COEN-4730/EECE-5730 Computer Architecture

Lecture 14
Quantum Computing

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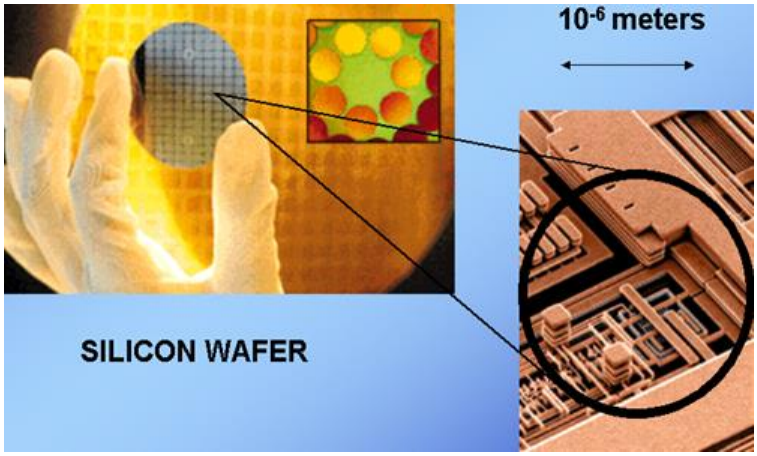
BE THE DIFFERENCE.

Outline

- Quantum Computing
- Quantum Simulators
- Tech Companies
- More Resources
- More online courses
- More recent research articles
- Books
- Skeptics
- Notes:
  - This presentation is far from being complete; it is "work in progress", with constantly added updates because things change quite rapidly on this topic…
  - This is an emerging field; and, I am not an expert in this area; the information presented here is aggregated from various sources.

Your Computer



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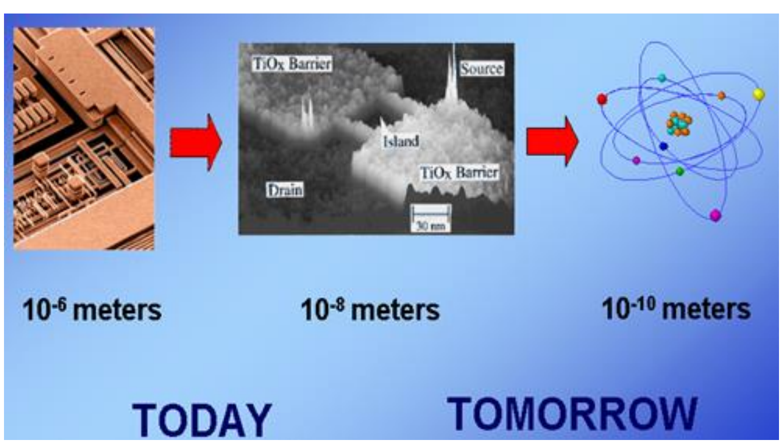
How Small Can They Be?



Here, quantum mechanics come into play!

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Limits of Classical Computation

- Reaching the Size & Operational Time limits:
    1. Quantum Physics has to be considered for device operation.
    2. Technologies based on Quantum Physics could improve the clock-speed of microprocessors, decrease power dissipation & miniaturize more!
- Is it possible to do much more? Is there any new kind of information processing based on Quantum Physics?

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Quantum

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Quantum Mechanics

- Quantum mechanics is a more fundamental theory than Newtonian mechanics and classical electromagnetism
- It provides accurate and precise descriptions for many phenomena that these "classical" theories cannot explain on the atomic and subatomic level

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Nobody understands quantum mechanics?

“No, you’re not going to be able to understand it… You see, my physics students don’t understand it either. That is because I don’t understand it. Nobody does… The theory of quantum electrodynamics describes Nature as absurd from the point of view of common sense. And it agrees fully with an experiment. So, I hope that you can accept Nature as She is - absurd.”

--Richard Feynman

“Anybody who thinks they understand quantum physics is wrong.”

-- Niels Bohr

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Quantum computing - the starting point

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

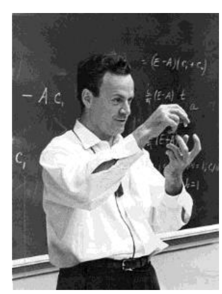
Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

History

- "I think I can safely say that nobody understands quantum mechanics" - Feynman
- 1982 - Feynman proposed the idea of creating machines based on the laws of quantum mechanics instead of the laws of classical physics.
- 1985 - David Deutsch developed the quantum Turing machine, showing that quantum circuits are universal.
- 1994 - Peter Shor came up with a quantum algorithm to factor very large numbers in polynomial time.
- 1997 - Lov Grover develops a quantum search algorithm with O(√N) complexity



What is Quantum?

- The **quantum** in "quantum computing" refers to the quantum mechanics that the system uses to calculate outputs.
- In physics, a quantum is the smallest possible discrete unit of any physical property. It usually refers to properties of atomic or subatomic particles, such as electrons, neutrinos, and photons.
- Such properties include: **spin of an electron** or **polarization of a photon** (important: we refer to these properties as they are just before they are detected/observed/measured).

Source: https://azure.microsoft.com/en-us/resources/cloud-computing-dictionary/what-is-quantum-computing

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Qubit

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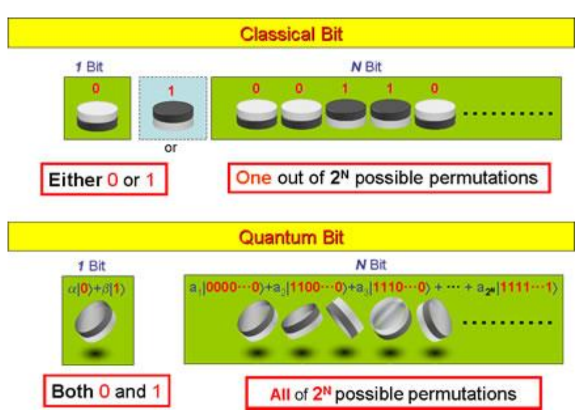
What is a Qubit?

- A **qubit** ("quantum bit") is the basic unit of information in quantum computing.
- Qubits play a similar role in quantum computing as (binary) bits play in classical computing, but they behave very differently.
- Classical bits are binary and can hold only a position of 0 or 1, but qubits can hold a superposition of all possible states.

Source: https://azure.microsoft.com/en-us/resources/cloud-computing-dictionary/what-is-quantum-computing

Qubit

- A bit of data is represented by a single atom that is in one of two states denoted by **|0>** and **|1>**. A single bit of this form is known as a qubit



Classic vs. Quantum Logic

CLASSICAL LOGIC: two distinct states "bit"

$0 \; or \; 1$

can do all operations from NOT and exclusive-OR gates

Single-bit operation   Two-bit operation

perform series of operations on bits to get final answer

QUANTUM LOGIC: superposition of two quantum levels "qubit" = quantum bit

$$\Psi = a|0\rangle + b|1\rangle$$

can do all operations from single-qubit and controlled-NOT functions

unitary transformations (e.g. rotations)   Two-qubit operation

"Entangle" qubits and allow quantum evolution to "project out" answer

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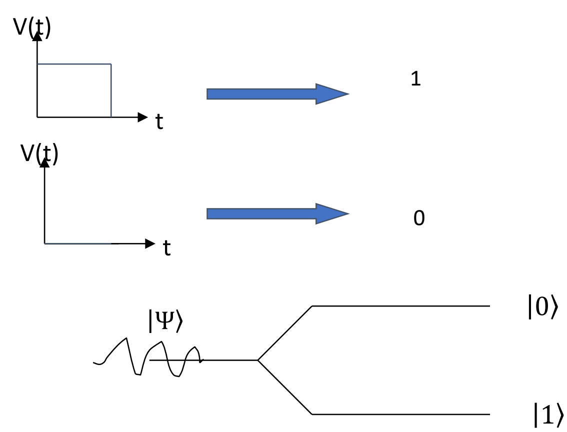
Bit & Quantum Bits



$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$ $|\alpha|^2 + |\beta|^2 = 1$

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Representation of Data

- In a quantum computer, one "qubit" (**qu**antum **bit**) **could be both 0 and 1 at the same time**.
- So, with three qubits of data, a quantum computer could store all eight combinations of 0 and 1 simultaneously. That means a three-qubit quantum computer could calculate eight times faster than a three-bit digital computer.
- Typical personal computers today calculate 64 bits of data at a time. A quantum computer with 64 qubits would be 2 to the 64th power faster, or about 18 billion billion times faster. (NOTE: billion billion is correct.)

