Berkeley Lab Quantum Computing

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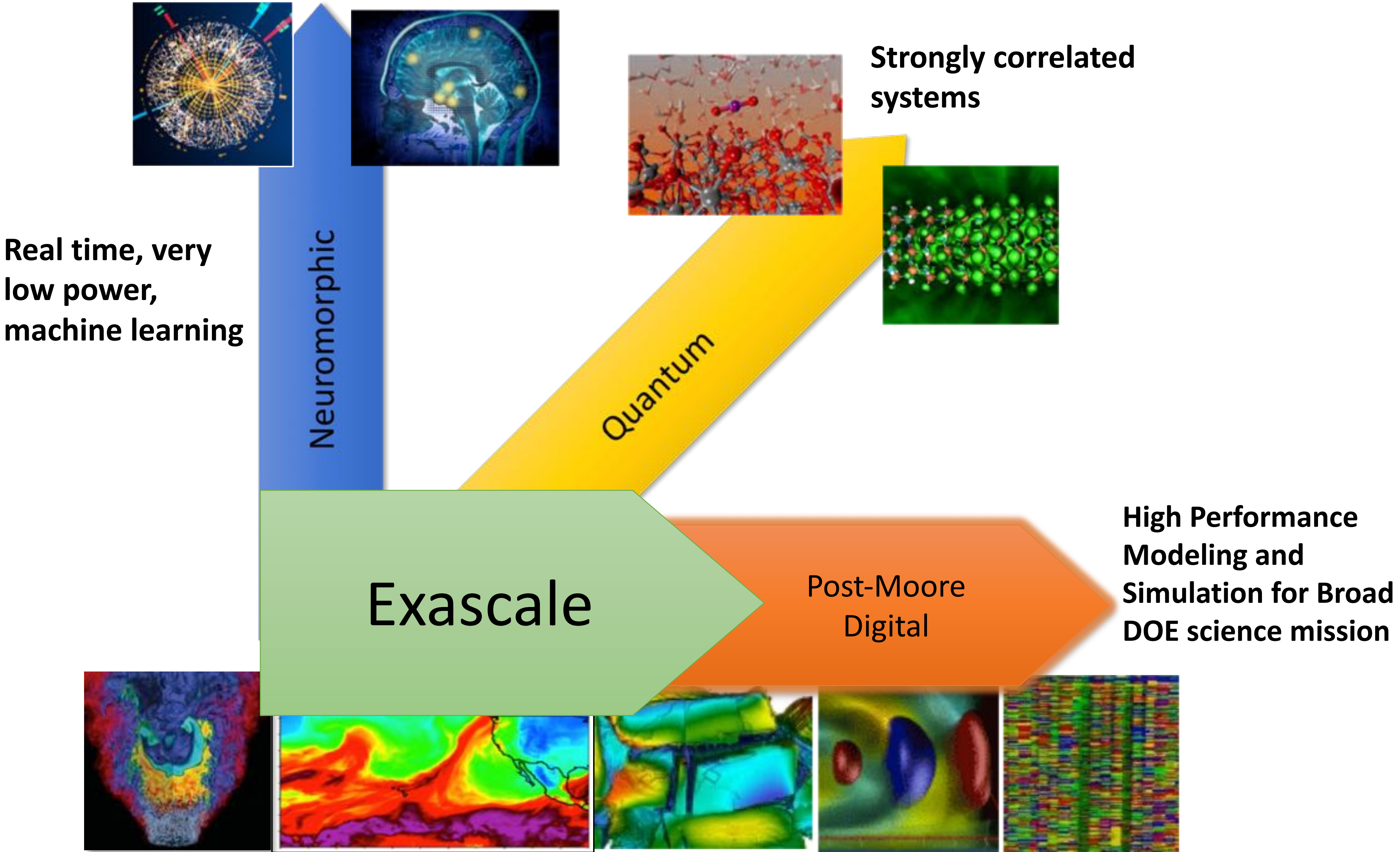
U.S. DEPARTMENT OF ENERGY

