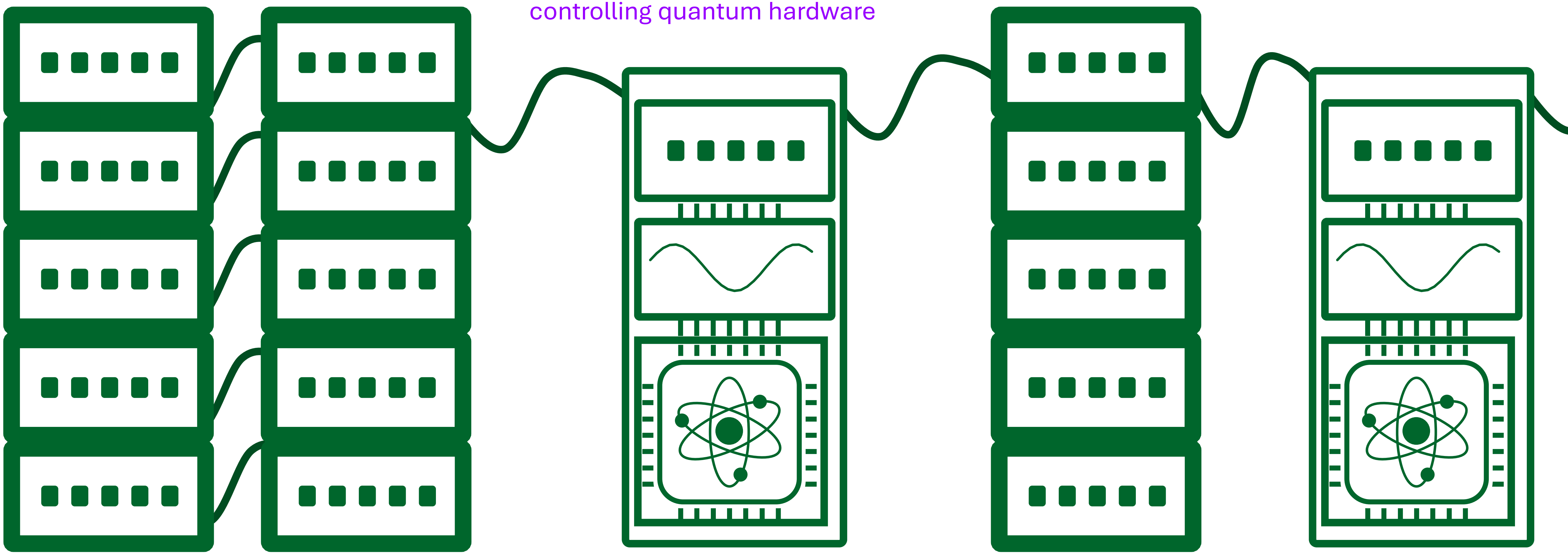

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