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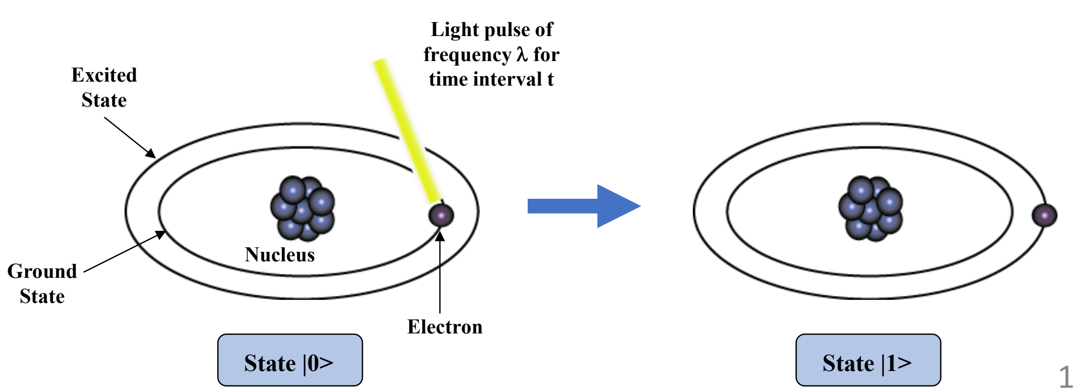
Representation of Data - Qubits

- A physical implementation of a qubit could use the two energy levels of an atom.
  - An **excited state** representing |1>
  - A **ground state** representing |0>



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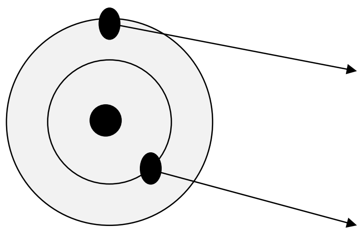
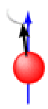
More Quantum Bits



$|e\rangle \equiv |1\rangle$

$|g\rangle \equiv |0\rangle$



$|spin\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$

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More on Qubit

- A qubit has two possible states: $|0\rangle$ & $|1\rangle$
- Unlike Bits, qubits can be in superposition state

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

- A qubit is a unit vector in 2D Vector Space (2D Hilbert Space)
- $|0\rangle$ & $|1\rangle$ are orthonormal computational basis
- We can assume that $|0\rangle = \begin{bmatrix}1\\0\end{bmatrix}$ & $|1\rangle = \begin{bmatrix}0\\1\end{bmatrix}$

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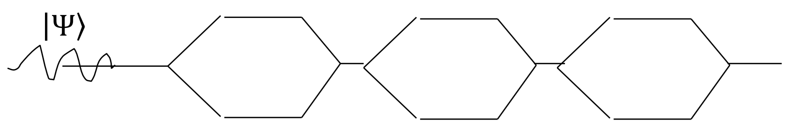
Qubit

- A measurement yields 0 with probability $|\alpha|^2$ & 1 with probability $|\beta|^2$
- Quantum state can not be recovered from qubit measurement.
- **A qubit can be entangled (see later slides) with other qubits.**
- There is an exponentially growing hidden quantum information.



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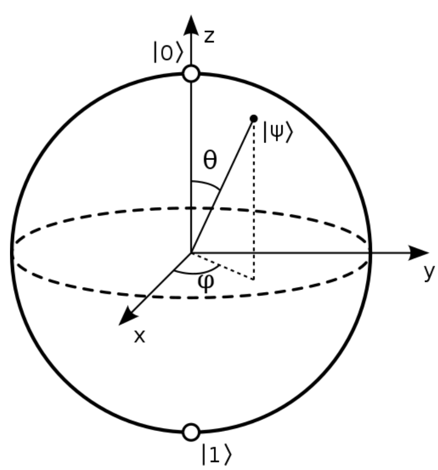
Representing qubits - the Bloch sphere



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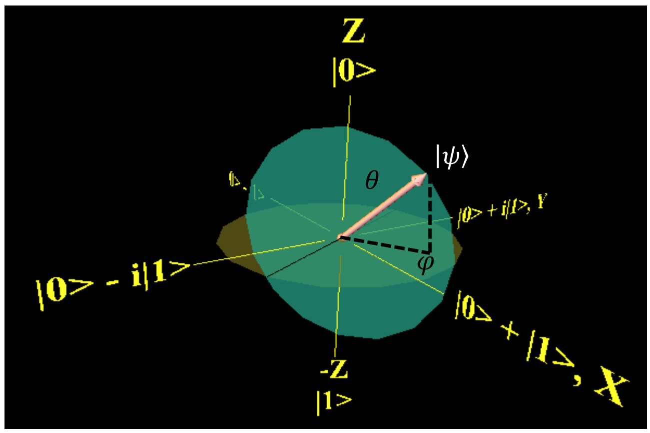
Math of Qubits

- Qubits can be represented in **Bloch Sphere.**

$$|\Psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$



Logical Qubit vs. Physical Qubit

- To address the issue of noise (see later slides) - several physical qubits are coaxed - each encoded in a superconducting circuit, say, or an individual ion - to work together to represent one qubit of information or "logical qubit".

Quantum Gates

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Classical vs. Quantum logic - gates and algorithms

Because the bits are different, the logic operations are different also

CLASSICAL LOGIC

Classic logic gates operate on discrete binary bits --- there are 7 types of logic gates:

Name	NOT	AND	NAND	OR	NOR	XOR	XNOR
Alg. Expr.	$\overline{A}$	AB	$\overline{AB}$	$A+B$	$\overline{A+B}$	$A\oplus B$	$\overline{A\oplus B}$
Symbol	A x	A B x					
Truth Table	A X 0 1 1 0	B A X 0 0 0 0 1 0 1 0 0 1 1 1	B A X 0 0 1 0 1 1 1 0 1 1 1 0	B A X 0 0 0 0 1 1 1 0 1 1 1 1	B A X 0 0 1 0 1 0 1 0 0 1 1 0	B A X 0 0 0 0 1 1 1 0 1 1 1 0	B A X 0 0 1 0 1 0 1 0 0 1 1 1

Classical algorithms consist of sequences of these logic operations, sometimes performed in parallel in large computers

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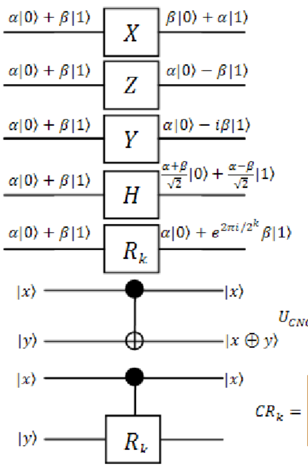
Classical vs. Quantum logic - gates and algorithms