Office of Science

Berkeley Lab Novel Computing Technologies Roadmap



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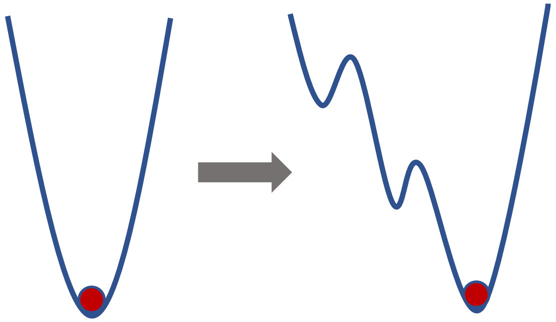
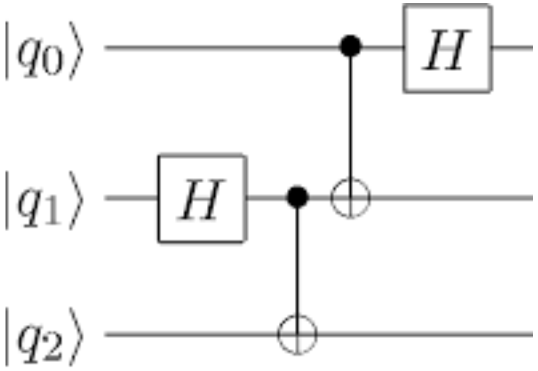
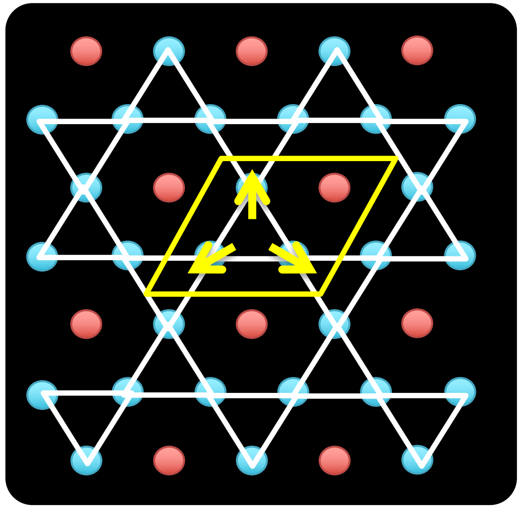
Quantum Computing Devices







Adiabatic Quantum Computing
Quantum Annealing

Digital (Circuit-based) Quantum Computing

Analog Quantum Computing

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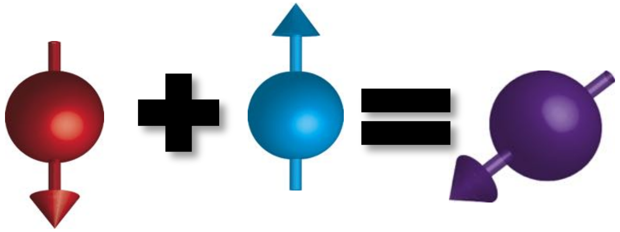
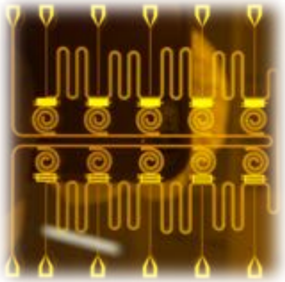
Analog example from D. Stamper-Kurn lab (UC Berkeley) simulating frustrated magnetism with ultracold atoms

Quantum Computing Requires Qubits



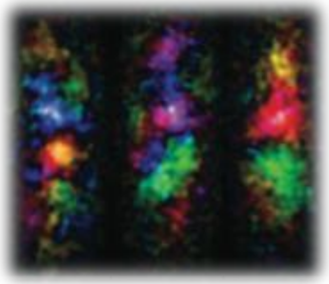
ELECTRONS

SPIN UP + SPIN DOWN

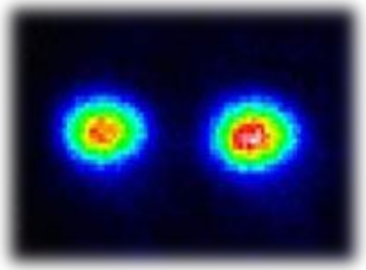


MSD, Berkeley Lab
Physics, UC Berkeley

CIRCUITS



ATOMS



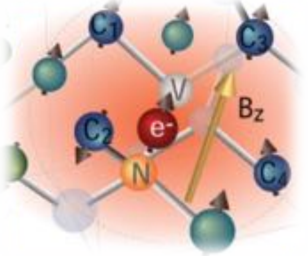
IONS

Tradeoffs in generality, coherence time, operation speed

Physical Qubit errors > 10 $^{-4}$

Bit errors < 10 $^{-10}$

Berkeley
AQuES Testbe



SOLID STATE

Quantum Algorithms

Fastest
- Grover's search (1996)
- QFT
- HHL Linear Algebra (2009)

Faster than best-known classical
- Shor's prime factoring (1994)
- Optimization (2014-)

- Algorithm development is difficult and relatively slow
  - Need hardware to test heuristics
- Opportunities in Chemistry, Materials, and Physics Simulations

Slower or no speedup

Faster

Slower

Compared with classical computation

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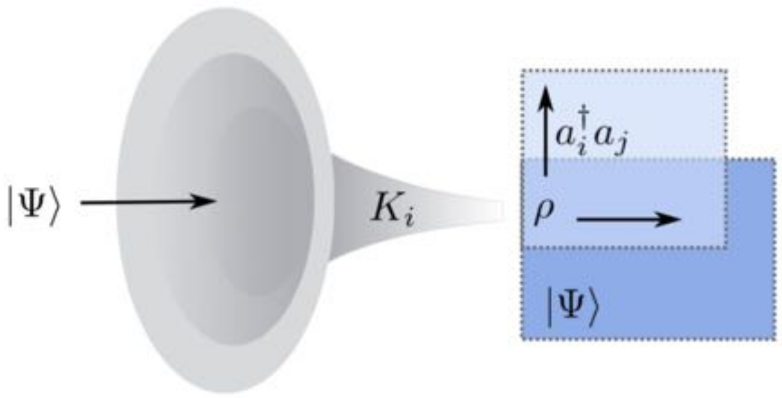
Recent Algorithm Development for Chemistry