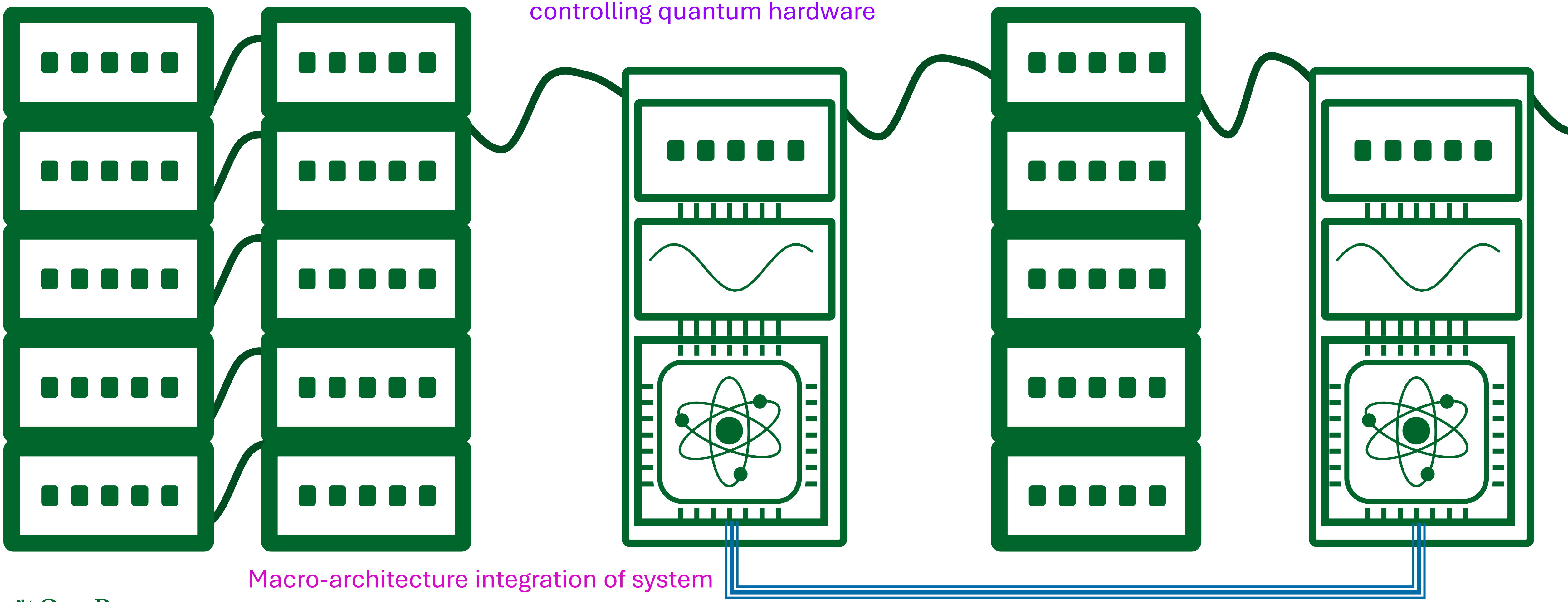
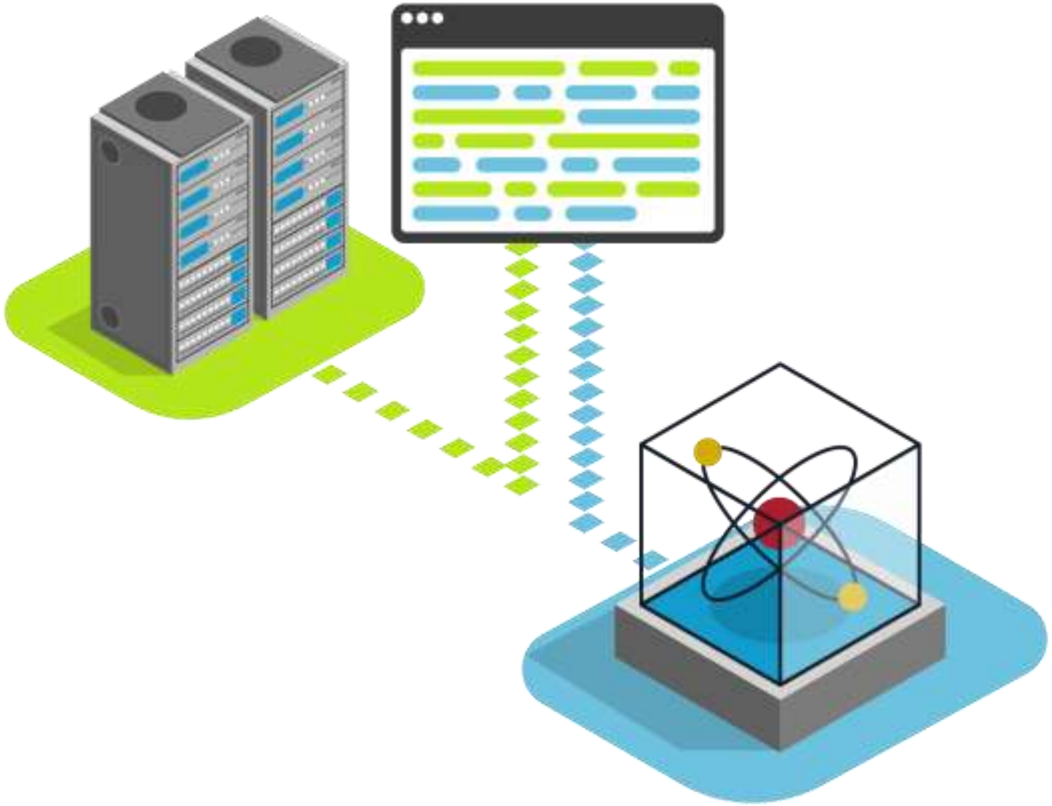