QUANTUM LOGIC

Quantum logic gates operate on single qubits and pairs of qubits



$$X = \begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}$$

$$Z = \begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}$$

$$Y = \begin{bmatrix}1 & 0\\ 0 & -i\end{bmatrix}$$

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

$$R_k = \begin{bmatrix}1 & 0\\ 0 & e^{2\pi i/2^k}\end{bmatrix}$$

$$U_{CNOT} = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix}$$

$$CR_k = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & e^{2\pi i/2^k}\end{bmatrix}$$

Gate name	# Qubits	Circuit Symbol	Unitary Matrix	Description
Hadamard	1	H	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$	Transforms a basis state into an even superposition of the two basis states.
T	1	T	$\begin{bmatrix}1 & 0\\ 0 & e^{i\pi/4}\end{bmatrix}$	Adds a relative phase shift of $\pi/4$ between contributing basis states. Sometimes called a $\pi/8$ gate, because diagonal elements can be written as $e^{-i\pi/8}$ and $e^{i\pi/8}$.
CNOT	2		$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix}$	Controlled-not; reversible analogue to classical XOR gate. The input connected to the solid dot is passed through to make the operation reversible.
Toffoli (CCNOT)	3		$\begin{bmatrix}1&0&0&0&0&0&0&0\\0&1&0&0&0&0&0&0\\0&0&1&0&0&0&0&0\\0&0&0&1&0&0&0&0\\0&0&0&0&1&0&0&0\\0&0&0&0&0&1&0&0\\0&0&0&0&0&0&0&1\\0&0&0&0&0&0&1&0\end{bmatrix}$	Controlled-controlled-not; a three-qubit gate that switches the third bit for states where the first two bits are 1 (that is, switches $\|110\rangle$ to $\|111\rangle$ and vice versa).
Pauli-Z	1	Z	$\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}$	Adds a relative phase shift of π between contributing basis states. Maps $\|0\rangle$ to itself and $\|1\rangle$ to $-\|1\rangle$. Sometimes called a "phase flip."
Z-Rotation	1	$R_z(\theta)$	$\begin{bmatrix}e^{-i\theta/2} & 0\\ 0 & e^{i\theta/2}\end{bmatrix}$	Adds a relative phase shift of (or rotates state vector about z-axis by) θ.
NOT	1	$\oplus$	$\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}$	Analogous to classical NOT gate; switches $\|0\rangle$ to $\|1\rangle$ and vice versa.

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Quantum Gates

- A **Quantum Gate** is any transformation in Bloch sphere allowed by laws of QM, that is a **Unitary** transformation.

$$R(\theta,\varphi,\gamma) = \begin{bmatrix}\cos\theta & e^{i\varphi}\sin\theta\\ -e^{i\gamma}\sin\theta & e^{i(\varphi+\gamma)}\cos\theta\end{bmatrix}$$

- The time evolution of the state of a closed system is described by Schrodinger Eq.

$$i\hbar\frac{d}{dt}|\Psi\rangle = H|\Psi\rangle$$

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Examples of Quantum Gates

- NOT gate:

$$\alpha|0\rangle + \beta|1\rangle \;\text{———}\boxed{X}\text{———}\; \beta|0\rangle + \alpha|1\rangle$$

- Z gate:

$$\alpha|0\rangle + \beta|1\rangle \;\text{———}\boxed{Z}\text{———}\; \alpha|0\rangle - \beta|1\rangle$$

- Hadamard gate:

$$\alpha|0\rangle + \beta|1\rangle \;\text{———}\boxed{H}\text{———}\; \alpha\frac{|0\rangle + |1\rangle}{\sqrt{2}} + \beta\frac{|0\rangle - |1\rangle}{\sqrt{2}}$$

- Phase gate:

$$\alpha|0\rangle + \beta|1\rangle \;\text{———}\boxed{P}\text{———}\; \alpha|0\rangle + e^{i\varphi}\beta|1\rangle$$

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Multiple Qubits

- The state space of n qubits can be represented by **Tensor Product** in Hilbert space with 2^n orthonormal base vectors. E.g.:

$$|0\rangle \otimes |1\rangle = |01\rangle$$

states produced by Tensor Product is separable & measurement of one will not affect the other.

- **Entangled** state can not be represented by Tensor Product. E.g.:

$$\alpha|00\rangle + \beta|11\rangle \neq |\Psi_1\rangle \otimes |\Psi_2\rangle \qquad \alpha, \beta \neq 0$$

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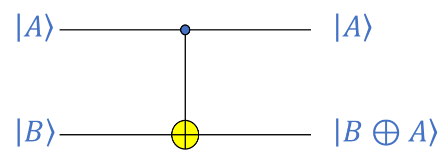
Multiple Qubit Gates

C-NOT Gate



Any Multiple qubit logic gate may be composed from C-NOT and single qubit gate.

C-NOT Gate is **Invertible** gates. There is not an irretrievable loss of information under the action of C-NOT.

Classical vs. Quantum logic - Gates and Algorithms

A few other important differences:

1. Quantum gates are reversible --- classical gates are not.

   That means that the input data is destroyed in the classical operations but is retained in the quantum system

2. Classical gates (if they work) give an exact result --- quantum gates give superpositions of states which are characterized by probabilities

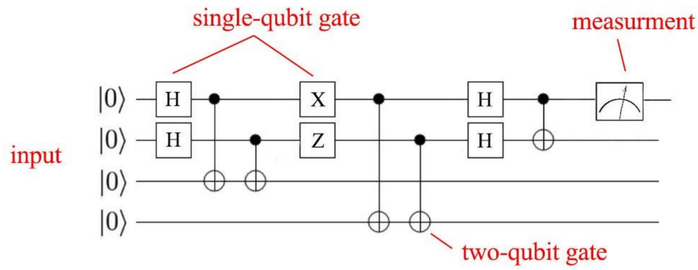
   That means: (1) that you need "high-fidelity" readouts of the state that can distinguish which state the system is in after an operation, and (2) even with perfect fidelity that you need to work with ensembles and do enough measurements to get the final state

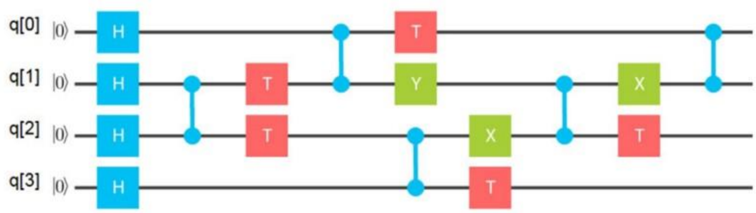
3. You need to implement "**error-correcting codes**" to mitigate accumulated measurements

   That means that there is an "overhead cost", i.e., to make N functioning qubits, you may need many more physical qubits --- that overhead depends on the system but can be 10-1000 times*

**This is one of prime motivations of topologically-protected qubit platforms since it is proposed that these give error-free operations that will eliminate the need for error-corrections (that is only partially true)*

Quantum Algorithms - consist of sequences of these logic operations, followed by measurements of the resulting quantum states





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Perspective of Quantum Computation & Information

- Quantum Parallelism
- Quantum Algorithms solve some of the most complex problems efficiently (Schor’s algorithm, Grover search algorithm)
- QC can simulate quantum systems efficiently!
- Quantum Cryptography: A secure way of exchanging keys such that eavesdropping can always be detected.
- Quantum Teleportation: Transfer of information using quantum entanglement.

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Quantum Computing

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What is quantum computing?

