Los Alamos NATIONAL LABORATORY

Quantum Computing Explained: Shaping the Future—and Careers at Los Alamos

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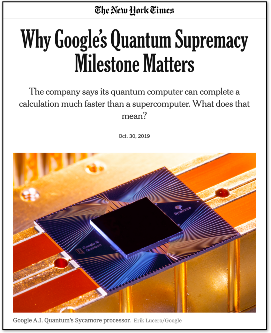
Motivation

🚀 You may have read in the news that quantum computers are here 🚀


The New York Times

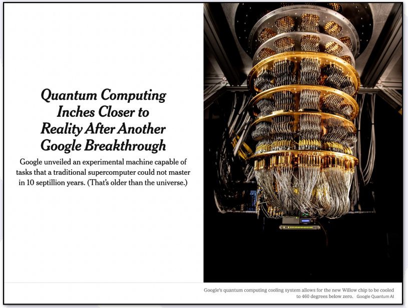
Why Google's Quantum Supremacy Milestone Matters

The company says its quantum computer can complete a calculation much faster than a supercomputer. What does that mean?

Oct. 30, 2019

Google A.I. Quantum's Sycamore processor. Erik Lucero/Google

2019


Quantum Computing Inches Closer to Reality After Another Google Breakthrough

Google unveiled an experimental machine capable of tasks that a traditional supercomputer could not master in 10 septillion years. (That's older than the universe.)

Google's quantum computing cooling system allows for the new Willow chip to be cooled to 460 degrees below zero. Google Quantum AI

2024

But not yet with the size and error rate we need for utility scale.

Outline

How do classical computer represent numbers?

Decimal numbers (0-9)

$$126 = \underbrace{1 \times 10^2}_{\text{hundreds}} + \underbrace{2 \times 10^1}_{\text{tens}} + \underbrace{6 \times 10^0}_{\text{ones}}$$

We use that representation in our daily live: 💵, 📅, 🗺️

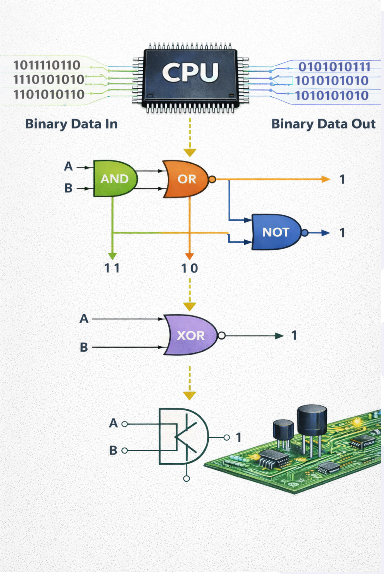
Binary numbers (0-1)

$$126 = 1111100 = 1 \times \underbrace{2^6}_{64} + 1 \times \underbrace{2^5}_{32} + 1 \times \underbrace{2^4}_{16} + 1 \times \underbrace{2^3}_{8} + 1 \times \underbrace{2^2}_{4} + 0 \times 2^1 + 0 \times 2^0$$

We use this representation in our daily life: 📱, 💻

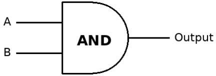
Exercise: Write your age in binary representation.

How do classical computers work?