Macro-architecture integration of system resources including quantum computers

Algorithmic innovations use alternating representations to process data, learn meaning, and make decisions

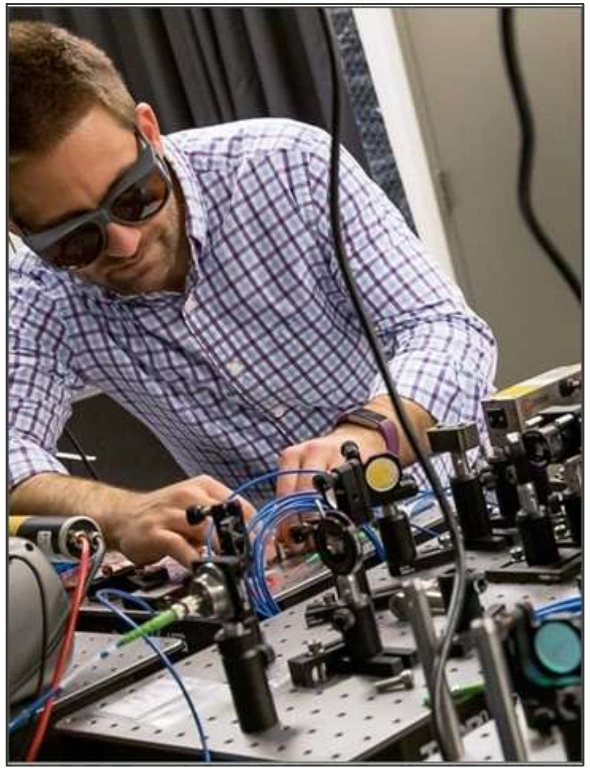


Quantum computation is a superset of classical computation

Many classical "heuristics" complement quantum processing

Finding the balance between algorithmic methods requires context, trial and error approach

Access to quantum computers is essential for practical advances in integration, scaling, and tooling

Online Access	Commercial Systems	Hybrid Integrations	Custom Experiments
			

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The Quantum Computing User Program is a first step to building a community of quantum computer users

Enable Research

Provide a broad spectrum of user access to the best available quantum computing systems

Evaluate Technology

Monitor the breadth and performance of early quantum computing applications

Engage Community

Support growth of the quantum ecosystem by engaging with users, developers, vendors, and providers

Quantum Computing User Forum 20-24 July

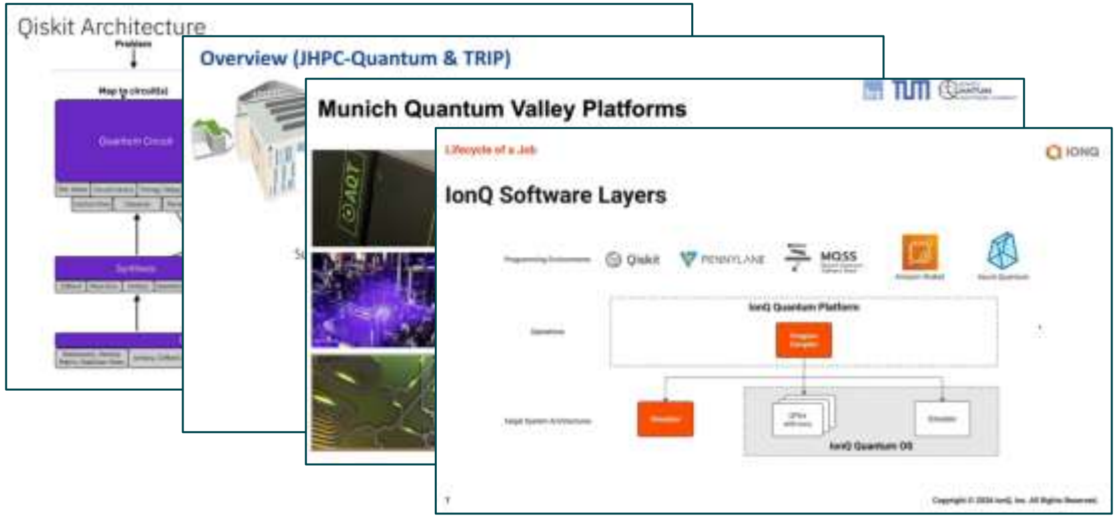
On-premises installations accelerate the transition of quantum computing to a trusted scientific instrument for discovery, innovation, and national competitiveness

