Quantum Computing Trends

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Quantum Information Science (QIS)

- Quantum mechanics explains how world works at microscopic level, which governs behavior of all physical systems, regardless of their size
- Information science revolutionized how information is collected, stored, computed, analyzed, manipulated, protected, and moved
- We see convergence of two 20th century greatest revolutions in the form of Quantum Information Science (QIS)
Quantum Information Science

QIS exploits unique quantum effects such as superposition, interference, and entanglement to obtain, compute, and transmit information in the ways that are superior compared to classical technology (digital, Newtonian).

The key concept is entanglement (“spooky action at a distance”, EPR pair). Works only for very small object (electrons, photons, atoms etc). It is proven to be essential to achieve “quantum advantage” or for “quantum teleportation”.

<table>
<thead>
<tr>
<th>Classical</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcome</td>
<td></td>
</tr>
<tr>
<td>00</td>
<td>1/4</td>
</tr>
<tr>
<td>01</td>
<td>1/4</td>
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<tr>
<td>10</td>
<td>1/4</td>
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<tr>
<td>11</td>
<td>1/4</td>
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</table>

<table>
<thead>
<tr>
<th>Quantum</th>
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<tbody>
<tr>
<td>Outcome</td>
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<tr>
<td>00</td>
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<tr>
<td>01</td>
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<td>10</td>
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<tr>
<td>11</td>
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Key concepts

- Qubit - basic unit of quantum information, which is the quantum version of the classical binary bit. It can exist in superposition – any state between 0 and 1
- Qubit fidelity – how long qubit stays coherent/operational
- Quantum effects - superposition, interference, and entanglement
- NISQ - Noisy Intermediate-Scale Quantum technology, often refers in the context of modern very noisy quantum computers
- QASM - Quantum Assembly used for programming quantum computers
- Quantum supremacy - demonstration of that a programmable quantum device can solve a problem (any problem) that no classical computer can solve in any feasible amount of time
- Quantum advantage - same as supremacy, but for useful applications
Why quantum computing?

Commercialization of a quantum use case

**Quantum ready**
Use case development

**Quantum advantage**
Use case commercialization

![Graph showing the transition from classical computing to quantum computing over time](image)
Why quantum computing?

Quantum computing’s potential for significant speedup over classical computers

<table>
<thead>
<tr>
<th>Type of scaling</th>
<th>Time to solve problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classical algorithm with exponential runtime</td>
<td>10 secs 2 mins 330 years 3300 years Age of the universe</td>
</tr>
<tr>
<td>Quantum algorithm with polynomial runtime</td>
<td>1 min 2 mins 10 mins 11 mins ~24 mins</td>
</tr>
</tbody>
</table>
Quantum Simulator Use Cases: Simulation of Supremacy Circuits

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, [...] John M. Martinis

_Nature_ **574**, 505–510(2019)  Cite this article

799k  Accesses  693  Citations  6025  Altmetric  Metrics

(CNN Business): Google claims it has designed a machine that needs only 200 seconds to solve a problem that would take the world’s fastest supercomputer 10,000 years to figure out.
## Customers Early Applications

<table>
<thead>
<tr>
<th>Optimization</th>
<th>Machine Learning</th>
<th>Quantum Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-period portfolios</td>
<td>Image recognition</td>
<td>Quantum solid state</td>
</tr>
<tr>
<td>Internet ad placement</td>
<td>Higgs Boson Detection</td>
<td>Quantum Molecules</td>
</tr>
<tr>
<td>Satellite Placement</td>
<td>Tree cover classifier</td>
<td>Quantum molecular dynamics</td>
</tr>
</tbody>
</table>

*ONLINE ADVERTISING*
Quantum Computing for Finance

Stochastic Modeling:
Derivative Pricing: Options. Collateralized Debt Obligations
Risk Modeling: Value at Risk, Economic Capital Requirement, Credit Value Adjustments

Combinatorial Optimization:
Portfolio Optimization: Combinatorial Formulations, Convex Formulations
Swap Netting, Optimal Arbitrage, Identifying Creditworthiness, Financial Crashes

Machine Learning:
Anomaly Detection, Asset Pricing, Implied Volatility

## Modern Quantum Computers

Operate at almost absolute zero temperature -460 F or -273 C, colder than deep space

