Google AI Quantum

Applications and Challenges with Near-term Quantum Hardware

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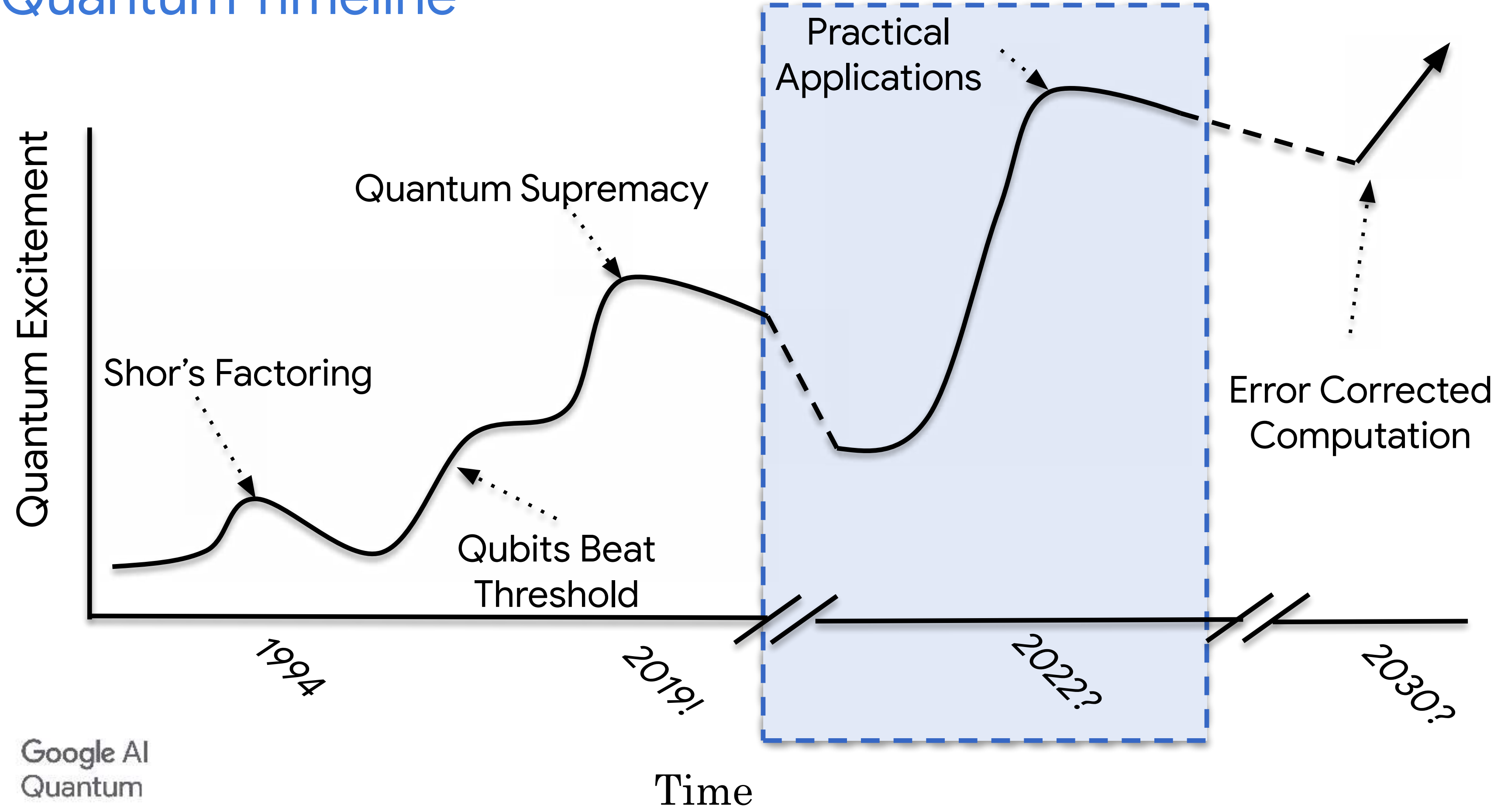
Quantum Timeline



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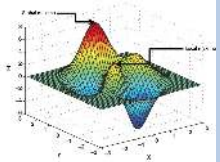
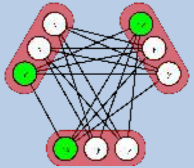
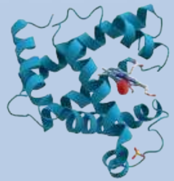
Early application areas

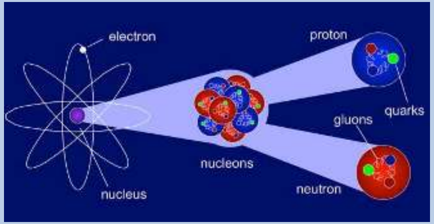
Optimization





Quantum Simulation





Quadratic Speedup

Exponential Speedup

1 year → 2 weeks

10^{82} years → 300 seconds

Age of universe ~ 14 x 10^{9} years

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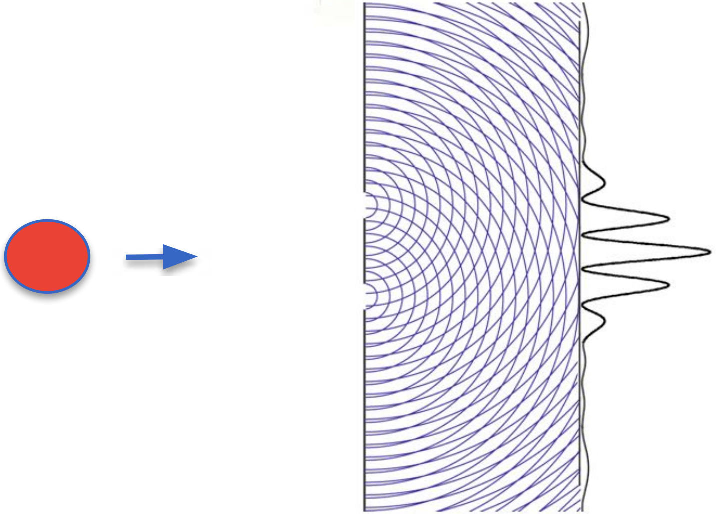
What is quantum?

“Classical”



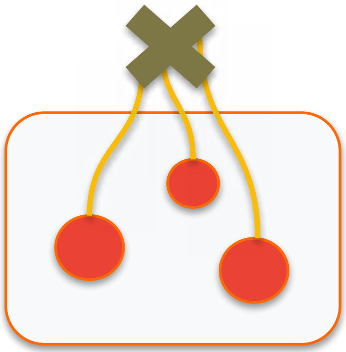
“Quantum”

Quantum System – A physical system operated in a regime where we need effects like discrete energy levels and interference are required to accurately describe it.