Benefits of interdisciplinary collaboration

Year	Reference	Representation	Algorithm	Time Step Depth	Coherent Repetitions	Total Depth
2005	Aspuru-Guzik et al. [1]	JW Gaussians	Trotter	$\mathcal{O}(\text{poly}(N))$	$\mathcal{O}(\text{poly}(N))$	$\mathcal{O}(\text{poly}(N))$
2010	Whitfield et al. [2]	JW Gaussians	Trotter	$\mathcal{O}(N^5)$	$\mathcal{O}(\text{poly}(N))$	$\mathcal{O}(\text{poly}(N))$
2012	Seeley et al. [3]	BK Gaussians	Trotter	$\tilde{\mathcal{O}}(N^4)$	$\mathcal{O}(\text{poly}(N))$	$\mathcal{O}(\text{poly}(N))$
2013	Perruzzo et al. [4]	JW Gaussians	UCC	Variational	Variational	$\mathcal{O}(\text{poly}(N))$
2013	Toloui et al. [5]	CI Gaussians	Trotter	$\mathcal{O}(\eta^2 N^2)$	$\mathcal{O}(\text{poly}(N))$	$\mathcal{O}(\text{poly}(N))$
2013	Wecker et al. [6]	JW Gaussians	Trotter	$\mathcal{O}(N^5)$	$\mathcal{O}(N^6)$	$\mathcal{O}(N^{11})$
2014	Hastings et al. [7]	JW Gaussians	Trotter	$\mathcal{O}(N^4)$	$\mathcal{O}(N^4)$	$\mathcal{O}(N^8)$
2014	Poulin et al. [8]	JW Gaussians	Trotter	$\mathcal{O}(N^4)$	$\sim N^2$	$\sim N^6$
2014	McClean et al. [9]	JW Gaussians	Trotter	$\sim N^2$	$\mathcal{O}(N^4)$	$\sim N^6$
2014	Babbush et al. [10]	JW Gaussians	Trotter	$\mathcal{O}(N^4)$	$\sim N$	$\sim N^5$
2015	Babbush et al. [11]	JW Gaussians	Taylor	$\tilde{\mathcal{O}}(N)$	$\tilde{\mathcal{O}}(N^4)$	$\tilde{\mathcal{O}}(N^5)$
2015	Babbush et al. [12]	CI Gaussians	Taylor	$\tilde{\mathcal{O}}(N)$	$\tilde{\mathcal{O}}(\eta^2 N^2)$	$\tilde{\mathcal{O}}(\eta^2 N^3)$
2015	Wecker et al. [13]	JW Gaussians	UCC	Variational	Variational	$\mathcal{O}(N^4)$
2016	McClean et al. [14]	BK Gaussians	UCC	Variational	Variational	$\mathcal{O}(\eta^2 N^2)$
2017	Babbush et al. [15]	JW Plane Waves	Trotter	$\mathcal{O}(N)$	$\mathcal{O}(\eta^{1.83} N^{0.67})$	$\mathcal{O}(\eta^{1.83} N^{1.67})$
2017	Babbush et al. [15]	JW Plane Waves	Taylor	$\tilde{\mathcal{O}}(1)$	$\tilde{\mathcal{O}}(N^{2.67})$	$\tilde{\mathcal{O}}(N^{2.67})$
2017	Babbush et al. [15]	JW Plane Waves	TASP	Variational	Variational	$\mathcal{O}(N)$

Bounding computational complexity ever more tightly, from O(N^{11}) in 2013 to O(N^3)-O(N) in 2017
Source: McClean & Babbush (Google)



Quantum Subspace expansion to allow for simulation of excited state and error mitigation

Adapting algorithms to achieve useful accuracy with imperfect qubits

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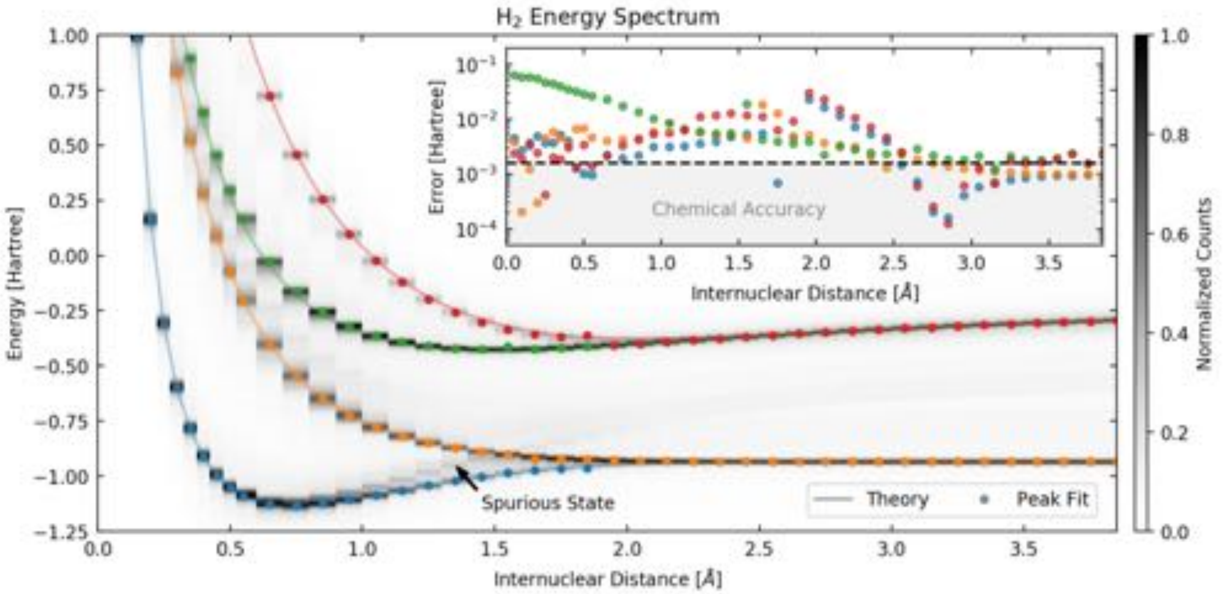
Early Results: Variational Quantum Eigensolver