Hybrid system design requires input from many disciplines to program, orchestrate, and manage workflow complexity

openQSE is an open, modular ecosystem for integrating HPC and quantum computing through interoperable, vendor-neutral technologies

openQSE Development Community

- Oak Ridge National Laboratory
- Argonne National Laboratory
- Lawrence Berkely Laboratory
- Leibniz Supercomputing Centre
- RIKEN
- ASTAR
- Barcelona Super Computing
- Ellison Institute of Technology Oxford
- Indian Institute of Science
- University of Illinois
- University of Arizona
- Alice & Bob
- Q-CTRL
- Qblox
- IBM
- Munich Quantum Software
- Amazon Web Services
- Hewlett Packard Enterprise
- Dell Technologies
- IonQ
- Quantinuum
- Pasqal
- Xanadu
- Quantum Brilliance
- Advanced Micro Devices
- NVIDIA
- Microsoft

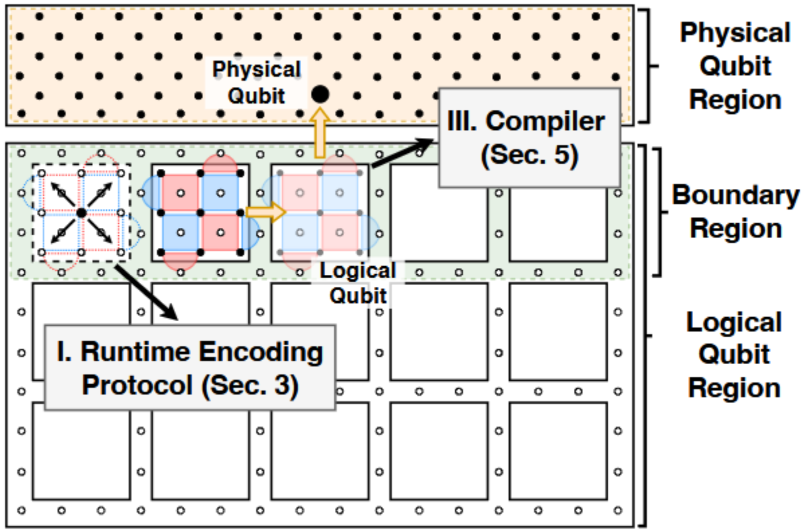


www.youtube.com/@openqse

A. Shehata et al., “Quantum–HPC Software Stacks and the openQSE Reference Architecture: A Survey,” arxiv:2604.20912 (2026)

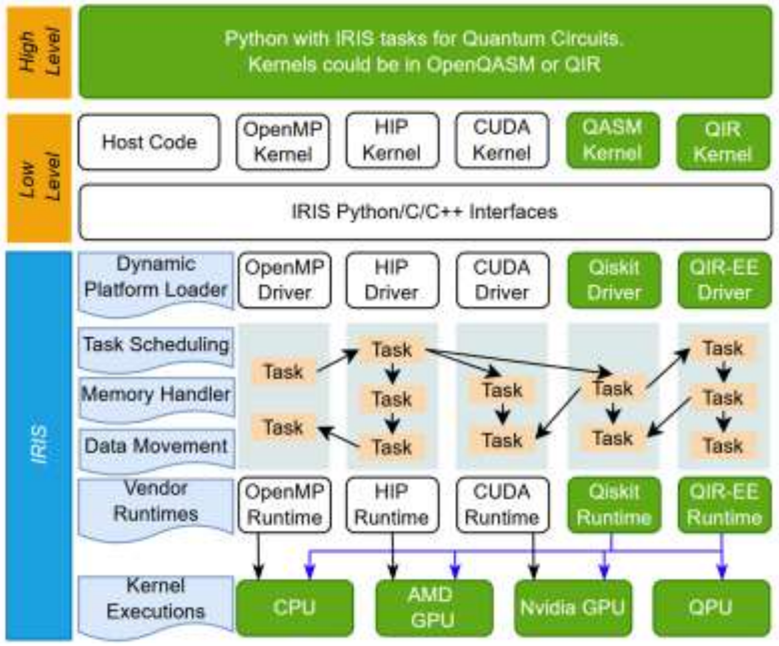
Tooling is enabling the programming and execution of computing resources within integrated hierarchical systems