- “Use of quantum mechanical systems to perform mathematical computations”
- Quantum computers harness the unique behavior of quantum physics—such as superposition, entanglement, and quantum interference—and apply it to computing.
- This introduces new concepts to traditional programming methods.

Source: https://azure.microsoft.com/en-us/resources/cloud-computing-dictionary/what-is-quantum-computing

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Universal Computation

- **Classical Computing Theorem:**

  Any functions on bits can be computed from the composition of **NAND** gates alone, known as **Universal** gate**.**

- **Quantum Computing Theorem:**

  Any transformation on qubits can be done from composition of any two quantum gates.

  E.g., 3 phase gates & 2 Hadamard gates, the universal computation is achieved.

- **No cloning Theorem:**

  Impossible to make a copy from unknown qubit.

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Quantum Computation

- Classical Computation:
  - Classical logic bit: “0” and “1”
- Quantum Computation:
  - Quantum bit, “Qubit”, can be manipulated using the rules of quantum physics
  - Orthogonal quantum states |0> , |1> and their superposition $|\Psi\rangle = c_0|0\rangle + c_1|1\rangle$
- **A Quantum State of M bits is a superposition of 2^M states.**
- The quantum computation is a parallel computation in which all 2^M basis vectors are acted upon at the same time.
- If one wanted to simulate a quantum computer using a classical computer one would need to multiply together 2^M dimensional unitary matrices, to simulate each step.
- A quantum computer can factorize (integer factorization - basis of RSA cryptography) a 250-digit number in seconds while an ordinary computer will take 800000 years!

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Quantum Computation

$$
\begin{array}{ll}
0 & \boxed{|\Psi(0)>} \\
 & \quad \downarrow U(t_1,t_0) \\
1 & \boxed{|\Psi(1)>} \\
 & \quad \downarrow U(t_2,t_1) \\
 & \boxed{\;\cdots\;} \\
 & \quad \downarrow U(t_n,t_{n-1}) \\
n & \boxed{|\Psi(n)>} \\
 & \quad \downarrow \\
 & \boxed{P(\Phi)=|<\Phi|\Psi(n)>|^2}
\end{array}
$$

Preparation:

The initial preparation of the state defines a wave function at time $t_0=0$.

State evolution:

Evolved by a sequence of unitary operations

Measurement:

Quantum measurement is projective

Collapsed by measurement of the state

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Data Retrieval

- In general, an **n qubit register** can represent the numbers 0 through 2^n-1 simultaneously.
- If we attempt to retrieve the values represented within a superposition, the superposition randomly collapses to represent just one of the original values.

In equation: $|\psi> = \alpha_1 |0> + \alpha_2 |1>$, α_1 represents the probability of the superposition collapsing to $|0>$.

The α's are called **probability amplitudes**.

In a balanced superposition, $\alpha = 1/\sqrt{2^n}$ where n is the number of qubits.

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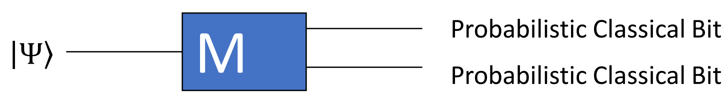
Measurement

- A **measurement** can be done by a projection of each $|\Psi\rangle$ in the basis states, namely $|0\rangle$ and $|1\rangle$
- Measurement can be done in any orthonormal and linear combination of states $|0\rangle$ & $|1\rangle$
- Measurement changes the state of the system & can not provide a snapshot of the entire system



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Measuring multi-qubit systems

- If we measure both bits of:

$$\alpha_{00}|0\rangle|0\rangle + \alpha_{01}|0\rangle|1\rangle + \alpha_{10}|1\rangle|0\rangle + \alpha_{11}|1\rangle|1\rangle$$

- We get: $|x\rangle|y\rangle$
- With probability: $|\alpha_{xy}|^2$

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Measurement

- $\sum|\alpha|^2$, for amplitudes of all states matching an output bit-pattern, gives the probability that it will be read.
- Example:
  - **0.316|00› + 0.447|01› + 0.548|10› + 0.632|11›**
- The probability to read the rightmost bit as 0 is:
  - $|0.316|^2 + |0.548|^2 = 0.4$
- Measurement during a computation changes the state of the system but can be used in some cases to increase efficiency (measure and halt or continue).

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Superposition

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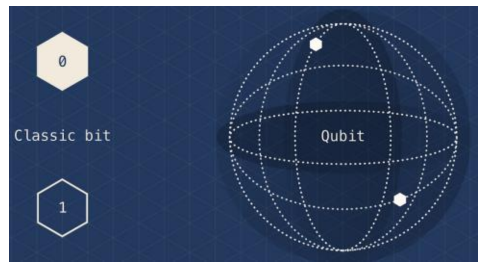
Superposition

- In superposition, **quantum particles** are a combination of all possible states. They fluctuate until they're observed and measured.
- One way to picture the difference between binary position and superposition is to imagine a coin. Classical bits are measured by "flipping the coin" and getting heads or tails.
- However, if you were able to look at a coin and see both heads and tails at the same time, as well as every state in between, the coin would be in superposition.
- In a quantum system - the qubit can be both one and zero and anything in between at the same time. This is the concept of **superposition**, where something can exist in multiple states at once. That is the **quantum state**.



Source: https://azure.microsoft.com/en-us/resources/cloud-computing-dictionary/what-is-quantum-computing

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Representation of Data - Superposition

- A single qubit can be forced into a **superposition** of the two states denoted by the addition of the state vectors:

$$|\psi> = \alpha_1\ |0> \ + \ \alpha_2\ |1>$$

- Where $\alpha 1$ and $\alpha 2$ are complex numbers and:

$$|\alpha_1|^2 \ + \ |\alpha_2|^2 \ = 1$$

A qubit in superposition is in both states |1> and |0> at the same time

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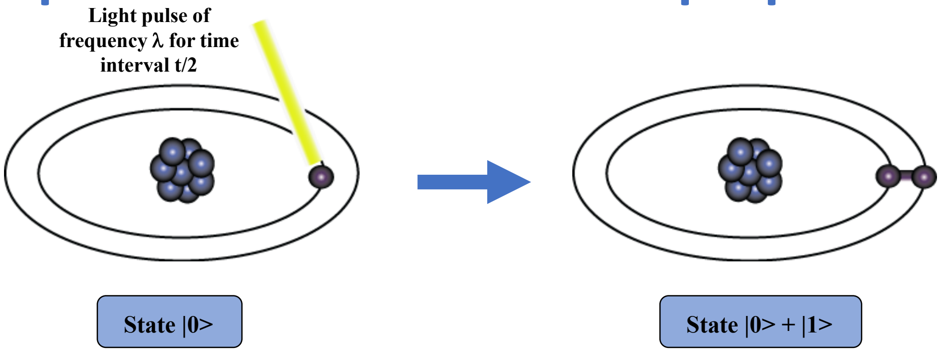
Representation of Data - Superposition



Consider a 3 bit qubit register. An equally weighted superposition of all possible states would be denoted by:

$$|\psi\rangle = \frac{1}{\sqrt{8}}|000\rangle + \frac{1}{\sqrt{8}}|001\rangle + \ldots + \frac{1}{\sqrt{8}}|111\rangle$$

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Entanglement, Interference

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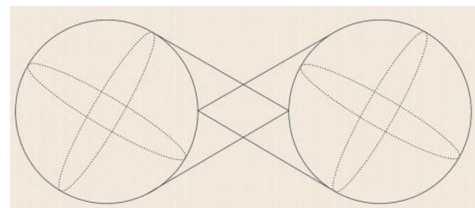
Entanglement

- Entanglement is the ability of quantum particles to correlate their measurement results with each other.
- When qubits are entangled, they form a single system and influence each other.
- We can use the measurements from one qubit to draw conclusions about the others.
- By adding and entangling more qubits in a system, quantum computers can calculate exponentially more information and solve more complicated problems.



