Sievert Lecture Series: The Rise of Quantum Machines

Lecture VIII: Current progress and ecosystem in quantum computing

Xinyuan You
Fermi National Accelerator Laboratory
Sievert Lecture Series: The Rise of Quantum Machines

Roadmap

- Quantum nature of reality
  - Quantum systems in nature and early technologies
- Quantum systems by design
  - Quantum information
- Quantum computing in principle
  - Quantum computing in practice
- The power of quantum computers
  - Current status of QCs and outlook
NISQ era and beyond

- **Noisy Intermediate-Scale Quantum technology**
  - Noisy: qubits are prone to decoherence, no error correction
  - Intermediate-Scale: processors with 50-100 qubits
- May surpass the capabilities of classical computers for *certain* tasks

"... will not change the world right away - we should regard it as a significant step toward the more powerful quantum technologies of the future."

— John Preskill (2018)
Current progress and ecosystem in quantum computing

- Superconducting circuits
- IBM Q experience
- Trapped ions & neutral atoms
- Quantum ecosystem
Quantum computer based on superconducting circuits

Basic elements:

- Capacitors and inductors
- Josephson junctions

First two levels encode a quantum bit

IBM 7-qubit processor

Advantage:
- Fast gate operation (10s ns)

Challenge:
- Short qubit lifetime (100s us)

Origin of decoherence and strategy of mitigation

W.D. Oliver, et al., MRS Bull. 38, 816 (2013)

A. Gyenis, et al., PRX Quantum 2, 030101 (2021)
Progress on superconducting qubit lifetime

### Progress on superconducting qubit scaleup

<table>
<thead>
<tr>
<th>Organization</th>
<th>Designation</th>
<th>Year</th>
<th># Qubits</th>
<th>T1 (us)</th>
<th>T2 (us)</th>
<th>Fid 1Q (%)</th>
<th>Fid 2Q (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBM Q</td>
<td>Tokyo</td>
<td>2018</td>
<td>20</td>
<td>84</td>
<td>50</td>
<td>99.81</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Montreal</td>
<td>2020</td>
<td>27</td>
<td>109</td>
<td>97</td>
<td>99.96</td>
<td>98.58</td>
</tr>
<tr>
<td></td>
<td>Osprey</td>
<td>2022</td>
<td>433</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Google</td>
<td>Bristlecone</td>
<td>2018</td>
<td>72</td>
<td></td>
<td></td>
<td>99.9</td>
<td>99.4</td>
</tr>
<tr>
<td></td>
<td>Sycamore</td>
<td>2019</td>
<td>53</td>
<td></td>
<td></td>
<td>99.85</td>
<td>99.35</td>
</tr>
<tr>
<td>Rigetti</td>
<td>Aspen-4</td>
<td>2019</td>
<td>13</td>
<td>30</td>
<td>20</td>
<td>99.88</td>
<td>94.28</td>
</tr>
<tr>
<td></td>
<td>Aspen-M</td>
<td>2022</td>
<td>80</td>
<td>29</td>
<td>22</td>
<td>98.94</td>
<td>91.13</td>
</tr>
<tr>
<td></td>
<td>Lyra</td>
<td>2023</td>
<td>336</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Find more in [https://databaseline.tech/quantum.html](https://databaseline.tech/quantum.html)
Cloud-based quantum computing platform


- Online tutorials and interactive textbooks
  - Qiskit textbook: [https://qiskit.org/textbook/preface.html](https://qiskit.org/textbook/preface.html)
Quantum computer based on trapped ions

- Ions of interest for quantum computing
e.g., Ca\(^+\), Sr\(^+\), Yb\(^+\)

- Quantum information can be encoded in
e.g., hyperfine states

- Trapping of charged ions
e.g., Paul trap

Wolfgang Paul
Nobel prize in physics 1989

Pros and cons of trapped ion quantum computer

 Advantages

- Long coherence time (10s seconds)
- Best gate and readout fidelity (> 99.9%)
- Perfect reproducibility