Robust determination of molecular spectra on a quantum processor

J. I. Colless,[1,2] V. V. Ramasesh,[1,2] D. Dahlen,[1,2] M. S. Blok,[1,2]
J. R. McClean,[3] J. Carter,[3] W. A. de Jong,[3] and I. Siddiqi[1,2,4,*]



- 2-qubit implementation for H_2 molecule attains chemical accuracy
- QSE (work by J. McClean @ LBNL), extraction of excited states and error mitigation

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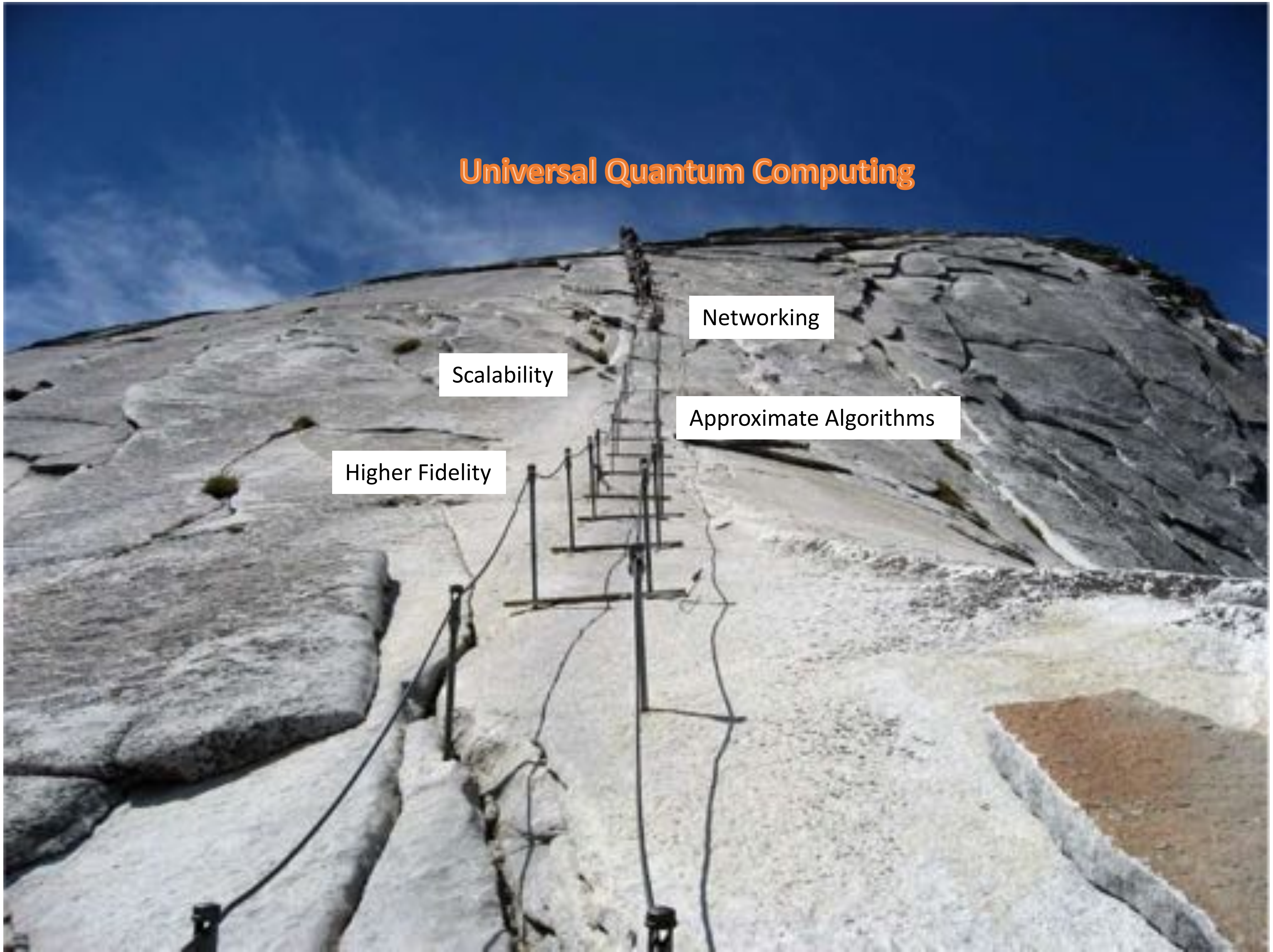
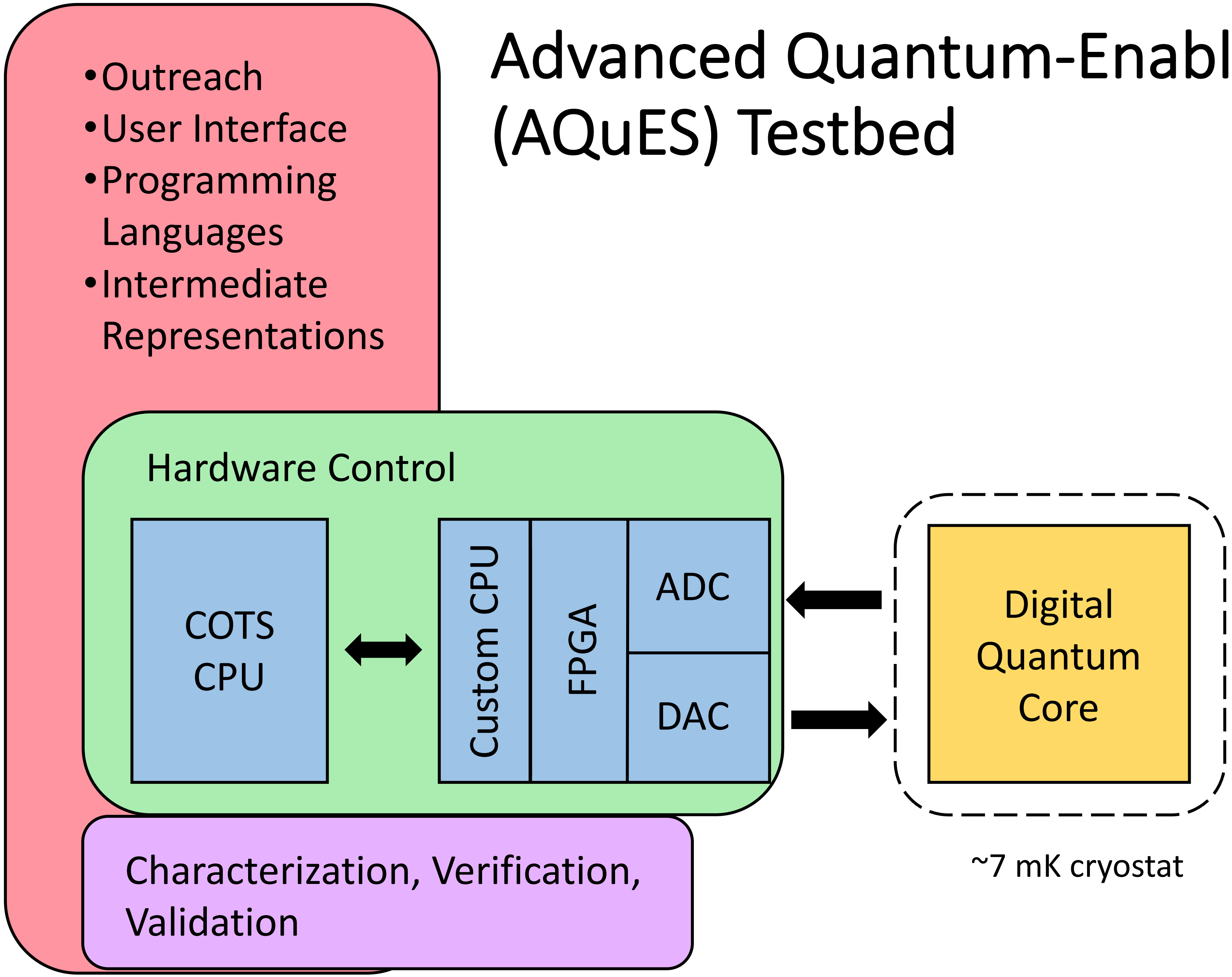
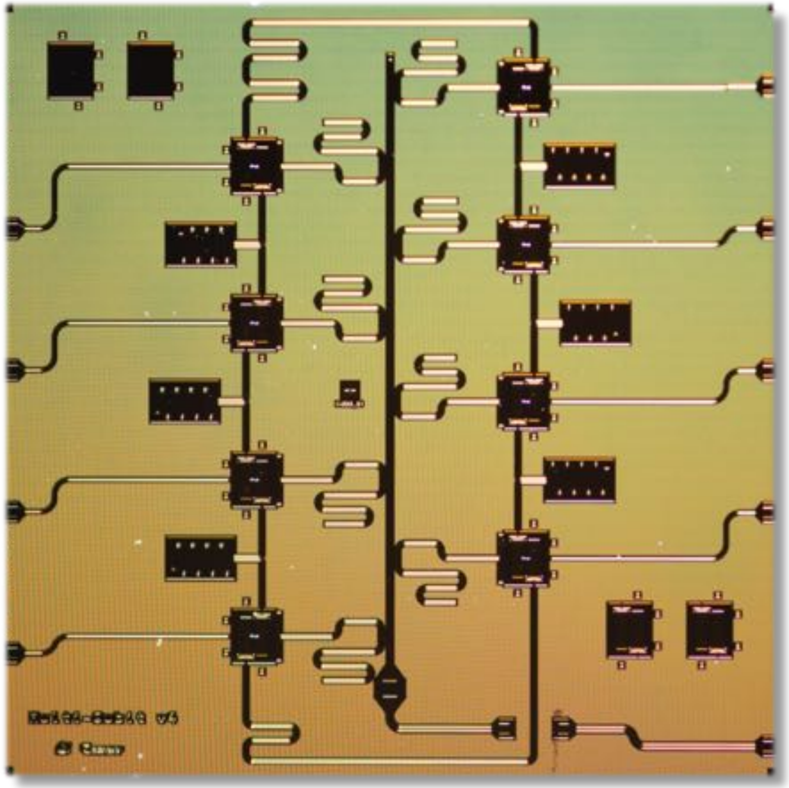