Source: https://azure.microsoft.com/en-us/resources/cloud-computing-dictionary/what-is-quantum-computing

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Entanglement

- Entanglement is a quantum phenomenon where the properties of two or more particles become interconnected in a way that one cannot assign a definite state to each individual particle anymore.
  - Instead, we must consider all particles at once that share a certain state.
  - Entanglement of the particles ultimately determines the properties of a material.
- To harness qubits power, multiple qubits must be linked together, a process called entanglement.
- With each additional qubit added, the computational power of the processor is effectively doubled.

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Relationships among data - Entanglement

- Entanglement is the ability of quantum systems to exhibit correlations between states within a superposition.
- Imagine two qubits, each in the state |0> + |1> (a superposition of the 0 and 1). We can entangle the two qubits such that the measurement of one qubit is always correlated to the measurement of the other qubit.

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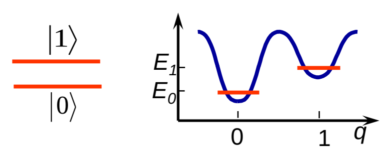
Key to Quantum Computation = Entanglement

qubit = quantum two-level system $|0\rangle$ *and* $|1\rangle$

Superposition: $\Psi = a|0\rangle + b|1\rangle$



Entanglement: interference of two qubits $\Psi = A|00\rangle + B|01\rangle + C|10\rangle + D|11\rangle$

Performing logic operations with entangled states allows the quantum evolution to sample multiple states…
effectively massive parallel computation

Quantum mechanically, a register of N entangled qubits can store 2^N states in superposition:

e.g., A 300-qubit register can simultaneously store $2^{300} \sim 10^{90}$ numbers

2037035976334486086268445688409378161051468393665936250636140449354381299763336706183397376

This is more than the total number of particles in the Universe?!

(A previous Google's SC quantum computer had 57 qubits = only 144,115,188,075,855,872 states)

Some problems benefit from this exponential scaling, enabling solutions of otherwise insoluble problems.

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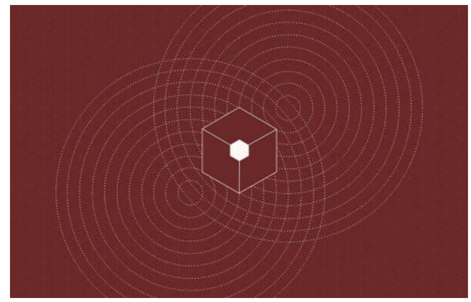
Quantum interference

- Quantum interference is the intrinsic behavior of a qubit, due to superposition, to influence the probability of it collapsing one way or another.
- Quantum computers are designed and built to reduce interference as much as possible and ensure the most accurate results.
- E.g., Microsoft uses topological qubits, which are stabilized by manipulating their structure and surrounding them with chemical compounds that protect them from outside interference.



Source: https://azure.microsoft.com/en-us/resources/cloud-computing-dictionary/what-is-quantum-computing

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Quantum Computers

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Quantum computers

- A quantum computer is a machine that performs calculations based on the laws of quantum mechanics, which is the behavior of particles at the sub-atomic level.
- To build a functional quantum computer:
  - Requires holding an object in a superposition state long enough to carry out various processes on them.
- Challenge:
  - Once a superposition meets with materials that are part of a measured system, it loses its in-between state - that is known as decoherence - and becomes a (boring) old classical bit.
- This challenge can be tackled from different angles
  - Use more robust quantum processes
  - Find better ways to check-for/correct errors
- Devices need to be able to shield quantum states from decoherence, while still making them easy to read.

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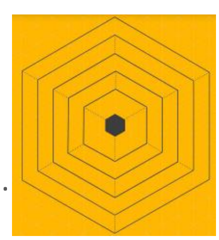
How does quantum computing work?

- A quantum computer has three main parts:
  1. An area that houses the qubits
  2. A method for transferring signals to the qubits
  3. A classical computer to run a program and send instructions
- Methods of qubit storage
  - Unit that houses the qubits is kept at a temperature just above absolute zero to maximize their coherence and reduce interference.
  - Vacuum chamber to help minimize vibrations and stabilize the qubits.



- Signals can be sent to qubits using a variety of methods, including: microwaves, laser, and voltage.

Source: https://azure.microsoft.com/en-us/resources/cloud-computing-dictionary/what-is-quantum-computing

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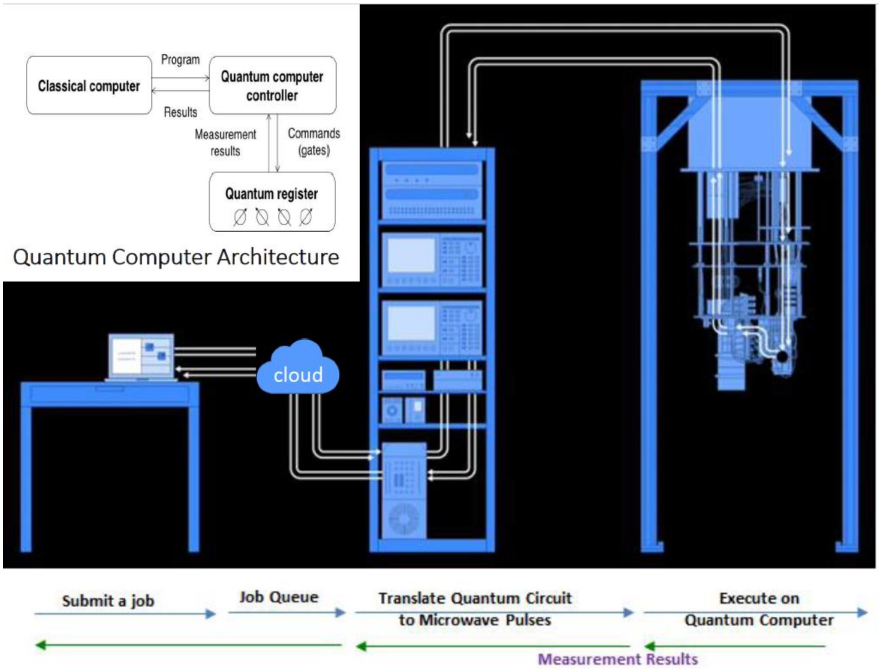
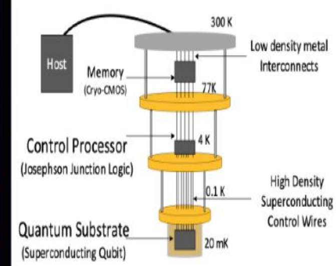


How does a quantum computer work?



The flow of submitting a job from a classical computer to a quantum computer, executing the job, and returning quantum measurement results to the classical computer.

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Physical Realization of QC

- Storage: Store qubits for long time
- Isolation: Qubits must be isolated from environment to decrease Decoherence
- Readout: Measuring qubits efficiently & reliably.
- Gates: Manipulate individual qubits & induce controlled interactions among them, to do quantum networking.
- Precision: Quantum networking & measurement should be implemented with high precision.