 Challenges

- Absolute gate time is slow (10s us)
- Difficult to scaleup

K. Hudek & E. Edwards/Univ. of Maryland/IonQ, Inc./JQI
## Progress on trapped ion quantum computing

<table>
<thead>
<tr>
<th>Organization</th>
<th>Designation</th>
<th>Year</th>
<th># Qubits</th>
<th>T1 (s)</th>
<th>T2 (s)</th>
<th>Fid 1Q (%)</th>
<th>Fid 2Q (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IonQ</td>
<td>Harmony</td>
<td>2019</td>
<td>11</td>
<td>10-100</td>
<td>1</td>
<td>99.72</td>
<td>96.54</td>
</tr>
<tr>
<td></td>
<td>Aria</td>
<td>2020</td>
<td>32</td>
<td>10-100</td>
<td>1</td>
<td>99.98</td>
<td>99.3</td>
</tr>
<tr>
<td></td>
<td>Forte</td>
<td>2022</td>
<td>32</td>
<td>10-100</td>
<td>1</td>
<td>99.98</td>
<td>99.6</td>
</tr>
<tr>
<td>Quantinuum</td>
<td>H1-1</td>
<td>2022</td>
<td>20</td>
<td></td>
<td></td>
<td>99.996</td>
<td>99.8</td>
</tr>
<tr>
<td></td>
<td>H1-2</td>
<td>2022</td>
<td>12</td>
<td></td>
<td></td>
<td>99.996</td>
<td>99.7</td>
</tr>
</tbody>
</table>

Find more in [https://databaseline.tech/quantum.html](https://databaseline.tech/quantum.html)
Quantum computer based on neutral atoms

- Atoms of interest for quantum computing
  e.g., Rb, Cs

- Quantum information can be encoded in
  e.g., hyperfine states

- Trapping of neutral atoms
  e.g., optical tweezer
  Arthur Ashkin
  Nobel prize in physics 2018

- Advantages
  Long lifetime (10s s), large scale

- Challenges
  Slow gates (ms)

### Organization

<table>
<thead>
<tr>
<th>Organization</th>
<th>Designation</th>
<th>Year</th>
<th># Qubits</th>
</tr>
</thead>
<tbody>
<tr>
<td>ColdQuanta</td>
<td>Hilbert</td>
<td>2024</td>
<td>1000</td>
</tr>
<tr>
<td>PASQAL</td>
<td></td>
<td>2022</td>
<td>324</td>
</tr>
<tr>
<td></td>
<td>QuEra&gt;</td>
<td>Aquila</td>
<td>2022</td>
</tr>
</tbody>
</table>

K. Singh et al., Phys. Rev. X 12, 011040 (2022)
National Quantum Initiative (2018)

- Accelerate research and development in quantum science and technology
- Facilitate collaboration between government agencies, industry, and academic researchers
- 13 quantum information science centers
Quantum effort worldwide

Global effort 2022
$30b (estimate)

US National Quantum Initiative $1.2b

European Quantum Flagship 1b € = $1.1b

Hungary HUF3.5b = $11m

Singapore S$150m = $109m

©2022 QURECA Ltd – Confidential and Proprietary
# Market overview of quantum computing

## Users
- Select examples
- **Material Science**
- Finance
- Life Sciences
- Other

## Applications
- Not mapped to verticals
- Not strictly categorized given diversity of operations¹

## Software offerings
- Includes control software
- **Cloud access to QPUs**
- Simulators / q-inspired / etc

## QPUs²
- **Superconducting**

## Hardware / components
- Select examples only – not representative of entire ecosystem
- **Cryogenics (includes testing)**

### Quantum Computing Market map – The Quantum Insider
Workforce development in quantum information science

- Diverse background

  Physicists, electrical engineers, computer scientists, material scientists, chemists, mathematicians…

- Many opportunities
  - Summer schools
  - Internships
  - Online education
Lecture VIII: Current progress and ecosystem in quantum computing

- Overview of current status of quantum computer
- Quantum ecosystem and workforce development