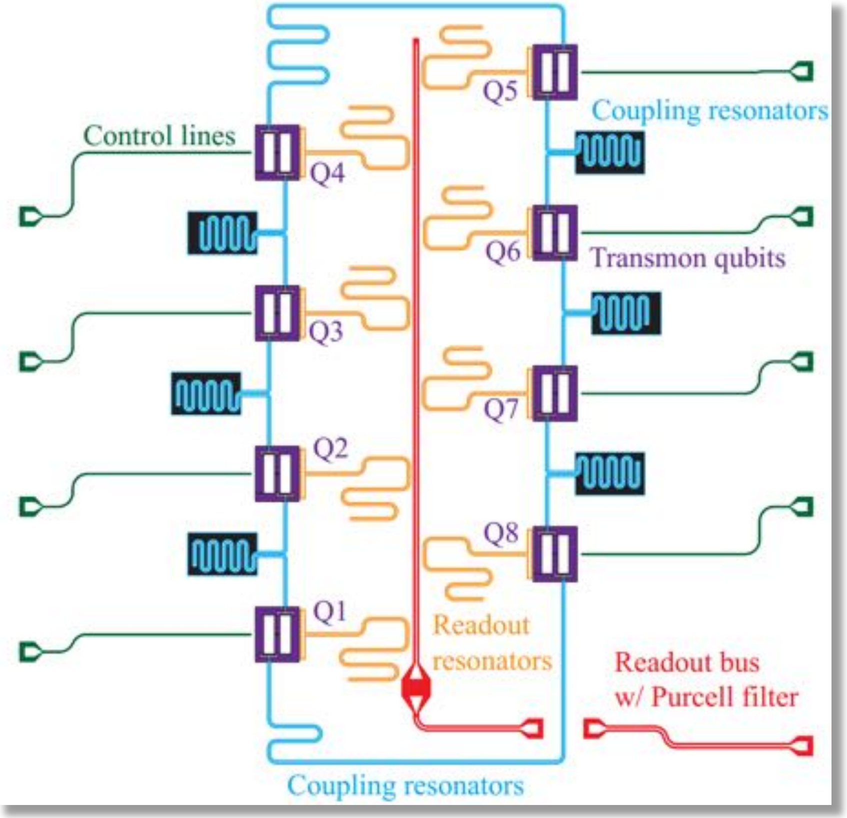
Universal Quantum Computing
Networking
Scalability
Approximate Algorithms
Higher Fidelity

Advanced Quantum-Enabled Simulation (AQuES) Testbed



Current Device Architecture





- 8-Qubit ring topology with nearest-neighbor coupling
- Independent control and simultaneous readout
- Measured lifetimes (T_2) consistently > 60 ms

Collaboration with Quantum Nanoelectronics Lab at UC Berkeley
Irfan Siddiqi, James Colless, Kevin O'Brien

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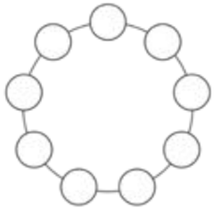
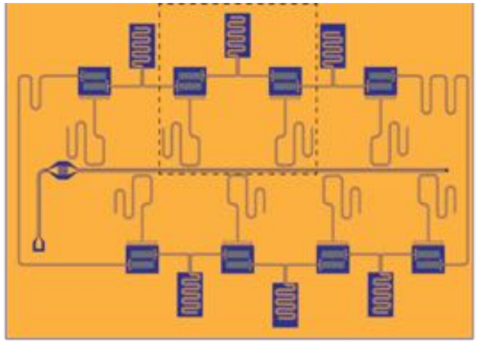
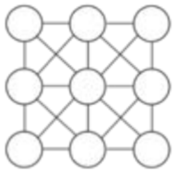
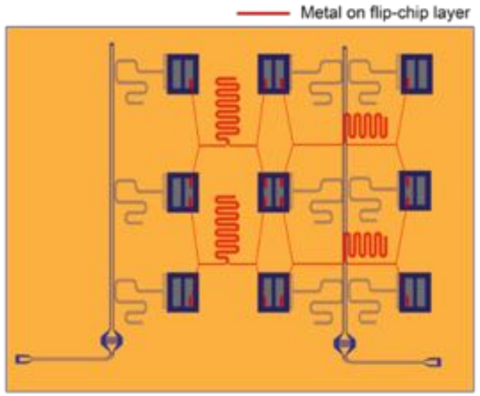
Explore Device Connectivity & Topology