Simulation

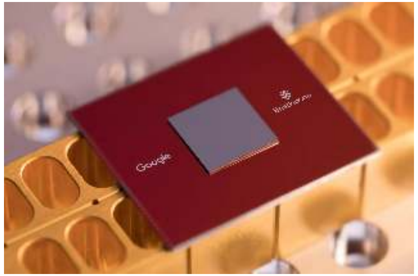
Orrery

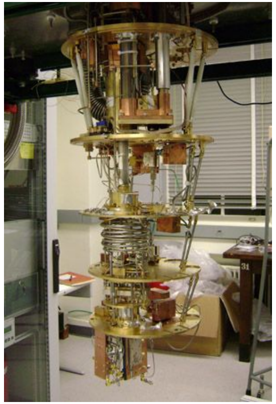
Antikythera Mechanism (125 B.C)

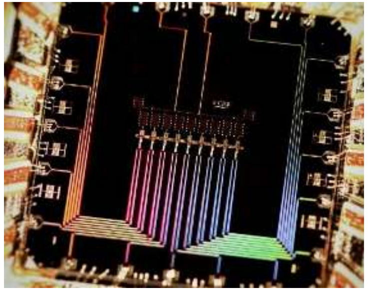


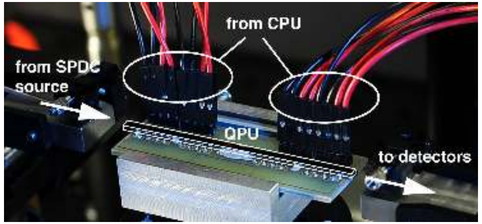
Quantum System → Quantum System

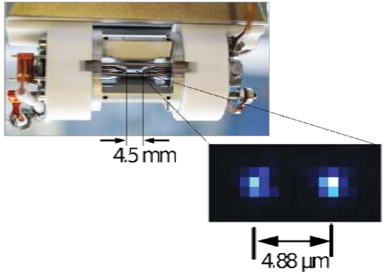
Quantum systems











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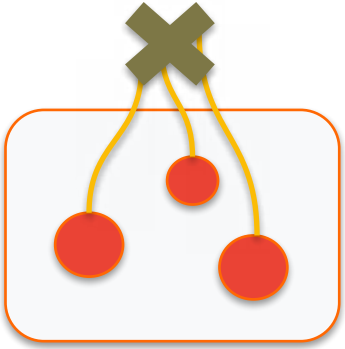
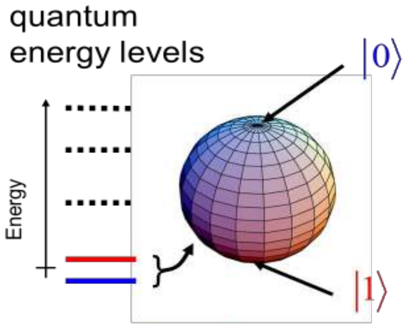
Quantum simulation - the quantum advantage





$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Quantum Simulation

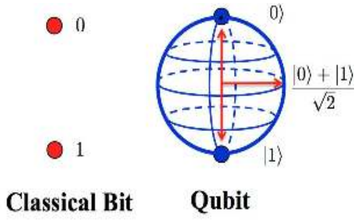
Abstraction

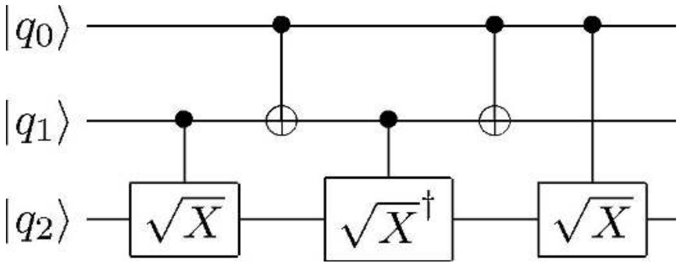
Quantum Computation

- Factoring Products of Two Large Primes
- Linear Partial Differential Equations
- Solution of Linear Equations

Prepare → Evolution → Measurement → $\{|\Psi_i\rangle, E_i\}$

Quantum computing abstraction





$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$X = \mathrm{NOT} = \sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$X|0\rangle = |1\rangle$$

$$X|1\rangle = |0\rangle$$

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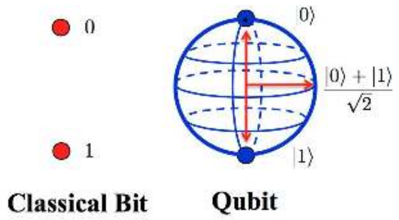
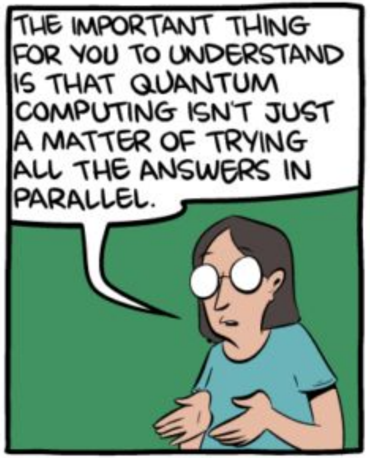
Debunking quantum myths

MYTH 1: Faster/better because it can use an exponential number of states



MYTH 2: Faster/better because bits can be 0 and 1 at the same time.

MYTH 3: Work by computing all the answers in parallel



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*https://www.smbc-comics.com/comic/the-talk-3

Challenges in quantum computation

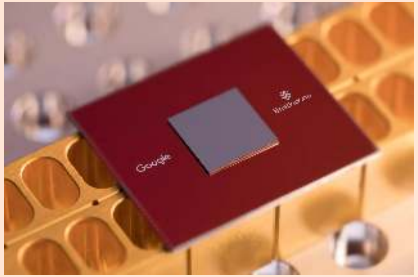
Prep $|\psi\rangle$ → Evolution → Measurement → $\{|\Psi_i\rangle, E_i\}$

Number of Qubits
+Scalable manufacture
+(N-1) qubit problem

Coherence Time & Fidelity
+Robust control & stable qubits
+Algorithm timescale problem

Information Extraction
+New input/output spec
+Full readout loses advantage

Better Hardware



Co-Design Better Algorithms

Previous: Coherence time flexible

Future:

- Improved coherence time flexibility, novel property extraction, and demonstration
- Qubit number flexible algorithms and larger demonstrations

Thinking differently for speedups

Classical:

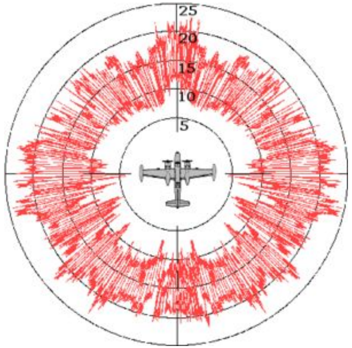
$$Ax = b$$

Solution translates to writing down the entries of x

Quantum*:

$$A|x\rangle = |b\rangle$$

Solution translates to preparing state x from which one can sample



Solving the problem, not reproducing the classical algorithm!