Computers are ranked by number of qubits decoherency time

<table>
<thead>
<tr>
<th>Qubit Modality</th>
<th>Superconducting (IBM, Google, Rigetti)</th>
<th>Trapped ions (IonQ, U. of Innsbruck)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>Al on the Silicon substrate</td>
<td>Yb+, Ca+, Sr+, Be+, Ba+, Mg+</td>
</tr>
<tr>
<td>Type</td>
<td>Transmon</td>
<td>Optical transitions</td>
</tr>
<tr>
<td>Control</td>
<td>Microwaves</td>
<td>Microwaves + optics</td>
</tr>
<tr>
<td>State</td>
<td>Junction phase</td>
<td>Atomic state of elecction</td>
</tr>
<tr>
<td>Approximate Decoherency Times (ns)</td>
<td>~100-200</td>
<td>Very long</td>
</tr>
<tr>
<td>1qb gate</td>
<td>10</td>
<td>5,000</td>
</tr>
<tr>
<td>2qb gate</td>
<td>40</td>
<td>50,000</td>
</tr>
<tr>
<td>Fidelity</td>
<td>1qb gate</td>
<td>99.9%</td>
</tr>
<tr>
<td></td>
<td>2qb gate</td>
<td>99.0%</td>
</tr>
<tr>
<td>Speed (MHz)</td>
<td>1qb gate</td>
<td>100.00</td>
</tr>
<tr>
<td></td>
<td>2qb gate</td>
<td>25.00</td>
</tr>
</tbody>
</table>
IBM quantum computers

The key piece of the Quantum Computer is the Dilution Refrigerator Working Temperature 15 mK uses mix of $^3\text{He}/^4\text{He}$

Source: IBM Research
DWave quantum computer

What Is A Quantum Computer
Google's Sycamore quantum computer
Ion trap quantum computer
Quantum computing is transitioning from scientific curiosity to technical reality. Advancing from discovery to prototype to useful machines takes time.
<table>
<thead>
<tr>
<th><strong>Company</strong></th>
<th><strong>Operational</strong></th>
<th><strong>Cloud Access</strong></th>
<th><strong>Framework</strong></th>
<th><strong>Announced</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>IBM</td>
<td>72 qubits</td>
<td>Open to Q hub members</td>
<td>Qiskit</td>
<td>120+ qubit in 2021</td>
</tr>
<tr>
<td>Rigetti</td>
<td>31 (8) qubits</td>
<td>Access by request</td>
<td>AWS and Forest</td>
<td>50+ qubit near future</td>
</tr>
<tr>
<td>Google</td>
<td>72 qubits</td>
<td>No access</td>
<td>Cirq</td>
<td>120+ qubit in 2021</td>
</tr>
<tr>
<td>Alibaba</td>
<td>11 qubits</td>
<td>-</td>
<td>Alyun</td>
<td>-</td>
</tr>
<tr>
<td>IonQ</td>
<td>32 qubits</td>
<td>Paid Access</td>
<td>AWS and Azure</td>
<td>-</td>
</tr>
<tr>
<td>Honeywell</td>
<td>10 qubits (512 volume)</td>
<td>Paid Access</td>
<td>Azure</td>
<td>-</td>
</tr>
<tr>
<td>D-Wave</td>
<td>5000Q (annealer)</td>
<td>Open (1 minute per month)</td>
<td>AWS and Leap</td>
<td>10,000Q near future</td>
</tr>
</tbody>
</table>

*Intel not included – announced 49 qubit chip in January 2018*
IonQ Quantum Computers

2016 Lab Scale
2020 Tabletop
2021 Benchtop
2023 Rackmount
Roadmap For Growth & Market Leadership

Note: Prepared on the basis of certain technical, market, competitive and other assumptions to be subsequently described in further detail, and which may not be satisfied. As a result, these projections are subject to a high degree of uncertainty and may not be achieved within the time-frames described or at all.

Note: Market inflection points are estimated based on alignment of IonQ technical roadmap with publicly documented quantum research problems in each market

1 Algorithmic qubit number defined as the effective number of qubits for typical algorithms, limited by the Q0 fidelity
2 Employ 16:1 error-correction encoding
3 Employ 32:1 error-correction encoding
Google’s path to an error corrected machine

- Can quantum outperform classical on any computation task?
- Can we demonstrate a path toward achieving low enough error rates for practical tasks?
- Can we achieve such a low error rate?
- Can we build a large enough system with low error rate?
Beyond-classical milestone: Random sampling

**Processor:** Gen-I Sycamore

**Component performance:**
- High-fidelity gate: iSwap-like (“Syc”)
- High-fidelity readout: Single, terminal

**Computation task:**
Beyond-classical sampling with random circuits
PsiQuantum

Goal build: 1 million qubit device in 5 years
Activities: manufacturing 300-millimeter wafers containing a 25 layer stack, single-photon detectors, and high-performance optical switches
ColdQuanta

Hilbert Commercial Roadmap

- Scaling to unexplored parts of the NISQ-era quantum parameter space
- Hardware + algorithms + use cases
- Active work with near-term customer use cases
Chinese quantum computers

1. Zuchongzi - 56 superconducting qubit quantum computer. It was used for sampling from a random distribution. They found Zuchongzi completed such a sampling task in 1.2 hours, one they estimated would take Summit at least 8.2 years to finish.