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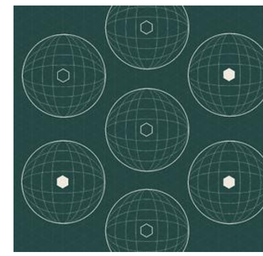
Quantum computer uses and application areas

- A quantum computer cannot do everything faster than a classical computer
- There are a few areas where quantum computers have the potential to make a big impact
  - **Quantum simulation**
  - Cryptography
  - Optimization
  - Quantum machine learning
  - Search



Source: https://azure.microsoft.com/en-us/resources/cloud-computing-dictionary/what-is-quantum-computing

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Aspects of Practical Implementation

- Requirements:
  - Qubit implementation itself
  - Control of unitary evolution
  - Initial state preparation (qubits)
  - Measurement of the final state(s)

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Implementation - Qubit Devices

- Any quantum mechanically coherent system could be used to implement the ideas of quantum computation.
  - Nuclear Magnetic Resonance (NMR)
  - single photons
  - nuclear spins
  - trapped ions
  - superconductors
- Advantage of solid-state implementations
  - Possibility of a scalable implementation of the qubits
- Superconducting devices
  - Promising implementation of qubit.
  - Minimum levels of decoherence among solid state implementations.
  - Two kinds of qubit devices either based on charge or flux degrees of freedom.

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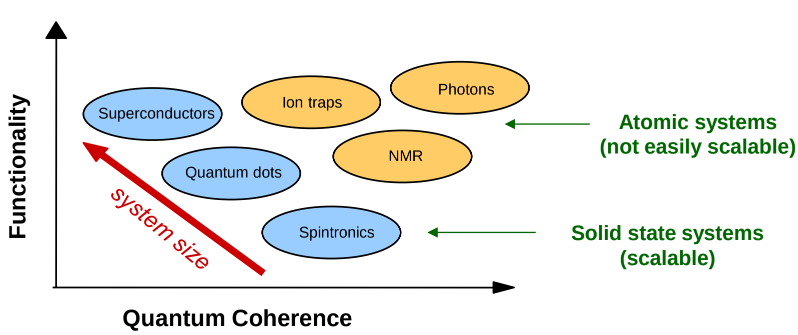
Qubit implementation

- Must be able to entangle, manipulate, and readout quantum states
  - **Functionality**
- Must be able to isolate system from the environment
  - **Quantum coherence**
- Develop architecture that allows coupling of multiple qubits
  - **Scalability**



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Quantum Computers

- Ion Trap
- Cavity QED (Quantum ElectroDynamics)
- NMR (Nuclear Magnetic Resonance)
- Spintronics
- Quantum Dots
- Superconducting Circuits (RF-SQUID, Cooper-Pair Box)
- Quantum Photonic
- Molecular Quantum Computer
- ...

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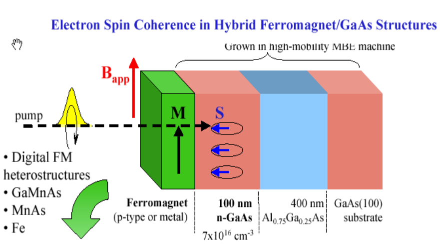
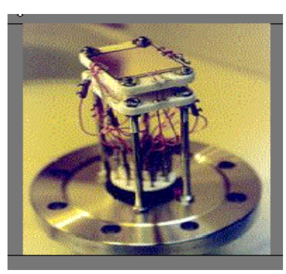
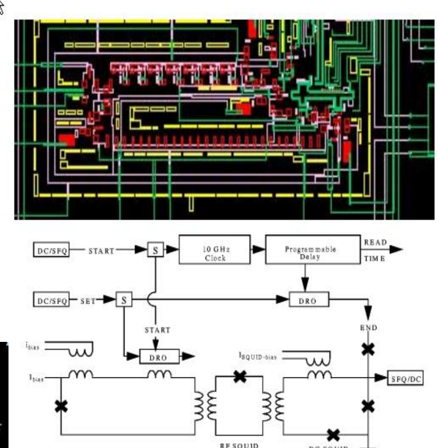


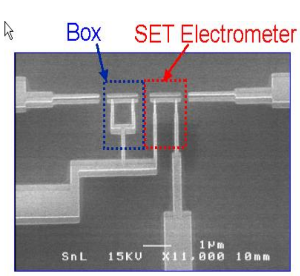
Spintronics



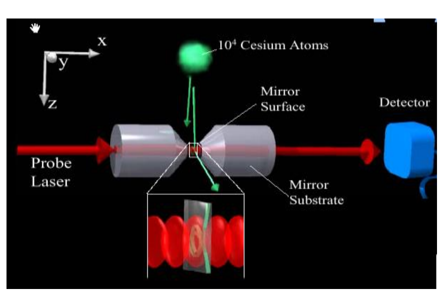
Atom Chip



RF-SQUID



Cooper Pair Box



Cavity QED

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Comparison of qubit technologies

Organization	Adiabatic/Annealing	Superconducting	Trapped Ion	Cold/Neutral Atom	Spin/Quantum Dot	Photonic	NV Diamond	Topological
Total Number = 97	**7**	**23**	**17**	**9**	**12**	**16**	**6**	**7**
Alibaba/CAS		x						
Alpine Quantum Technologies			x					
Archer Exploration					x			
Atom Computing				x				
Bleximo		x						
CEA-Leti / Inac					x			
Centre for Quantum Computation & Communication Technology					x	x		
Chalmers University of Technology		x						x
ColdQuanta				x				
Duke University			x			x		
D-Wave	x							
EeroQ				x				
Google	x	x						
Griffith Univ./Univ. Of Queensland						x		
Honeywell			x					
IBM		x						
ID Quantique						x		
Institut d'Optique				x				
Intel		x			x			
IonQ			x					
IQM Finland		x						
Korea Institute of Science & Technology							x	
MDR	x	x						
Microsoft								x
MIT Lincoln Lab	x	x	x				x	
MIT/Univ. of Innsbruck			x					
NEC	x							
NextGenQ			x					
Niels Bohr Institute								x
Nokia Bell Labs								x
Northrop Grumman	x							
NQIT			x					
NTT/Japan NII/Univ. of Tokyo						x		
Origin Quantum Computing		x			x			
Oxford		x	x			x	x	
Oxford Quantum Circuits		x						
Pasqal				x				

Organization	Adiabatic/Annealing	Superconducting	Trapped Ion	Cold/Neutral Atom	Spin/Quantum Dot	Photonic	NV Diamond	Topological
Penn State University				x				
PsiQuantum						x		
Qilimanjaro	x							
Quantic		x						
Quantum Circuits Inc		x						
Quantum Factory			x					
Quantum Motion Technologies					x			
Qubitekk						x		
QuiX						x		
QuTech		x			x		x	x
Raytheon BBN		x						
Rigetti		x						
RWTH Aachen					x			
Sandia National Laboratories			x	x	x			
SeeQC.EU		x						
SeQureNet						x		
Simon Fraser University					x			
Sparrow Quantum						x		
Toshiba						x		
TundraSystems Global						x		
TU Wein/NII Tokyo/NTT							x	
Universal Quantum			x					
Universitat Duisburg-Essen							x	
University of Bristol						x		
University of California Santa Barbara		x						x
Joint Quantum Institute / University of Maryland			x					x
University. of Science & Technology of China (USTC)		x						
University of Basel					x			
University of Sussex			x					
University of Washington			x					
University of Waterloo - IQC		x	x			x		
University of Wisconsin		x		x	x			
Weizmann Institute			x					
Wuhan Inst. Of Physics & Mathematics, Chinese Academy of Sciences				x				
Xanadu						x		
Yale Quantum Institute		x						

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Requirements for quantum computation *(DiVincenzo criteria)*