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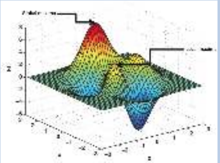
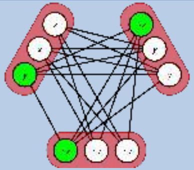
*A. Harrow, A. Hassidim, S. Lloyd, Phys. Rev. Lett. **103**, 150502 (2009)

**B. D. Clader, B. C. Jacobs, and C. R. Sprouse Phys. Rev. Lett. 110, 250504 (2013)

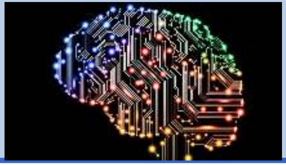
Early application areas

Optimization

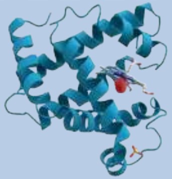


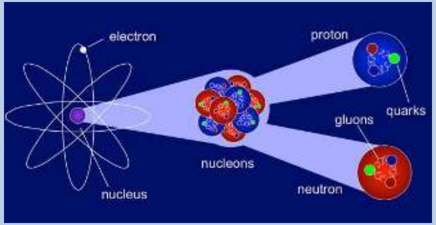


Relation Representation



Quantum Simulation





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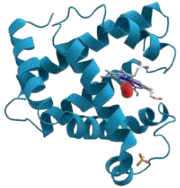
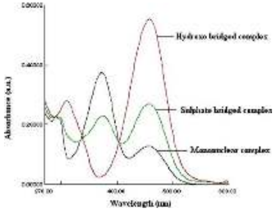
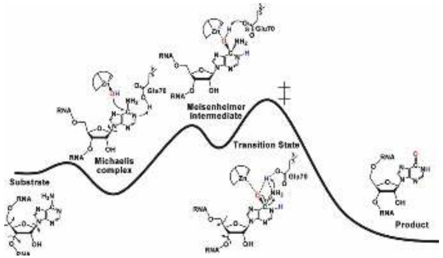
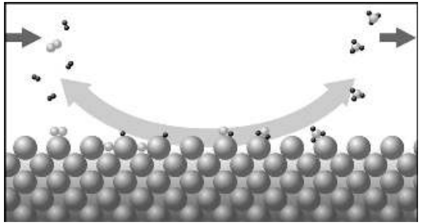
Simulating Chemistry



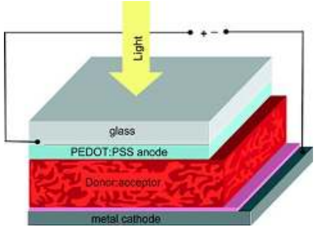
Understanding

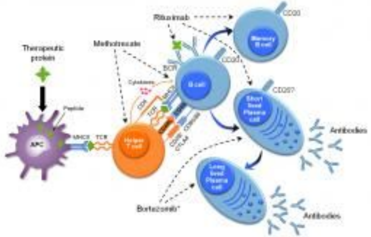






Control





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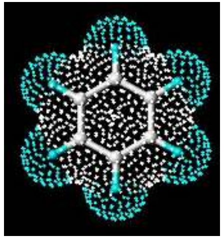
Electronic structure

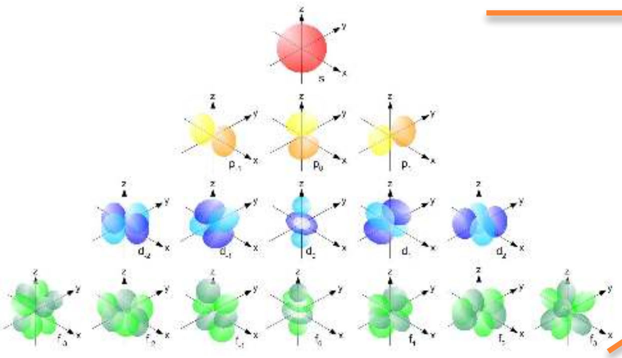


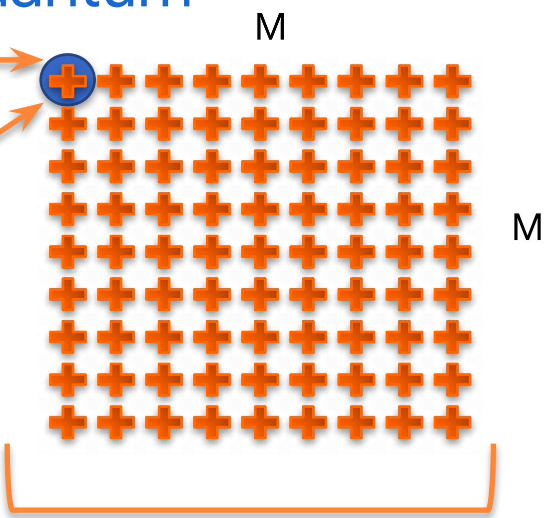
$$\mathcal{H}\left|\psi\right\rangle = E\left|\psi\right\rangle$$

"The underlying physical laws necessary for the mathematical theory of a large part of physics and **the whole of chemistry** are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble."

-Paul Dirac

Challenge of chemistry - power of quantum

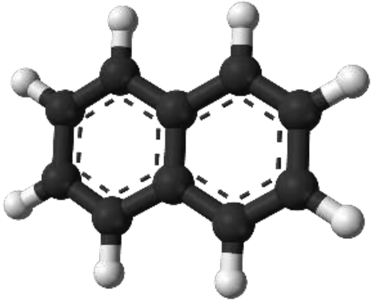




$D = M^N$

$M = 100$

$N = 80$



Particles in universe

10^{80}

$D = 100^{80} = 10^{160}$

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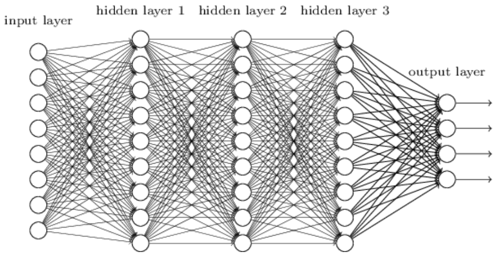
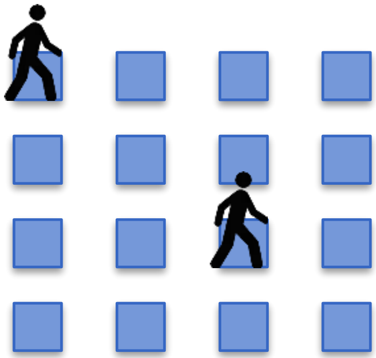
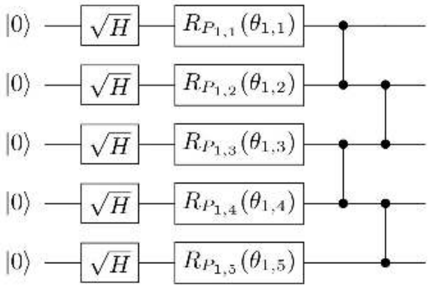
But classical probability distributions...?







$$P_1(\text{Store}_i) \qquad P_2(\text{Store}_j)$$

$$P_{12}(\text{Store}_i, \text{Store}_j) \neq P_1(\text{Store}_i)P_2(\text{Store}_j)$$

$$O(N^P)$$

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Key caveat: Our distributions may be complex valued