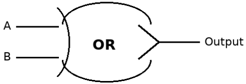


Let us look into logical gates

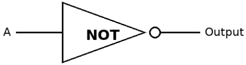
Logic Gates



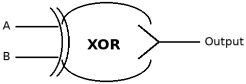
A	B	Output
0	0	0
0	1	0
1	0	0
1	1	1



A	B	Output
0	0	0
0	1	1
1	0	1
1	1	1

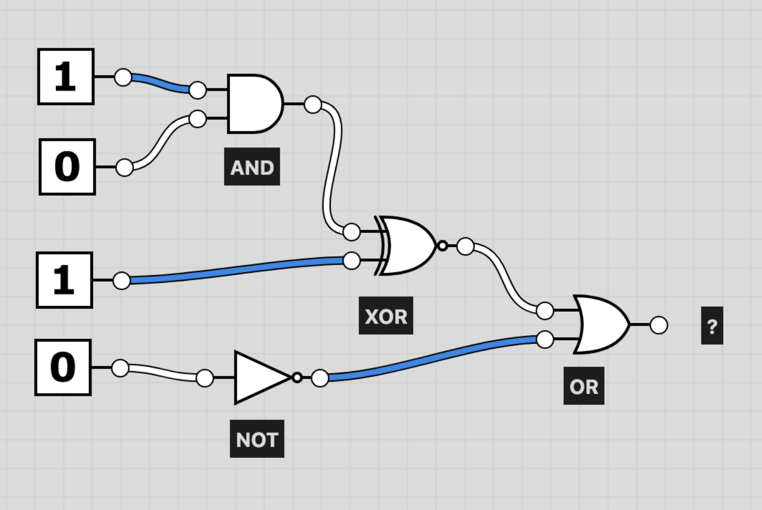


A	Output
0	1
1	0



A	B	Output
0	0	0
0	1	1
1	0	1
1	1	0

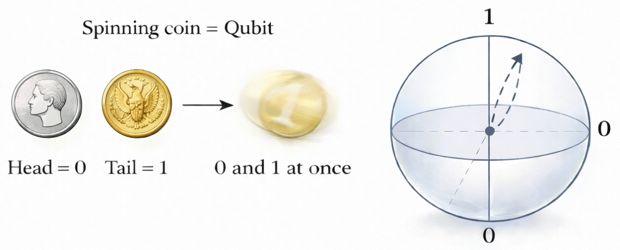
Sample circuit



Exercise: Solve the circuit.

Let us look at a quantum computer: Qubits instead of bits

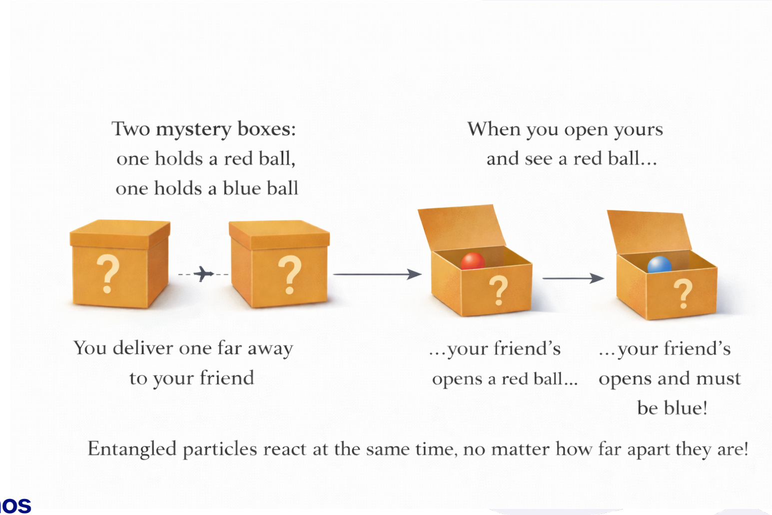
Recall on a classical computer, a bit can either be 0 or 1. However, on a quantum computer, a qubit can 0 and 1 at the same time.



A qubit is like a spinning coin—it's kind of both!

One cool feature: Entanglement

"Entanglement means two particles are connected so that what happens to one instantly affects the other."



Quantum circuits

Quantum circuits are similar to classical circuits but with qubits and gates

- have the same number of input and output bits
- be reversible: each input has a unique output

In the previous classical circuit exercise, we had one solution. For a quantum circuit, we have a range of solutions with counting the occurrences by running many shots:

Output	Occurrence
1	75%
0	25%

Mathematical representation of qubits and gates

We can define qubits as vectors

$$\langle 0| = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad \text{and} \quad \langle 1| = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

and gates as matrices

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

Gates acting on qubits

Acting on $\langle 0|$:

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} (a \times 1) + (b \times 0) \\ (c \times 1) + (d \times 0) \end{bmatrix} = \begin{bmatrix} a \\ c \end{bmatrix}$$

Acting on $\langle 1|$:

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} (a \times 0) + (b \times 1) \\ (c \times 0) + (d \times 1) \end{bmatrix} = \begin{bmatrix} b \\ d \end{bmatrix}$$

Example: not gate

Not on $\langle 0|$:

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} (0 \times 1) + (1 \times 0) \\ (1 \times 1) + (0 \times 0) \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Not on $\langle 1|$:

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} (0 \times 0) + (1 \times 1) \\ (1 \times 0) + (0 \times 1) \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

Example: cnot gate and Toffoli Gate

$$\text{CNOT}\,\langle 10| \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \langle 11|$$

$$T\,\langle 110| = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \langle 111|$$

Hadamard gate

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Apply

$$H \langle 0| = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

and

$$H \langle 1| = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Hint: Work row by row and keep $\frac{1}{\sqrt{2}}$ outside

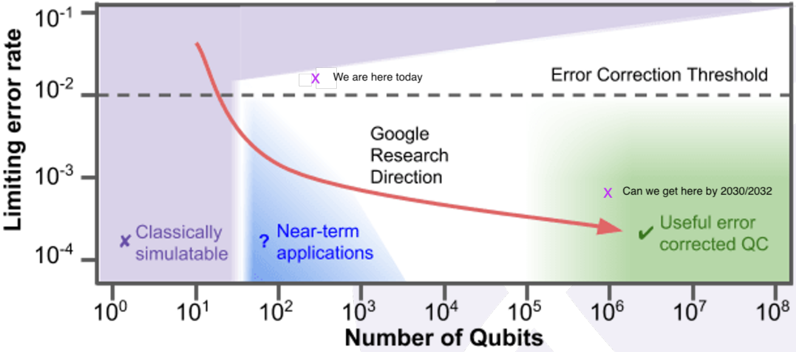
Hadamard gate (Solution)

$$H\langle 0| = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix} \cdot \begin{bmatrix}1\\ 0\end{bmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\ 1\end{bmatrix}$$

$$H\langle 1| = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix} \cdot \begin{bmatrix}0\\ 1\end{bmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\ -1\end{bmatrix}$$

So Hadamard creates a qubit that can give either 0 or 1 when measured.