1. Scalable physical system of qubits

qubit = quantum two-level system

$|0\rangle and |1\rangle$

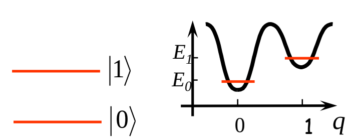
bit = classical two-level system

$0 or 1$

Superposition: $\Psi = a|0\rangle + b|1\rangle$

Two qubits --- *entanglement* :

$$\Psi = A|00\rangle + B|01\rangle + C|10\rangle + D|11\rangle$$



2. Ability to initialize qubits into a particular quantum state

initialization at the start of computation

supply of qubits in low entropy state for quantum error correction

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3. Universal set of quantum gates

Classical computer → all operations from NOT and exclusive-OR

Quantum computer → all operations from single qubit rotations and the two-qubit controlled-NOT

Quantum algorithm = sequence of unitary transformations $U_j = e^{iH_j t/\hbar}$

4. Qubit-specific measurement capability

Quantum measurement: $\Psi = a|0\rangle + b|1\rangle$

probability of $|0\rangle = |a|^2$ probability of $|1\rangle = |b|^2 = 1 - |a|^2$

Need to measure the state of each qubit without perturbing the state of the others

Ideal if the measurement does not destroy the quantum state of the measured qubit also → *non-demolition*

Figure of merit = quantum efficiency (<100%)

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5. Long decoherence times

Effect of the environment → entangles system with the environment (bad)… or, makes a measurement on the system

Decoherence time criterion is hard to define… depends on specific system and type of measurement to be made, but must be:

"long enough that the uniquely quantum features of the computation have a chance to come into play"

System must maintain phase coherence during the execution of sequences of logic operations (~10^4-10^5), but not for the duration of the entire calculation

Quantum error correction (Shor, 1996)

Implications:

reduce internal dissipation of the system

isolate system as much as possible from the environment

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What does a quantum computer look like?

Chinese 76-qubit photon-based quantum computer

IonQ, ion-trap-based 32-qubit quantum computer

IBM 53-qubit superconductor-based quantum computer

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Quantum Computing Race - Corporations

R&D investments reach $10.7 billion by 2024

hp
MITSUBISHI
intel
SK telecom
Booz | Allen | Hamilton
LOCKHEED MARTIN
BT
NOKIA
AIRBUS
FUJITSU
TOSHIBA
Google
Alibaba Group
NTT
Raytheon
IBM
Microsoft
NEC
kpn

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Noise

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Noise

- Quantum states are fickle and prone to errors.
- Calculations need to keep going in superposition for the duration of the computational cycle.
- But they can easily be thrown off by noise – which, could stem from various sources:
  - Disturbances in Earth's magnetic field
  - Local radiation
  - Cosmic rays
  - Influence that qubits exert on each other by proximity
- **Noise - "the central obstacle to building large-scale quantum computers"**
  - https://www.nature.com/articles/s41567-020-0992-8?ref=thestack.technology

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Noise

- Signals for configuring and programming a quantum computer come from outside the machines
  - They travel through coaxial cables (where they are amplified and filtered)
  - Eventually reach quantum device with its qubits at ~0.015K (-273.135 degrees C)
- Widely accepted that large-scale quantum computers will require some form of error correction
  - E.g., Error-correction scheme called quantum low-density parity check (qLDPC)
    - "High-threshold and low-overhead fault-tolerant quantum memory": https://arxiv.org/abs/2308.07915
    - Chips will be designed to hold a few qLDPC-corrected qubits in just 400 or so physical qubits; then, those chips together will be networked together.
    - qLDPC implementation proposed ideas: 1) using superconducting loops, 2) using individual atoms instead

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Noise

- Noise tackled by:
  - Minimizing exposure of chips and cables to heat and electromagnetic radiation in all its forms
  - Minimizing device defects, by constantly improving the performance of the electronics, and by using all sorts of novel mathematical schemes to compensate for noise
- Several physical qubits are coaxed - each encoded in a superconducting circuit, say, or an individual ion - to work together to represent one qubit of information or "logical qubit".
- Been projected that state-of-the-art error-correction techniques will require more than 1,000 physical qubits for each logical qubit. Machines that can do useful computations will require millions of physical qubits.

Source: https://www.nature.com/articles/d41586-023-03854-1

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Outline

- Quantum Computing
- Quantum Simulators
- Tech Companies
- More Resources
- More online courses
- More recent research articles
- Books
- Skeptics

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What are Quantum Computer Simulators?

- Quantum simulators - software programs that allow you to use a classical computer to run quantum circuits as if they were being run on a quantum computer.
  - https://ionq.com/resources/the-value-of-classical-quantum-simulators
- Quantum computing simulators are tools designed to emulate the behavior of quantum systems, offering an accessible platform to explore and develop quantum algorithms without the need for a physical quantum computer.
  - https://www.bluequbit.io/quantum-computing-simulators

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What are Quantum Computer Simulators?

- A quantum computer simulator (also called a quantum circuit simulator) is a machine - or rather a device - that, according to T. H. Johnson et al. in their paper *What is a quantum simulator?*, "actively uses quantum effects to answer questions about model systems and, through them, real systems[…] revealing information about an abstract mathematical function relating to a physical model."
  - [1] Johnson, T.H., Clark, S.R. & Jaksch, D. What is a quantum simulator?. EPJ Quantum Technol. 1, 10 (2014). https://doi.org/10.1140/epjqt10

Source: https://thequantuminsider.com/2022/06/14/top-63-quantum-computer-simulators-for-2022/

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Quantum Computer Simulators

- IBM
  - Qiskit is an open-source software development kit (SDK) for working with quantum computers at the level of circuits, pulses, and algorithms. It provides tools for creating and manipulating quantum programs and running them on prototype quantum devices on IBM Quantum Platform or on simulators on a local computer.
  - https://www.ibm.com/quantum/qiskit
- Google qsim
  - https://quantumai.google/qsim
- Amazon
  - https://aws.amazon.com/braket/pricing/ (see later slides on Amazon)
  - Simulating 44-Qubit quantum circuits using AWS ParallelCluster
  - https://aws.amazon.com/blogs/hpc/simulating-44-qubit-quantum-circuits-using-aws-parallelcluster/
- Microsoft
  - https://learn.microsoft.com/en-us/azure/quantum/machines/
- Intel Quantum Simulator (IQS, former qHiPSTER)
  - https://github.com/intel/intel-qs
- …

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Quantum Computer Simulators

- Top 63 Quantum Computer Simulators For 2022
  - https://thequantuminsider.com/2022/06/14/top-63-quantum-computer-simulators-for-2022/
- List of QC simulators - grouped by programming language
  - https://quantiki.org/wiki/list-qc-simulators
- Open-Source Quantum Software Projects
  - https://github.com/qosf/awesome-quantum-software
- List of Open Quantum Projects
  - https://qosf.org/project_list/
- …

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Programming Languages for Quantum Computers

- QCL (Quantum Computation Language) - a high level, architecture independent programming language for quantum computers, with a syntax derived from classical procedural languages like C or Pascal.
  - http://tph.tuwien.ac.at/~oemer/qcl.html
- …