Towards an important problem

$$N_2 + 3\ H_2 \rightarrow 2\ NH_3$$ → Fertilizer

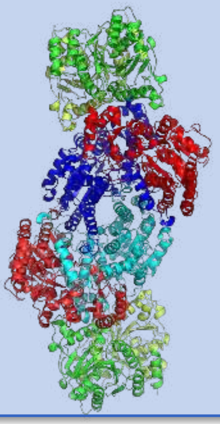
Humans: Haber Process

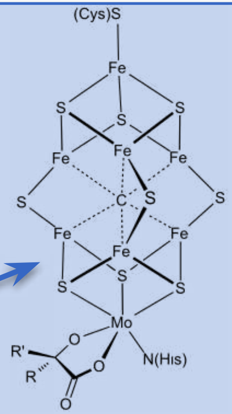
400°C & 200 atm

1-2% of ALL energy on earth, used on Haber process

Nature: Nitrogenase

25° C & 1 atm





FeMoco

Beyond current classical methods

Both electronic structure and substrate attachment almost totally unknown

Classically – No clear path to accurate solution
Quantum Mechanically – 150-200 logical qubits for solution

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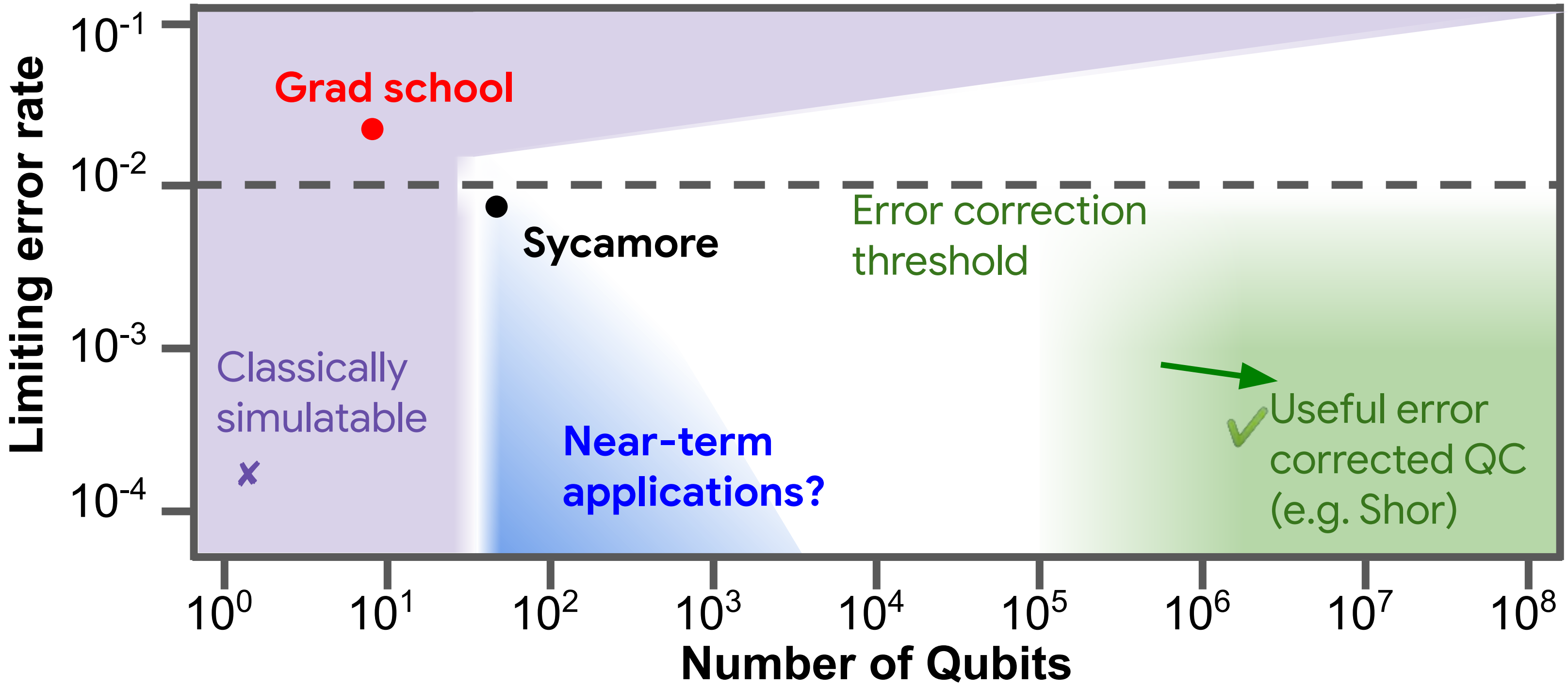
The road beyond supremacy



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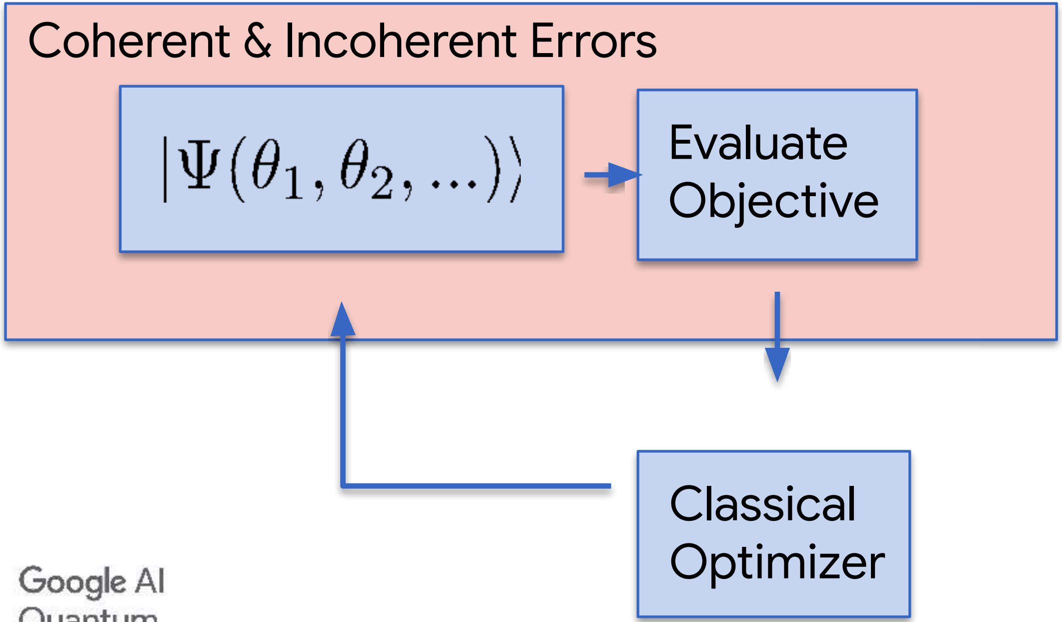
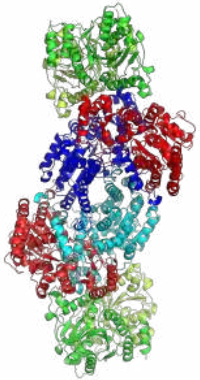
Quantum-Classical variational algorithms in a nutshell