Compilers and Debuggers



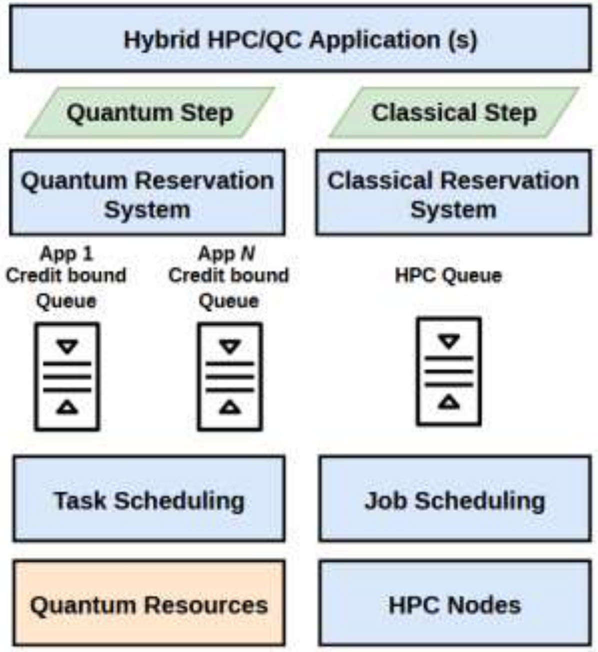
K. Yin et al., "iSwitch: QEC on Demand via In-Situ Encoding of Bare Qubits for Ion Trap Architectures," ASPLOS 2026; cf. arXiv:2504.16303

Run-time Environments



N. Rao Miniskar et al., "Q-IRIS: The Evolution of the IRIS Task-Based Runtime to Enable Classical-Quantum Workflows," SCA/HPCAsia 2026. cf. arXiv:2512.13931

Resource Management



A. Shehata et al., "Bridging paradigms: Designing for HPC-Quantum convergence," Future Generation Computer Systems 174, 107980 (2026)