- Flip-chip architecture allows improved qubit connectivity
- Requisite tools available at Molecular Foundry
- Reductions in circuit depth requirements – *enables co-design*
- Directly impacts scale of experiments
- Impact of noise in highly-connected architectures not well understood

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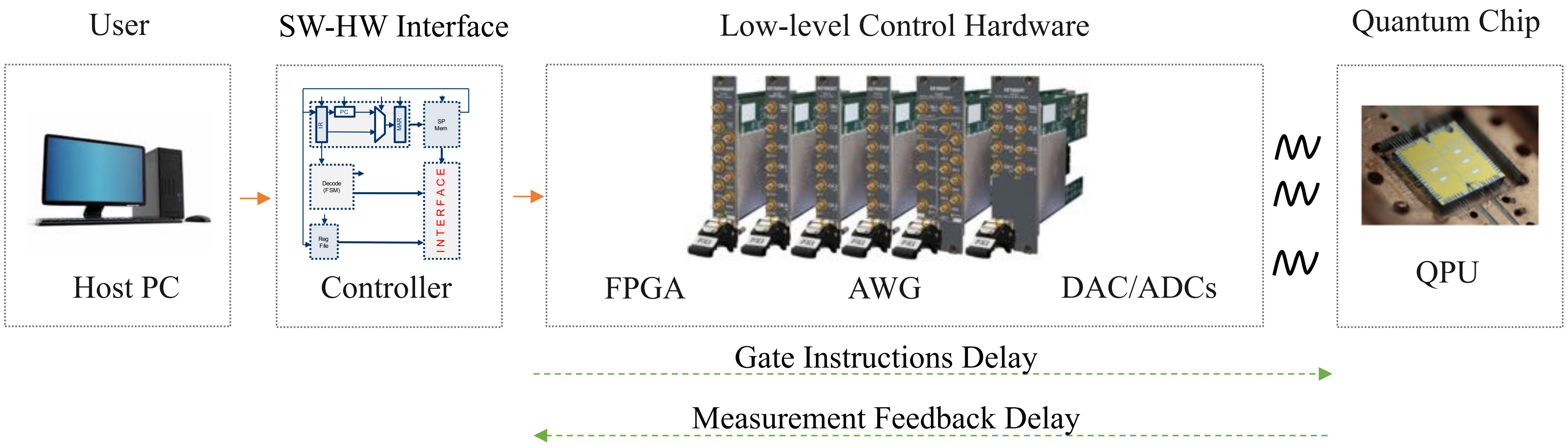
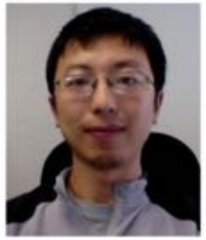
Quantum Controllers

- Quantum Controller that supports specialized Instruction Set
- Can be placed close to the Low-level HW
- Reduce Host-to-HW delay and amount of data to be transferred




Anastasiia Butko (CRD), Gang Huang (ATAP), Larry Dolittle (Eng)