Solve $H|\Psi_0\rangle = E_0|\Psi_0\rangle \quad \leftrightarrow \quad \underset{|\Psi(\theta_1, \theta_2, \ldots)\rangle}{\mathrm{Min}} \langle\Psi|H|\Psi\rangle$

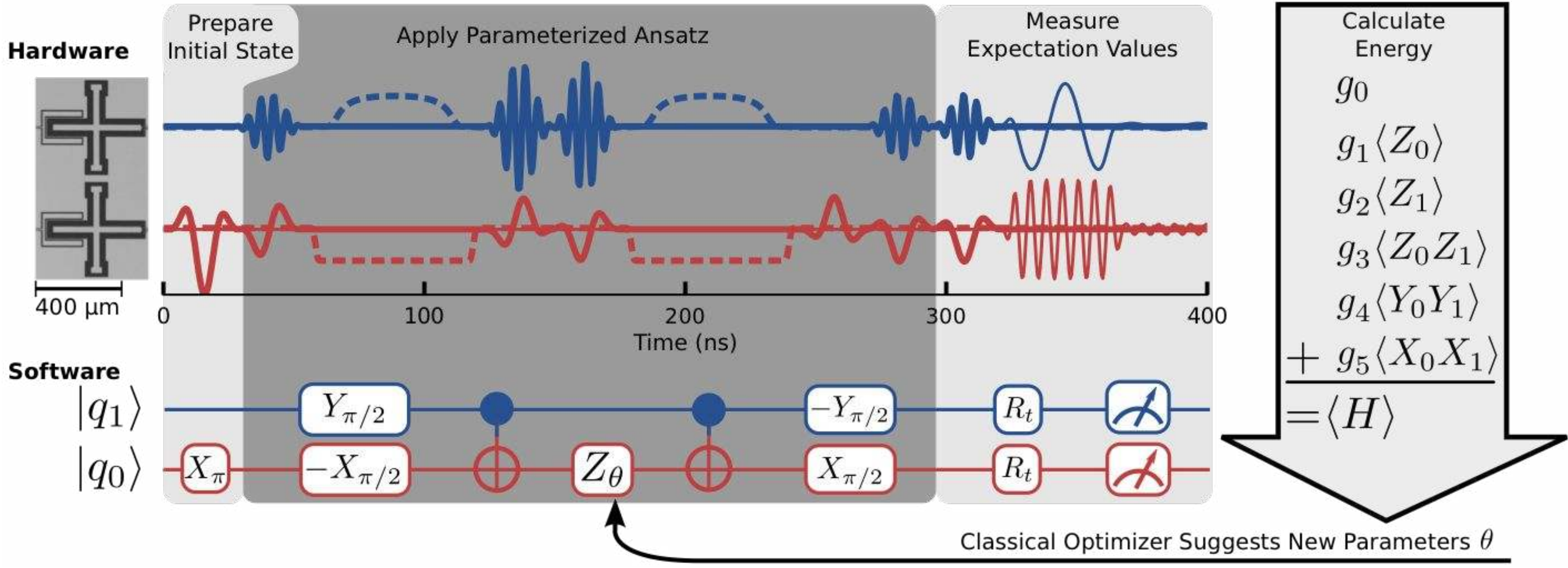




Chemistry
Nuclear Physics
Optimization (QAOA)
Machine learning
Algorithm learning
...

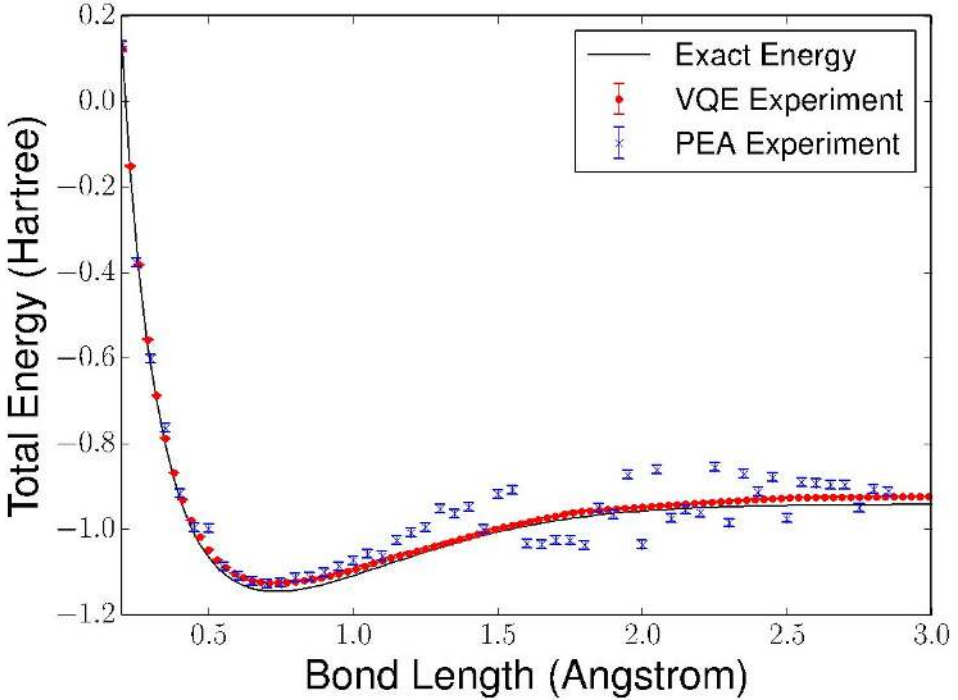
Peruzzo†, **McClean†**, Shadbolt, Yung, Zhou, Love, Aspuru-Guzik, O'Brien. *Nature Communications*, **5** (4213):1–7, 2014.
† Equal Contribution by authors

A network in hardware



P.J.J. O'Malley, R. Babbush,..., J.R. McClean et al.
"Scalable Simulation of Molecular Energies"
Physical Review X 6 (3), 031007 (2016)

