Quantum Supremacy using a Programmable Superconducting Processor

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- New design, scalable and low 1&2 qubit errors
- Quantum supremacy achieved
  - 200s quantum computer, checked 10k yr
- Computation on $10^{16}$ state (Hilbert) space
- Fidelity validated with 1&2 qubit errors
  - No additional decoherence physics when scaled
- First useful application: certified random numbers
- Beginning of NISQ era with powerful processors
Sycamore Processor: 54 qubits

New
fast
low errors
Control Hardware

Custom built
High speed
High precision
2-qubit Swap Calibration
Low Errors using Fast 2-Qubit Gates (12 ns)

<table>
<thead>
<tr>
<th>Error Type</th>
<th>Isolated</th>
<th>Simultaneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-qubit (e₁)</td>
<td>0.15%</td>
<td>0.16%</td>
</tr>
<tr>
<td>Two-qubit (e₂)</td>
<td>0.36%</td>
<td>0.62%</td>
</tr>
<tr>
<td>Two-qubit, cycle (e₂c)</td>
<td>0.65%</td>
<td>0.93%</td>
</tr>
<tr>
<td>Readout (eᵣ)</td>
<td>3.1%</td>
<td>3.8%</td>
</tr>
</tbody>
</table>

Need to quote Average and Simultaneous
Low Errors for Arbitrary 2-qubit Gates

Excitation preserving unitary
(Fermionic simulation for NISQ)

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos(\theta) & -i \sin(\theta) & 0 \\
0 & -i \sin(\theta) & \cos(\theta) & 0 \\
0 & 0 & 0 & e^{i\varphi}
\end{pmatrix}
\]

CZ/CNOT for $\varphi = \pi$

Brooks Foxen, ArXiv 2001.08343
Control Sequence

- General purpose algorithm
  - Cycle with 1- and 2-qubit gates
- Simultaneous gates all qubits
- Simplest circuit for quantum supremacy
  - Pseudo-random 1-qubit gates
Validation Algorithm for Quantum Supremacy

- Checks general-purpose circuit
- Randomly chosen gates: qubit speckle
  - Sensitive to single qubit errors
  - Complex & difficult to simulate

Cross entropy fidelity is useful:
  - System validation
  - Learn control map
Quantum Supremacy Data

Classically verifiable

250 gates

Sycamore sampling (N)

5 hours

Classical verification

$m = 14$ cycles

XEB Fidelity, $\mathcal{F}_{\text{XEB}}$

- Prediction from gate and measurement errors

Full circuit
Elided circuit
Patch circuit

number of qubits, $n$

10 15 20 25 30 35 40 45 50 55
Quantum Supremacy Data

250 gates

Sycamore sampling ($N_s = 1M$): 200 seconds

Classical verification

Classically verifiable

$m = 14$ cycles

Prediction from gate and measurement errors

- Full circuit
- Elided circuit
- Patch circuit

$n = 53$ qubits

Prediction

Elided ($\pm 5\sigma$ error bars)

Patch

1 week
100 years
10 millennia
4 years
600 years
20 cycles

number of qubits, $n$

number of cycles, $m$
Quantum Science Results

1) Same fidelity: full, elided, patch, predicted
   Errors NOT depend on entanglement and computation complexity!

1) No new decoherence physics:
   Probability prediction, Fidelity = $\prod_i (1-e_i)$
   Error correction should work

1) Quantum works at $2^{53} = 10^{16}$ Hilbert space
   Previously tested to $\sim 10^3$

1) Test model of digitized errors
   One error gives zero fidelity
   Consistent with error probability
   Tests each gate (of $\sim 500$)
1. Compile chemistry to qubits
   a. Hartree-Fock
   b. Fermionic operators, 2nd quant.
   c. Coupling sequence (swaps)
   d. Suite of measurements, ...

2. Run quantum circuit for swap θ’s

   ![Diagram of quantum circuit and qubits]

1. Correct imperfections, to F≈99%
   b. Excitation loss
   c. Measurement bias, ...

2. Variational optimization of θ’s

- Double the qubits/electrons as prior largest chemistry simulation
- More than 10X the number of gates

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**Q-Chemistry on Sycamore**

**H$_{12}$ dissociation (Sycamore)**

![Graph of H-H distance vs. energy]

- Energy [Hartree]
- H-H distance [Å]

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**Tools:**

- OpenFermion
- Cirq
Quantum Computers NOT a commodity:  
Performance matters greatly 
Breakthrough enables better performance 
in future devices  
Customers & programmers:  
Develop new supremacy algorithms 
1 idea away from compelling application
Improving Computer Simulation

- “We expect that lower simulation costs than reported here will eventually be achieved, but we also expect that they will be consistently outpaced by hardware improvements on larger quantum processors.”

- Strongly support **running** validation programs
  - Tricky to write efficient supercomputer code, failures
  - IBM: non-standard use of disk memory
  - All data posted for checking

- Absolutely guarantee a 57+ qubit Sycamore processor
  - First processor successful
  - Did not collapse over finish line

- Distraction from real issue: quantum-hardware performance
Progress Towards Error Correction

In same device:
more qubits and connectivity, lower errors