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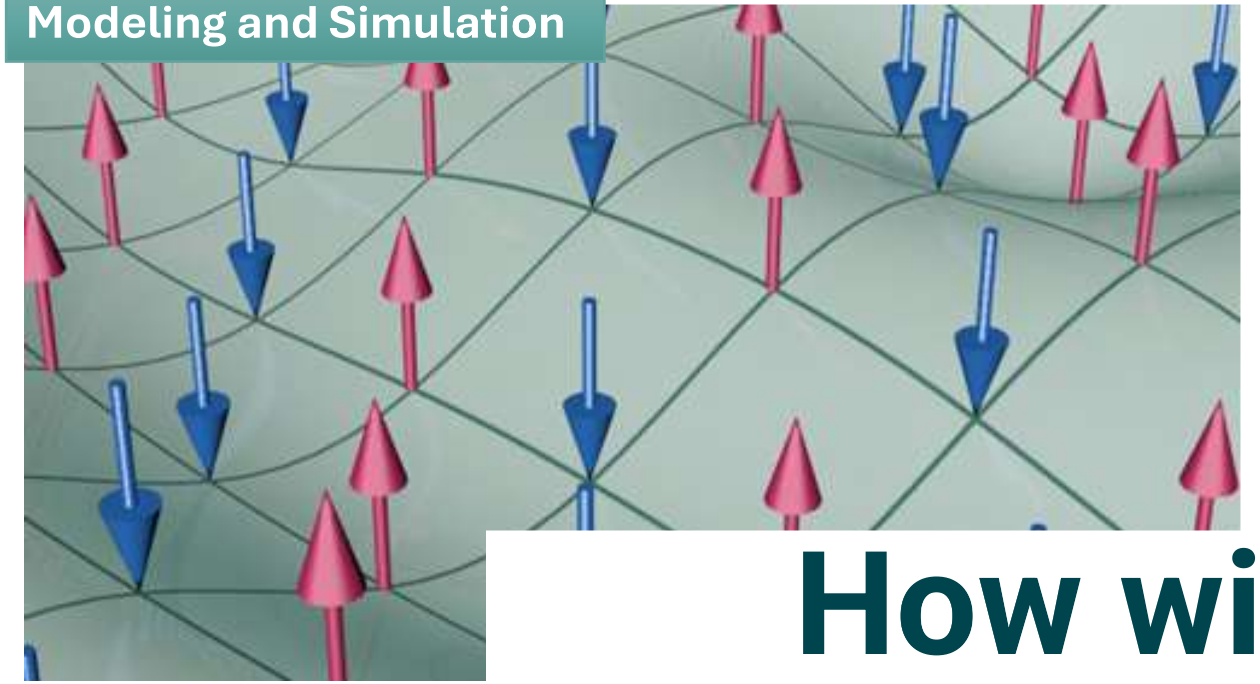
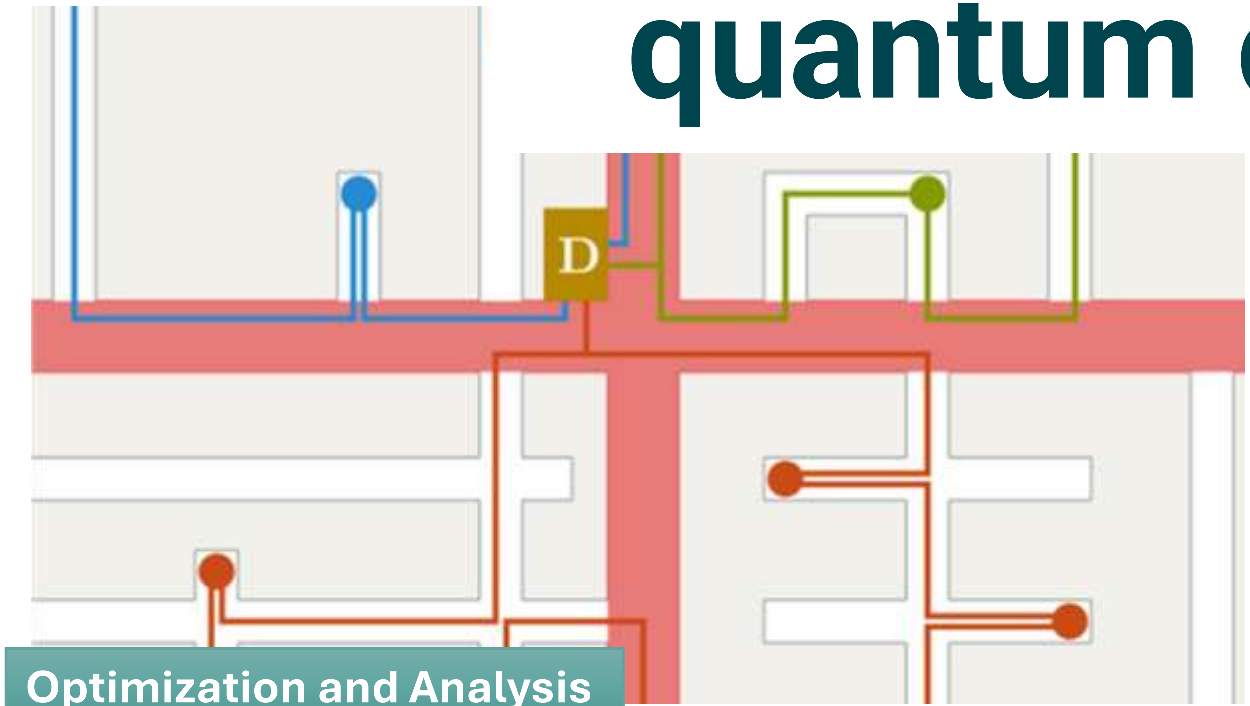
Modeling and Simulation