Displays natural error suppression



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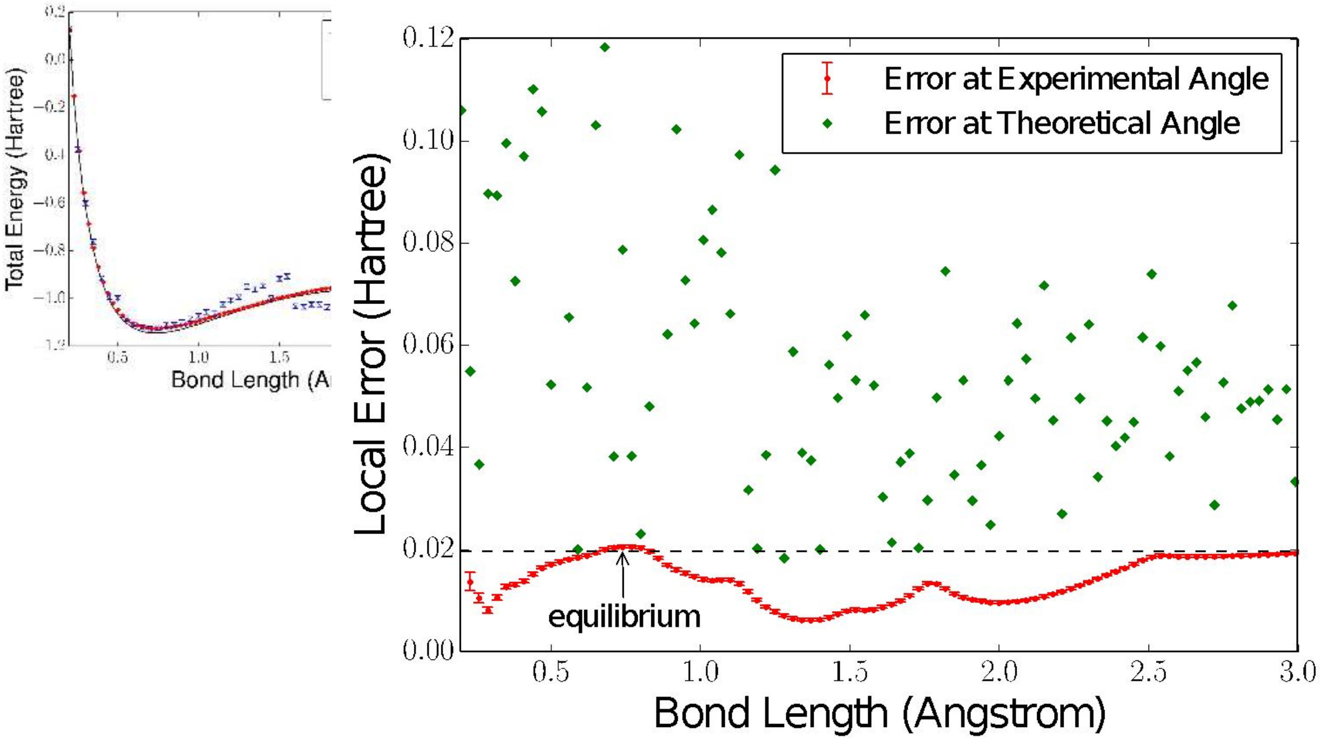
Displays natural error suppression



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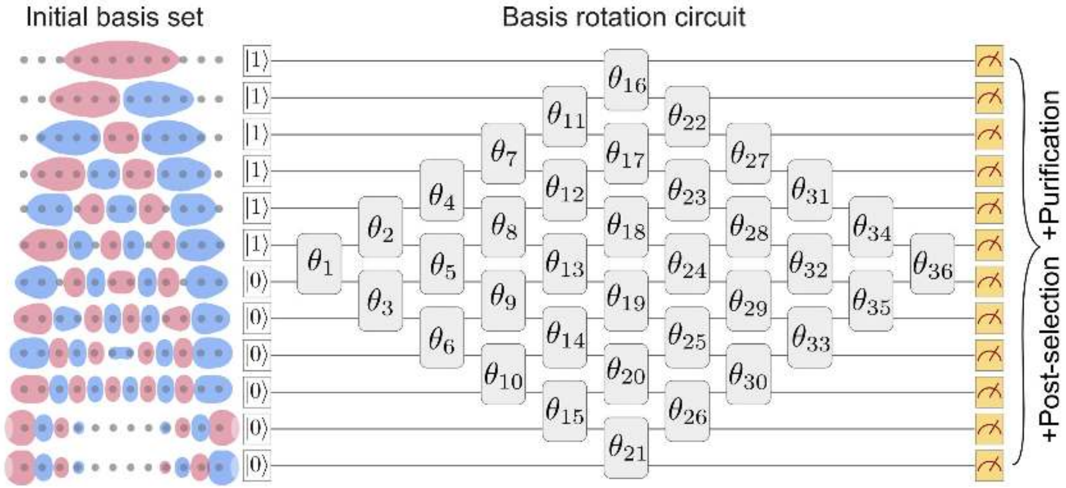
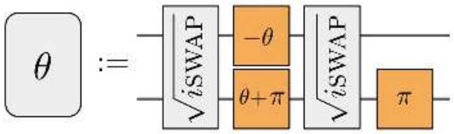
Implementation on Sycamore

$$U_\kappa = \exp\left(\sum_{p,q=1}^{N} \kappa_{pq} a_p^\dagger a_q\right)$$



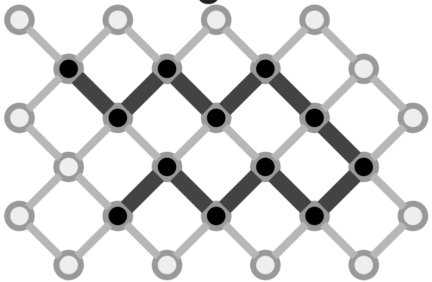


$\theta := e^{-i\theta Z/2}$

fsim gate

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\alpha}\cos\theta & e^{i\beta}\sin\theta & 0 \\ 0 & e^{i\gamma}\sin\theta & e^{i\delta}\cos\theta & 0 \\ 0 & 0 & 0 & e^{i\varphi} \end{pmatrix}$$

Sycamore Subgrid



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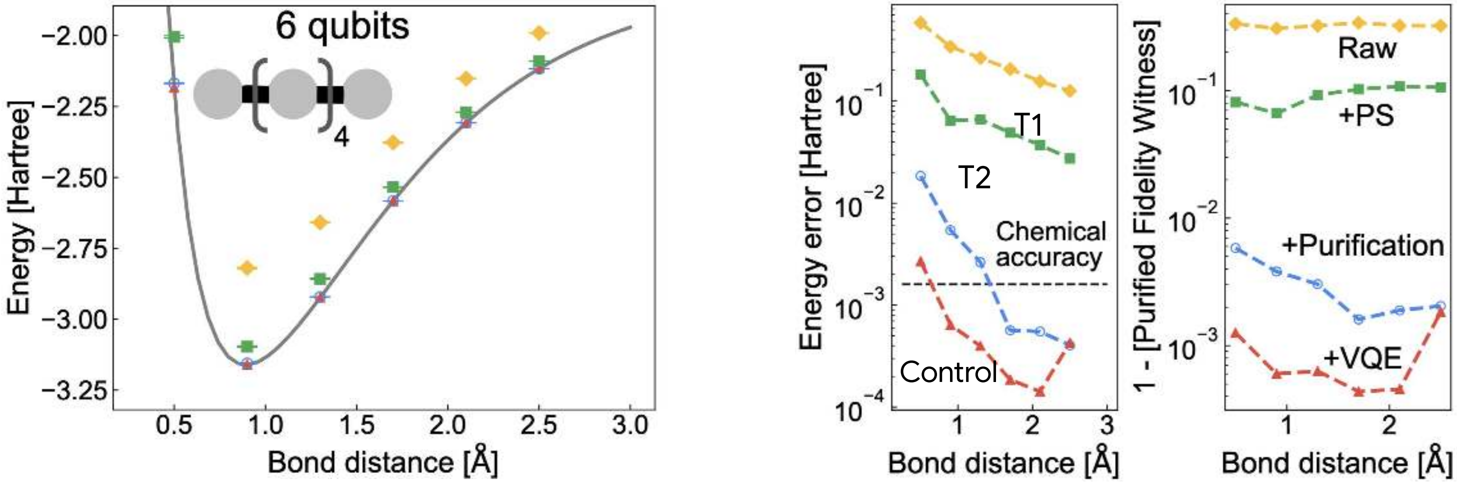
Hydrogen chain to benchmark out device



