Next steps in Quantum Computing: CS’s Role

Challenges and Opportunities in Technologies

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Current Approaches to Qubits

**A bit of the action**
In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

<table>
<thead>
<tr>
<th>Qubit Type</th>
<th>Superconducting loops</th>
<th>Trapped ions</th>
<th>Silicon quantum dots</th>
<th>Topological qubits</th>
<th>Diamond vacancies</th>
<th>Photons</th>
<th>Neutral Atoms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longevity (seconds)</strong></td>
<td>0.00005</td>
<td>0.03</td>
<td>N/A</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Logic success rate</strong></td>
<td>99.4%</td>
<td>99.9%</td>
<td>~99%</td>
<td>N/A</td>
<td>99.2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Number entangled</strong></td>
<td>14</td>
<td>2</td>
<td>N/A</td>
<td>6</td>
<td>30-100 (2018-2020)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Superconducting loops**: A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.
- **Trapped ions**: Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.
- **Silicon quantum dots**: These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.
- **Topological qubits**: Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.
- **Diamond vacancies**: A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.

### Notes:
- **Longevity** is the record coherence time for a single qubit superposition state.
- **Logic success rate** is the highest reported gate fidelity for logic operations on two qubits.
- **Number entangled** is the maximum number of qubits entangled and capable of performing two-qubit operations.

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Historic Trend of Gate Operations

- Turchette et al.
- Sackett et al.
- Rowe et al.
- Leibfried et al.
- Benhelm et al.
- *Ballance et al.*
- *Gaebler et al.*
- *Steffen et al.*
- *DiCarlo et al.*
- *Chow et al.*
- *Barends et al.*

* Corrected for SPAM errors

D.Lucas, Oxford

* exclude SPAM errors
Where Do We Go from Here?

~ $\frac{1}{\# \text{ Gates}}$

$\# \text{ Gates} \sim O(N^3)$

$\# \text{ Gates} \sim O(N^2)$

$\# \text{ Gates} \sim O(N)$

Systems Today

Reaching FT

NISQ Opportunities?

Physical Error Probability $\sim 1/(\# \text{ Gates})$

Opportunities for New Research

- How do we make this all work?
- What hardware is needed to make it happen?
  - Cross-cutting topics
  - Co-design opportunities
  - Abstraction layers?
  - Circuit optimization
  - Architecture optimization
  - System design
  - Connectivity of qubits
  - Quantum control