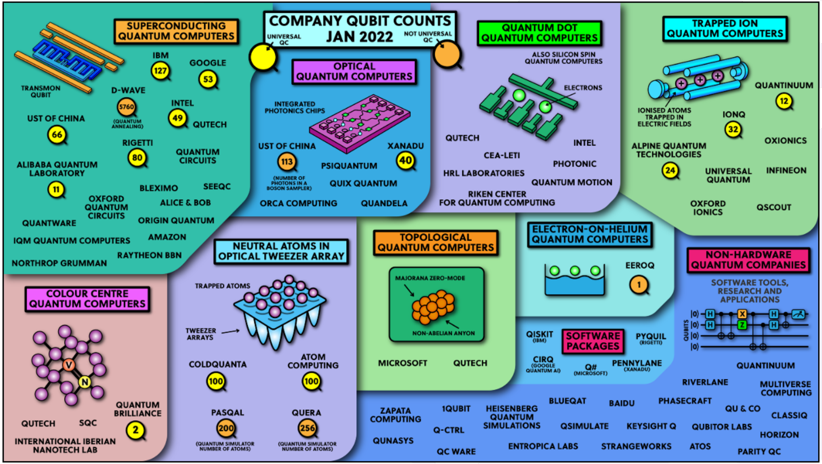
Where are we today?



Conclusion: today these computers are just barely working!

Courtesy: `https://www.hpcwire.com/2018/04/26/google-frames-quantum-race-as-two-dimensional/`

Which technology will get us there?



Three Types of Commercial Quantum Computers

	Available Today		Available *Very* Soon?
	Noisy Analog	Noisy Gate-Based	Fault-Tolerant Gate-Based
Who?	D-Wave, QuEra, PASQAL	IBM Q, Quantum AI, IONQ, rigetti, XANADU, QUANTINUUM, qci	PsiQuantum, atom computing, D-Wave, qci, Quantum AI, ALICE & BOB **Public Roadmaps** IBM Q, PASQAL, Infleqtion, QuEra

QBI: Quantum Benchmarking Initiative

In the simplest terms, the Quantum Benchmarking Initiative (QBI) seeks to determine whether it's possible to build an industrially-useful computer by 2033. Specifically, QBI is designed to rigorously verify and validate whether any quantum computing approach can achieve utility-scale operation — meaning its computational value exceeds its cost.

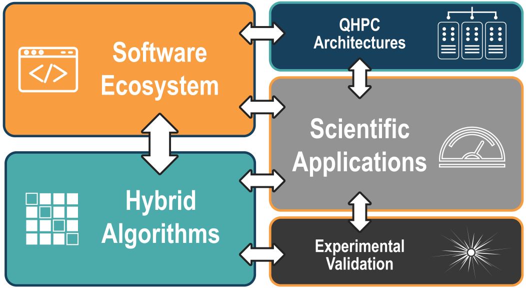
Public announced companies:

Atom Computing (neutral atoms), Diraq (spin qubits), IBM (superconducting), IonQ (trapped-ion), Nord Quantique (superconducting), Photonic Inc. (spin qubits), Quantinuum (trapped-ion), Quantum Motion (spin qubits), QuEra Computing (neutral atom), Silicon Quantum Computing Pty. Ltd (precision atom), and Xanadu (photonic).

https://www.darpa.mil/research/programs/quantum-benchmarking-initiative

Quantum Science Center

Pioneering quantum-accelerated high-performance computing, developing open-source software for quantum-classical workflows that accelerate scientific advancements across multiple disciplines.



https://www.qscience.org/about/

Quantum Computing Summer School Fellowship

https://www.lanl.gov/engage/collaboration/internships/summer-schools/quantumschool

Open research questions

- Which technology will win the race and which company will built it by 2030/2032?
- For what application will be quantum computers beneficial?
- What is the most efficient quantum error-correcting code?

Workforce development

- As with the beginning of classical computers, we need programmers for quantum computers
- We need domain scientist for preparing applications for quantum computers
- We need engineers to operate the quantum computers.
- As we go many more roles will be investigated.

Where things will lead and when developments will occur remain uncertain, but the coming years promise exciting research opportunities.