Applications and Challenges with Near-term Quantum Hardware

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Quantum Timeline

Quantum Excitement

Shor's Factoring

Qubits Beat Threshold

Quantum Supremacy

Practical Applications

Error Corrected Computation

Time

1994

2019!

2022?

2030?
Early application areas

- Optimization
- Quantum Simulation

**Optimization**

- Quadratic Speedup: 1 year → 2 weeks, $10^{82}$ years → 300 seconds

**Quantum Simulation**

- Exponential Speedup: Age of universe ~ $14 \times 10^9$ years
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
Quantum simulation - the quantum advantage

Quantum Simulation

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

\[ |0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \]
\[ |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \]

\[ X = \text{NOT} = \sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \]
\[ X |0\rangle = |1\rangle \]
\[ X |1\rangle = |0\rangle \]
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

*https://www.smbc-comics.com/comic/the-talk-3*
Challenges in quantum computation

**Prep $|\psi\rangle$**

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

**Evolution**

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

**Measurement**

- 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:**

\[ A x = t \]

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

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Early application areas

- **Optimization**
- **Relation Representation**
- **Quantum Simulation**
Simulating Chemistry

Understanding

Control
Electronic structure

\[ H |\psi\rangle = E |\psi\rangle \]

“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

\[ D = M^N \]

\[ M = 100 \]

\[ N = 80 \]

\[ D = 100^{80} = 10^{160} \]

Particles in universe

\[ 10^{80} \]
But classical probability distributions...?

\[ P_1(\text{Store}_i) \quad P_2(\text{Store}_j) \]

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

\[ O(N^P) \]

Key caveat: Our distributions may be complex valued
**(Towards an important problem)**

\[ \text{N}_2 + 3 \text{H}_2 \rightarrow 2 \text{NH}_3 \]

**Humans: Haber Process**
- 400°C & 200 atm
- 1-2% of ALL energy on earth, used on Haber process

**Nature: Nitrogenase**
- 25°C & 1 atm

Both electronic structure and substrate attachment almost totally unknown

**Beyond current classical methods**

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

Number of Qubits

Limiting error rate

Grad school

Classically simulatable

Near-term applications?

Sycamore

Error correction threshold

Useful error corrected QC (e.g. Shor)
Quantum-Classical variational algorithms in a nutshell

Solve \( H |\Psi_0\rangle = E_0 |\Psi_0\rangle \) ⇔ Min \( \langle \Psi | H |\Psi\rangle \)

|\Psi(\theta_1, \theta_2, \ldots)\rangle

Coherent & Incoherent Errors

Evaluate Objective

Classical Optimizer

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

† 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
Displays natural error suppression
Implementation on Sycamore

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

**fsim gate**

\[
\begin{pmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & e^{i\alpha} \cos \theta & e^{i\beta} \sin \theta & 0 \\
0 & e^{i\gamma} \sin \theta & e^{i\delta} \cos \theta & 0 \\
0 & 0 & 0 & e^{i\phi} \\
\end{pmatrix}
\]

**Sycamore Subgrid**

**Google AI Quantum**
Hydrogen chain to benchmark out device

Fidelity Witness

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<th>estimate</th>
<th>raw</th>
<th>+ps</th>
<th>+pure</th>
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<td>0.571</td>
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<td>0.784(3)</td>
<td>0.9704(5)</td>
<td>0.9834(4)</td>
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<tr>
<td>H₁₂</td>
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<td>0.010(2)</td>
<td>0.654(3)</td>
<td>0.9424(9)</td>
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Supremacy
Error model

Google AI Quantum
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

$$C = \sum_{i<j} w_{ij} Z_i Z_j$$
$U_C(\gamma) = \sum_n e^{-i\gamma \omega_{pq} Z Z} \cdot \text{SWAP}_{p \rightarrow q}$
Optimization

$$\langle C \rangle = \langle + | U_{C}^{\dagger}(\gamma) U_{B}^{\dagger}(\beta) C U_{B}(\beta) U_{C}(\gamma) | + \rangle$$

Noiseless Simulation vs. Experiment

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!