Fidelity Witness

system	estimate	raw	+ps	+pure	+VQE
H_6	0.571	0.674(2)	0.906(2)	0.9969(1)	0.99910(9)
H_8	0.412	0.464(2)	0.827(2)	0.9879(3)	0.99911(8)
H_{10}	0.277	0.316(2)	0.784(3)	0.9704(5)	0.9834(4)
H_{12}	0.174	0.010(2)	0.654(3)	0.9424(9)	0.9913(3)

Supremacy
Error model

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Optimization Problems

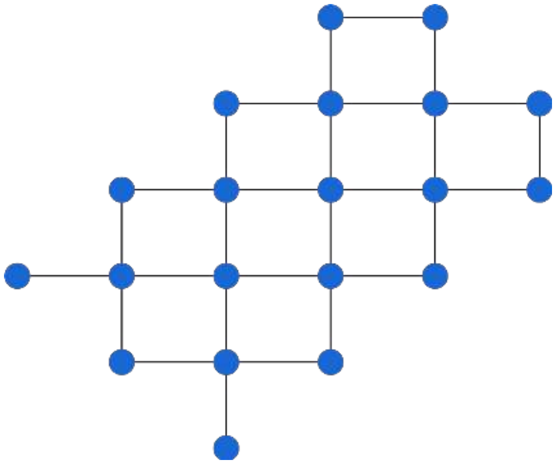
- Possibility of quantum enhanced optimization has driven interest in the field
- This group has a storied history with optimization problems!
- Every industry would benefit from improvements
- Optimization is really hard!

Compiling complex cost functions

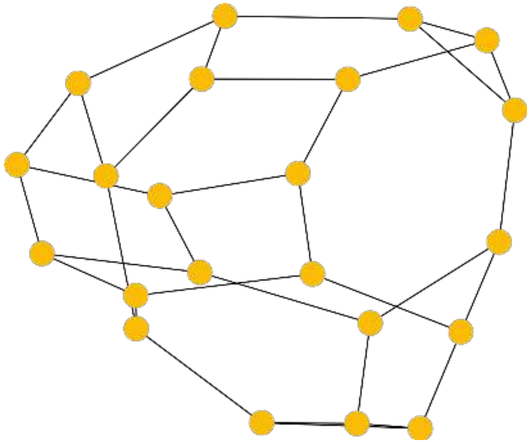
We can think of any 2-body C(x) as a graph