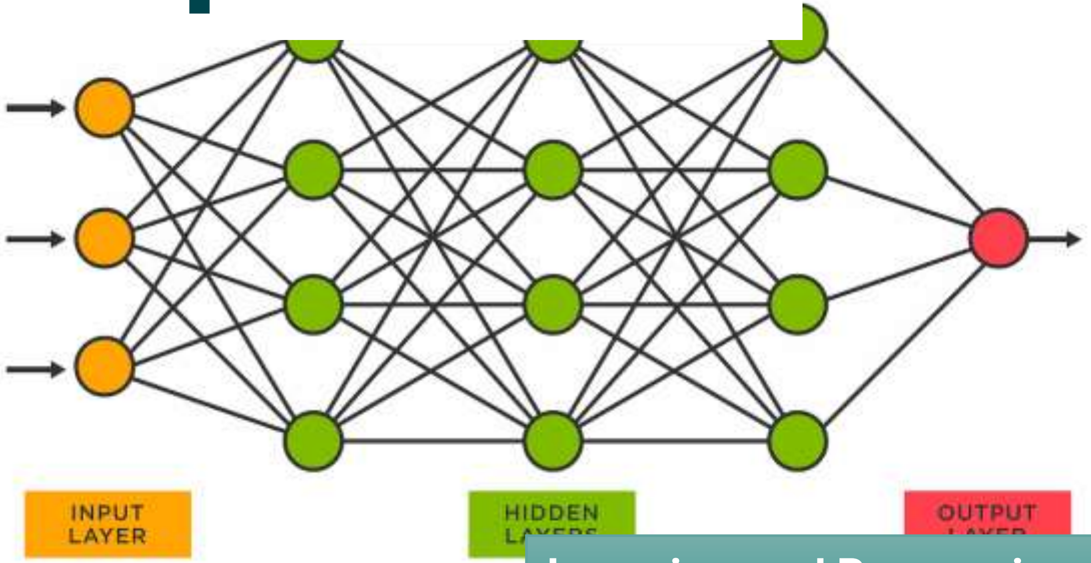
Verification and Validation

How will we use quantum computers?

Optimization and Analysis



Learning and Processing



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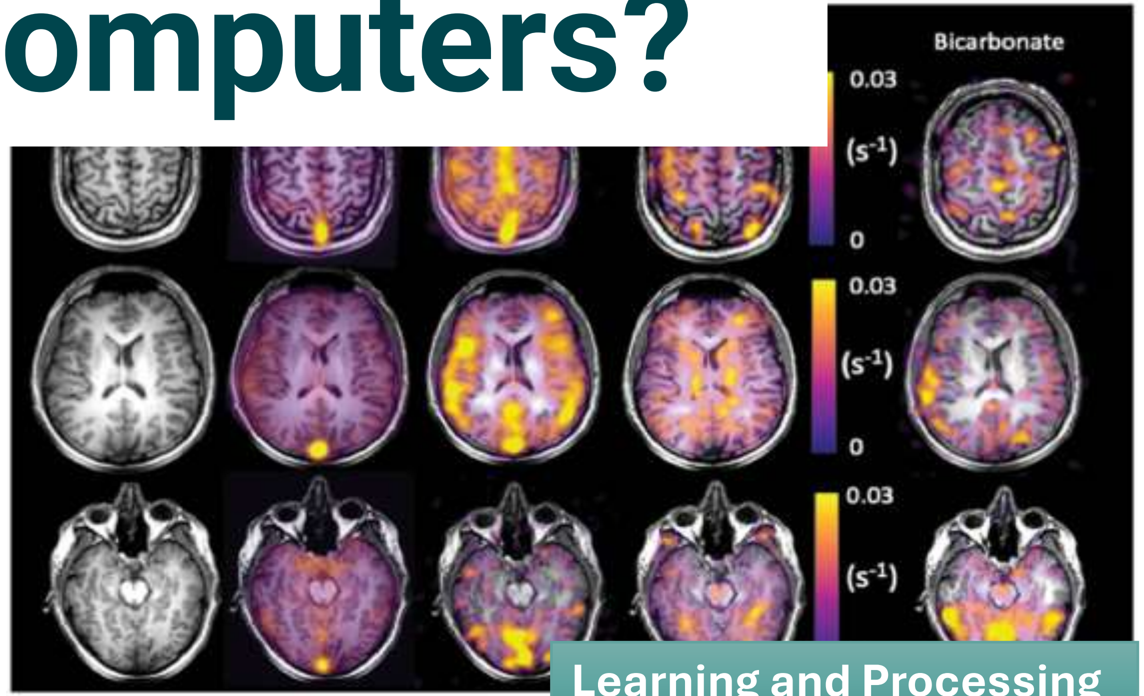

Learning and Processing

Economic impact from quantum technologies is estimated to exceed $2.7T by 2035

McKinsey & Company, Quantum Technology Monitor, April 2026

We must continue developing disruptive technologies, forging new partnerships, and cultivating elite technical talent

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