2. Jiuzhang 2.0 - a photonic quantum computer. It is used for Gaussian boson sampling, a task where the machine analyzes random patches of data. Using 113 detected photons, they estimated Jiuzhang 2.0 could solve the problem roughly $10^{24}$ faster than classical supercomputers.
Microsoft

Azure Quantum
The full-stack, cloud ecosystem to enable quantum impact today.

Application Areas
- Optimization
- Machine Learning
- Quantum Simulation

Software Tools & Services
- Q# (Development Tools)
- QDK (Quantum Development Kit)
- Microsoft 1QBit (Quantum Solutions)
- Simulators
- Resource Estimators

Classical Hardware
- Microsoft Azure
  - Be future ready
  - Build on your terms
  - Operate hybrid seamlessly
  - Trust your cloud

Quantum Hardware
- Microsoft
  - Topological (Future)
- IonQ
- Honeywell
- Superconducting
Amazon

Amazon Braket
QCUP

Oak Ridge Leadership Computing Facility (OLCF) Quantum Computing User Program (QCUP)

https://www.olcf.ornl.gov/olcf-resources/compute-systems/quantum-computing-user-program/

Quantum Project Application:
https://www.olcf.ornl.gov/for-users/documents-forms/quantum-project-proposal/

Quantum Account Application:

Available quantum systems: IBM, Rigetti, Honeywell
Current Public and Private Funding Situation

China: $15 billion
European Union: $7.2 billion
U.K. $1.2 billion
Russia: $790 million
India and Japan $1 billion each
U.S. $1.3 billion
Private funding $1.7 billion in 2021

National Laboratory for Quantum Information Science in Hefei
Patent filings for quantum technology by country

The United States used to produce more patents for quantum technology than China, but in the past decade China has leaped ahead.

Source: Patinformatics LLC

THE WASHINGTON POST
Patent filings for quantum computers by country

China has overtaken the United States in quantum technology patents overall, but the United States still has a large lead in patents for quantum computers.
Major Players in U.S.

Technological giants: IBM, Google, Microsoft, Amazon, Intel, Tesla, Alibaba, JPMorgan Chase

NSF Quantum Leap Challenge Institutes (total 5)

DOE National Quantum Centers:
ANL: Q-NEXT · Next Generation Quantum Science and Engineering
BNL: C2QA · Co-design Center for Quantum Advantage
FNAL: SQMS · Superconducting Quantum Materials and Systems Center
LBNL: QSA · Quantum Systems Accelerator
ORNL: QSC · The Quantum Science Center
**Major Cross-Cutting Challenge:**
Manipulating and interconnecting entangled states of matter.

**Mission:** Deliver quantum interconnects and establish a national resource to provide pristine materials for new quantum devices.

- Nearly 100 researchers from 3 national laboratories, 10 universities, and 10 industry partners
- $115M from DOE and an additional $93M from industry partners

**Q-NEXT Mission**
- Deliver quantum interconnects
- Establish national foundries
- Demonstrate communication links, networks of sensors, and simulation testbeds

**Executive Team:**
- P. Kearns
- D. Awschalom
- S. Guha

**Thrust Leaders:**
- J. Heremans
- M. Holt
- M. Suchara
Acknowledgements

Q-NEXT: Quantum Simulation Team

Sahil Gulania, ANL  Bo Peng, PNNL  Niri Govind, PNNL

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DOD DARPA: This research was partially supported by the the Defense Advanced Research Projects Agency (DARPA) project
Quantum Simulator Use Cases

- Verification of quantum advantage and supremacy claims
- Verification of large quantum devices
- Co-design quantum computers
- Energy efficiency studies of quantum computers
- Design of new quantum algorithms
- Finding parameters for variational quantum algorithms
Quantum simulators developed at Argonne National Laboratory: QTensor and QuaC

Time for a quantum circuit simulation

Simulated 1,000,000 qubit QAOA circuit with depth p=6 in 1 hour and 20 minutes on 512 nodes of supercomputer Theta
Limitations of quantum simulators

<table>
<thead>
<tr>
<th>Qubits</th>
<th>Memory</th>
<th>Time per operation</th>
</tr>
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<tbody>
<tr>
<td>10</td>
<td>16 KB</td>
<td>Microseconds on a smartwatch</td>
</tr>
<tr>
<td>20</td>
<td>16 MB</td>
<td>Milliseconds on a smartphone</td>
</tr>
<tr>
<td>30</td>
<td>16 GB</td>
<td>Seconds on a laptop</td>
</tr>
<tr>
<td>40</td>
<td>16 TB</td>
<td>Seconds on a PC cluster</td>
</tr>
<tr>
<td>50</td>
<td>16 PB</td>
<td>Minutes on modern supercomputers</td>
</tr>
<tr>
<td>60</td>
<td>16 EB</td>
<td>Hours on post-exascale supercomputers?</td>
</tr>
<tr>
<td>70</td>
<td>16 ZB</td>
<td>Days on supercomputers in distant future?</td>
</tr>
</tbody>
</table>