$$C = \sum_{i<j} w_{ij} Z_i Z_j$$

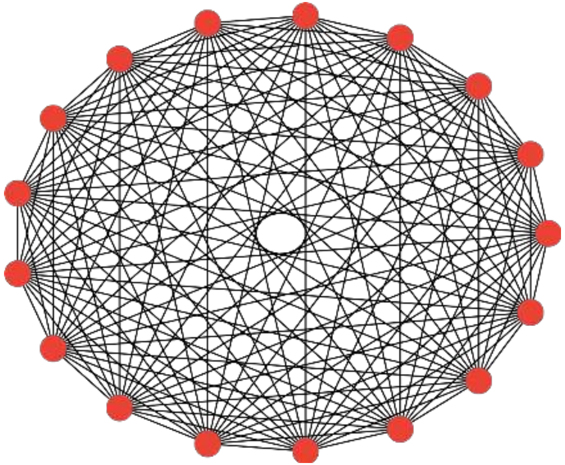
Hardware Grid



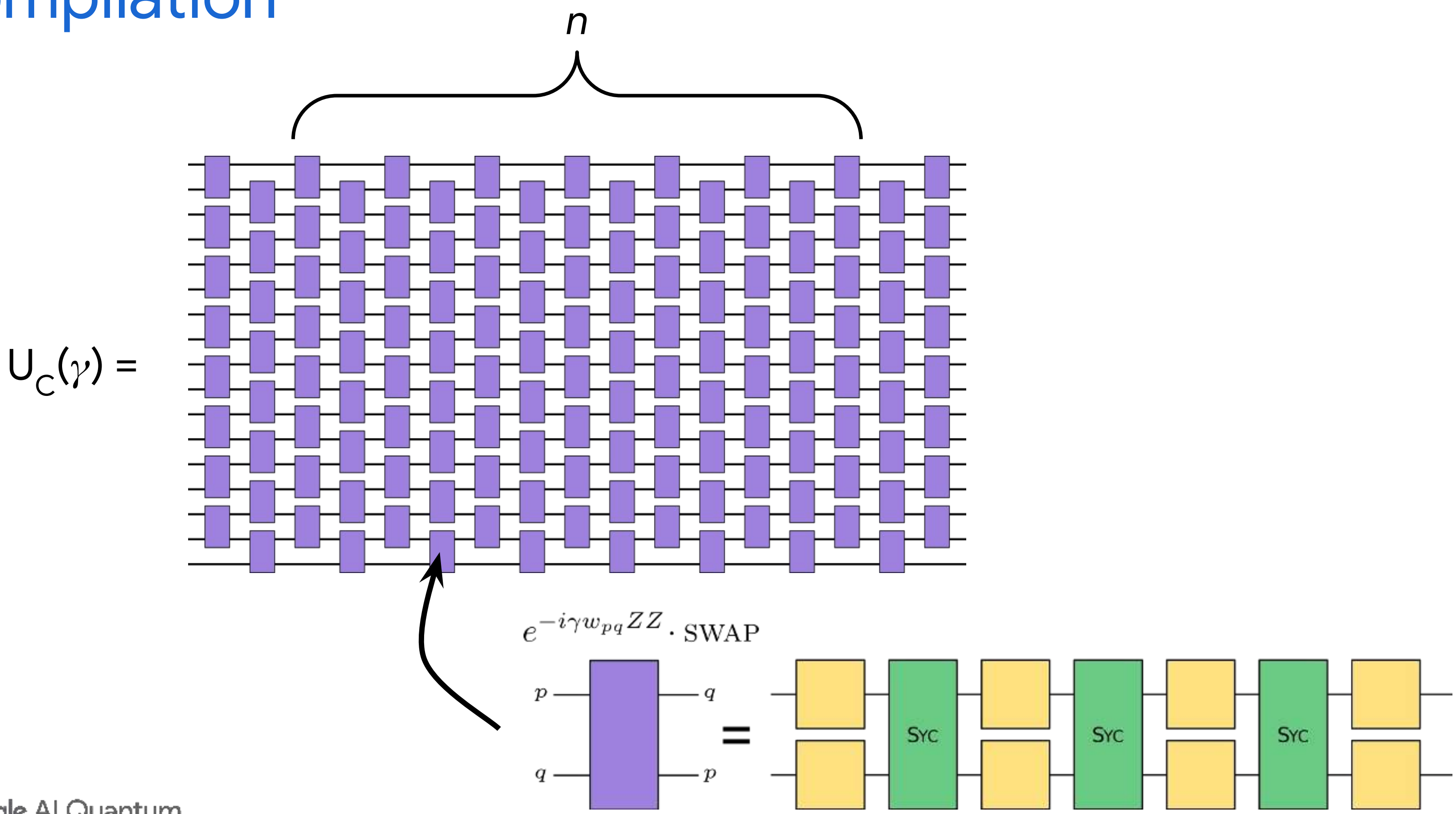
3-Regular MaxCut



Sherrington-Kirkpatrick (SK) Model

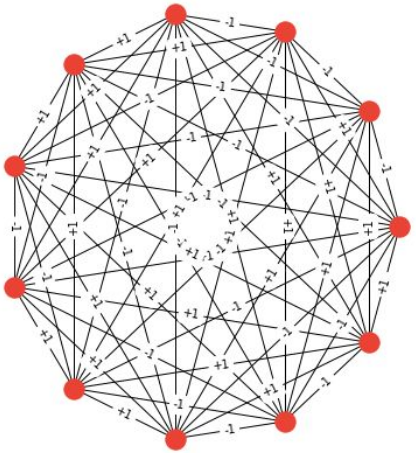


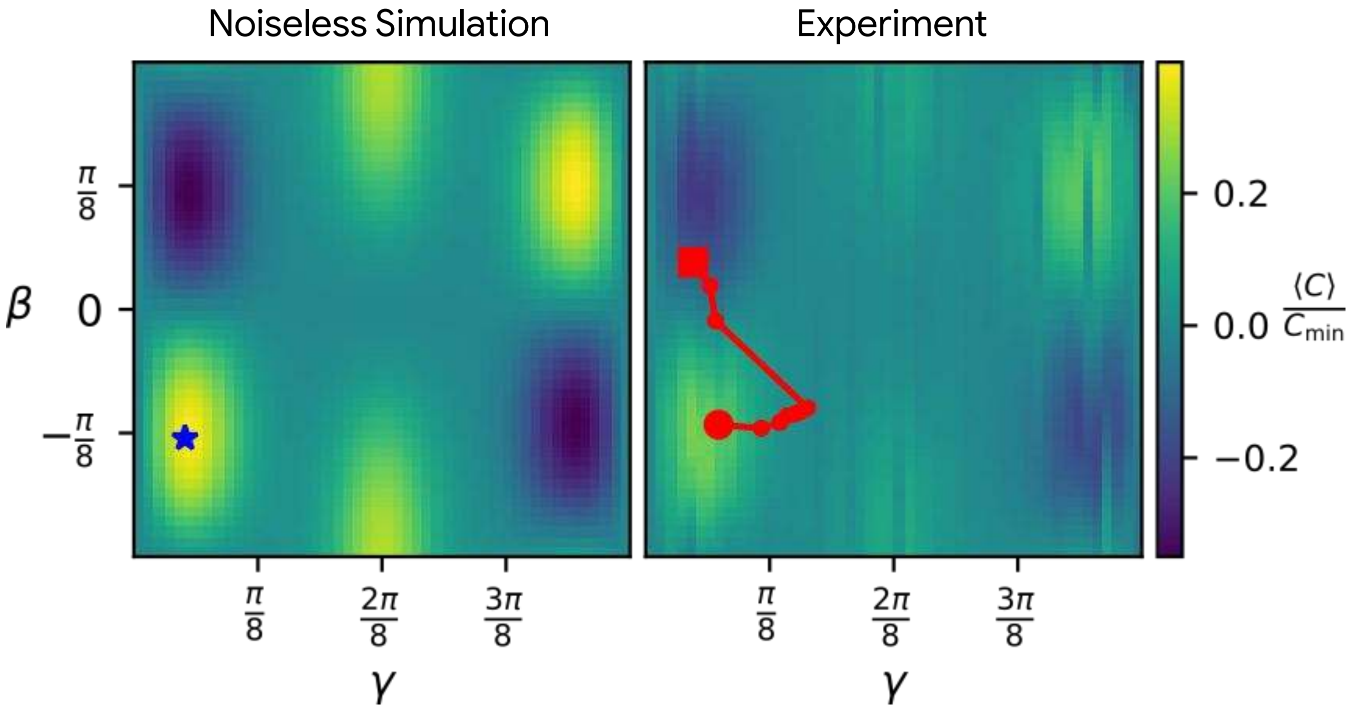
Compilation



Optimization

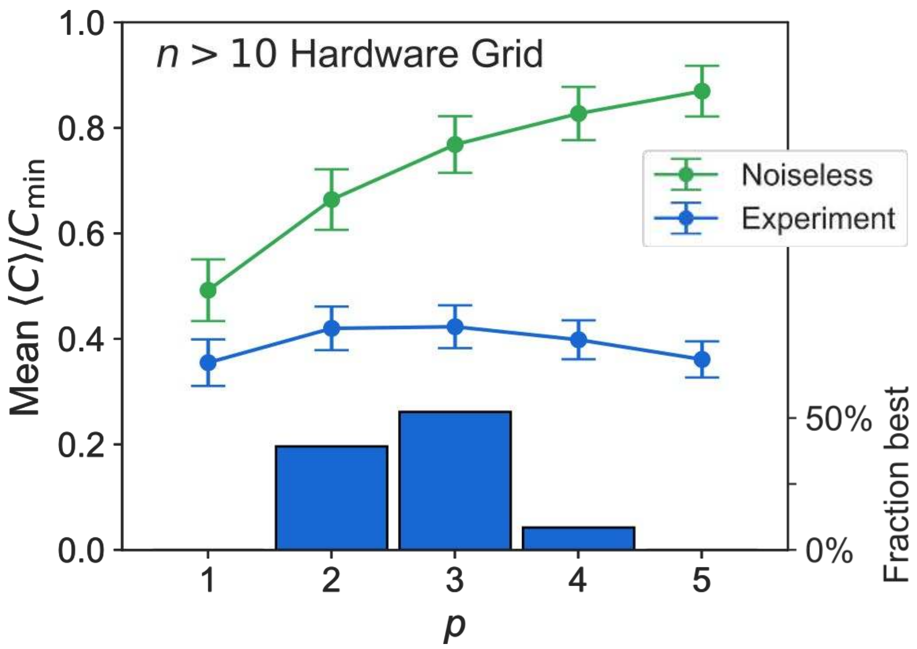
$$\langle C \rangle = \langle + | U_C^\dagger(\gamma) U_B^\dagger(\beta)\, C\, U_B(\beta) U_C(\gamma) | + \rangle$$





SK model, $n = 11$

Scaling with Depth



- In the ideal noiseless case, increasing *p* increases performance
- With noise, there is a tradeoff
- Average performance peaks at *p* = 3
- On a per-instance basis, most peak at *p* = 3

Conclusions

- Quantum applications have unique challenges but we are rapidly making progress
- We have reached a system size where classical simulation becomes increasingly challenging/expensive
- These large devices require new technology, and control techniques, characterization methods
- Sycamore processor has ushered in the NISQ era with a new focus on practical algorithms for near term devices

Thank you!