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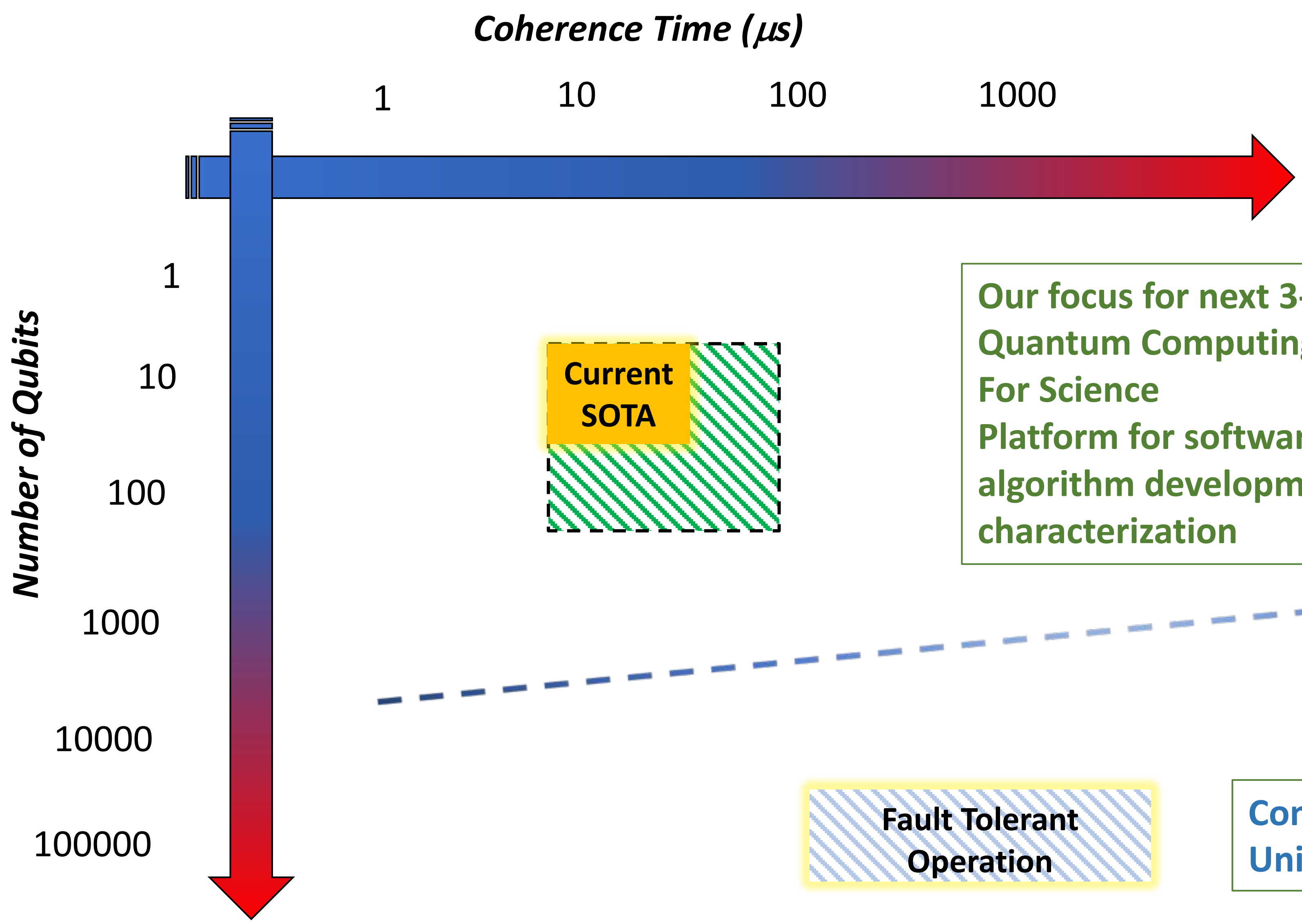
Testbed Roadmap



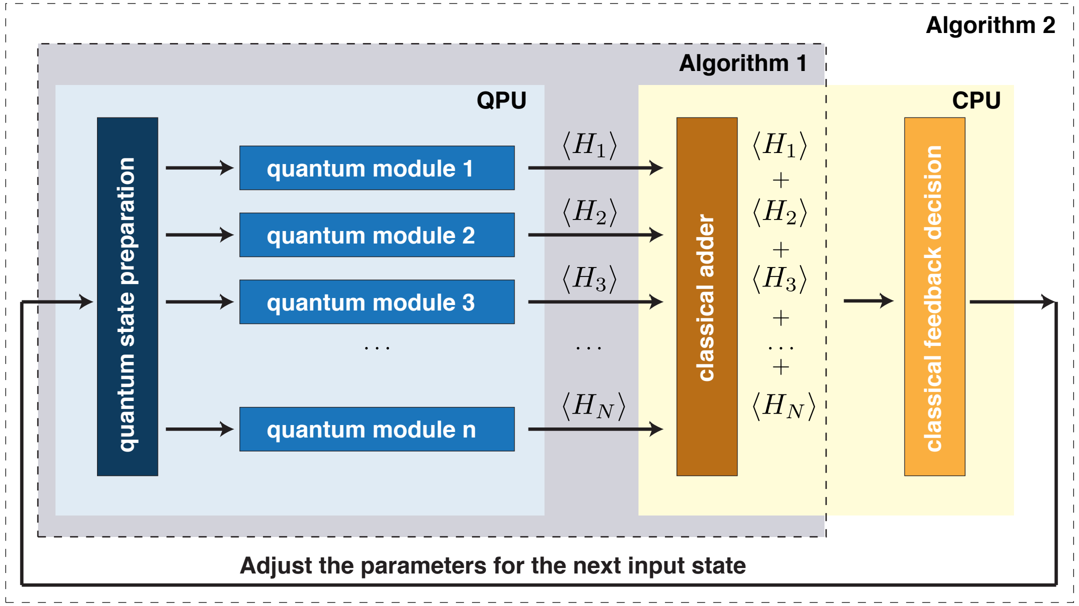
Bert de Jong (CRD),
Norman Yao (MSD)

Our focus for next 3-5 Years:
Quantum Computing *with Co-Design* For Science
Platform for software design, algorithm development, and characterization

Commercial focus:
Universal Quantum Computing

Berkeley Lab QAT: Quantum Algorithms, Mathematics and Compilation Tools for Chemical Sciences

- *Bert de Jong*, Norman Yao, Jonathan Carter, Costin Iancu, Aydin Buluc (LBL), Alan Aspuru-Guzik (Harvard), Stefan Wild (ANL)
- Dynamics of chemical systems
  - Non-equilibrium behavior
  - Electron transport, response to external perturbations or driving forces
  - Exploring first and second quantization
- Quantum machine learning (led by Harvard)
- Improving software stack with better compilers and optimizers
- Advancing stochastic optimizers and linear algebra



Opportunities for postdoctoral fellows in both projects

Contact jtcarter@lbl.gov or wadejong@lbl.gov

Questions