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Name	Tagline	Programming language	Licence	Supported OS
Cirq	Framework for creating, editing, and invoking Noisy Intermediate Scale Quantum (NISQ) circuits.	Python	Apache-2.0	Windows, Mac, Linux
Cliffords.jl	Efficient calculation of Clifford circuits in Julia.	Julia	MIT	Windows, Mac, Linux
dimod	Shared API for Ising/quadratic unconstrained binary optimization samplers.	Python	Apache-2.0	Windows, Linux, Mac
dwave-system	Basic API for easily incorporating the D-Wave system as a sampler in the D-Wave Ocean software stack.	Python	Apache-2.0	Linux, Mac
FermiLib	Open source software for analyzing fermionic quantum simulation algorithms.	Python	Apache-2.0	Windows, Mac, Linux
Forest (pyQuil & Grove)	Simple yet powerful toolkit for writing hybrid quantum-classical programs.	Python	Apache-2.0	Windows, Mac, Linux
OpenFermion	The electronic structure package for quantum computers.	Python	Apache-2.0	Windows, Mac, Linux
ProjectQ	An open source software framework for quantum computing.	Python, C++	Apache-2.0	Windows, Mac, Linux
PyZX	Python library for quantum circuit rewriting and optimisation using the ZX-calculus.	Python	GPL-3.0	Windows, Mac, Linux
QGL.jl	A performance orientated QGL compiler.	Julia	Apache-2.0	Windows, Mac, Linux
Qbsolv	Decomposing solver that finds a minimum value of a large quadratic unconstrained binary optimization problem by splitting it into pieces.	C	Apache-2.0	Windows, Linux, Mac
Qiskit Terra & Aqua	Quantum Information Science Kit for writing experiments, programs, and applications.	Python, C++	Apache-2.0	Windows, Mac, Linux
Qiskit Tutorials	A collection of Jupyter notebooks using Qiskit.	Python	Apache-2.0	Windows, Mac, Linux
Qiskit.js	Quantum Information Science Kit for JavaScript.	JavaScript	Apache-2.0	Windows, Mac, Linux
Qrack	Comprehensive, GPU accelerated framework for developing universal virtual quantum processors.	C++	GPL-3.0	Linux, Mac
Quantum Fog	Python tools for analyzing both classical and quantum Bayesian networks.	Python	BSD-3-Clause	Windows, Mac, Linux
Quantum++	A modern C++11 quantum computing library.	C++, Python	MIT	Windows, Mac, Linux
Qubiter	Python tools for reading, writing, compiling, simulating quantum computer circuits.	Python, C++	BSD-3-Clause	Windows, Mac, Linux
Quirk	Drag-and-drop quantum circuit simulator for your browser to explore and understand small quantum circuits.	JavaScript	Apache-2.0	Windows, Mac, Linux
reference-qvm	A reference implementation for a Quantum Virtual Machine in Python.	Python	Apache-2.0	Windows, Mac, Linux
ScaffCC	Compilation, analysis and optimization framework for the Scaffold quantum programming language.	C++, Objective C, LLVM	BSD-2-Clause	Linux, Mac
Strawberry Fields	Full-stack library for designing, simulating, and optimizing continuous variable quantum optical circuits.	Python	Apache-2.0	Windows, Mac, Linux
XACC	eXtreme-scale Accelerator programming framework.	C++	Eclipse PL-1.0	Windows, Mac, Linux
XACC VQE	Variational quantum eigensolver built on XACC for distributed, and shared memory systems.	C++	BSD-3-Clause	Windows, Mac, Linux

https://doi.org/10.1371/journal.pone.0208561.t001

Quantum Programming Languages

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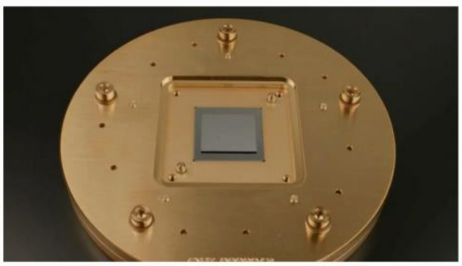
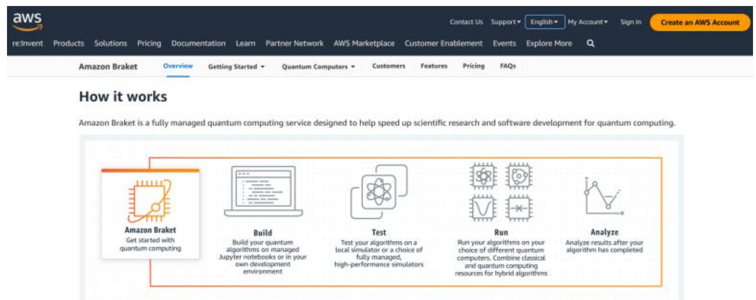
Amazon

- Amazon Introduces New Quantum Chip To Reduce Errors
  - https://www.forbes.com/sites/craigsmith/2023/11/28/amazon-introduces-new-quantum-chip-to-reduce-errors/?sh=4383289d1f58



A superconducting-qubit quantum chip in package assembly developed and manufactured at the AWS Center for Quantum Computing in Pasadena, Calif. [-] AWS



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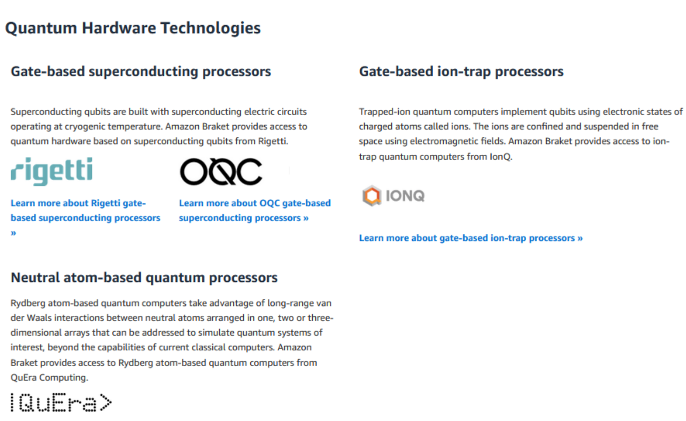
Amazon Braket

- https://aws.amazon.com/braket/
- https://aws.amazon.com/braket/faqs/
- Amazon Braket is a fully managed service that helps you get started with quantum computing.



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Amazon Quantum Solutions Lab

- https://aws.amazon.com/quantum-solutions-lab/
  - Will help you get ready for quantum computing.
  - Engagements are collaborative research programs that allow you to work with leading experts in quantum computing, machine learning, optimization, and high-performance computing.

Use Cases

Read how the Amazon Quantum Solutions Lab is solving problems with customers. Discover more in the AWS Quantum Technologies Blog.

Robot path optimization

BMW Group partnered with the Amazon Quantum Solutions Lab to develop an algorithm to optimize robot motion with a number of constraints. Together we demonstrated a 10% improvement in robot motion runtime.

Read their research paper »

Fraud detection

Fraud spans multiple industries and can be difficult to detect. The Amazon Quantum Solutions Lab demonstrated the feasibility of graph-based fraud detection using hybrid quantum annealing techniques.

Read their research paper »

Binary paint shop

The Volkswagen Group and the Amazon Quantum Solutions Lab used Quantum Approximate Optimization to minimize the number of paint swaps in a POC for a small number of vehicles with a random order of cars to paint.

Read their research paper »

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What simulators does Amazon Braket offer?

- Quantum circuit simulators run on classical computers.
- Amazon Braket offers you a choice of four quantum circuit simulators:
  - the local simulator in the SDK
  - three on-demand simulators:
    - SV1, a general purpose quantum circuit simulator,
    - DM1 that enables you to simulate the effect of noise on your circuits, and
    - TN1, a high performance tensor network simulator.

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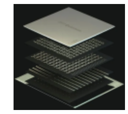
IBM



- June 2023 - IBM claims advance in quantum computing
- New chip, Eagle Processor, has 127 "qubits", twice as many as the previous IBM processor.
- Working around “quantum noise” that introduces errors in calculations, to get reliable results at a scale “beyond brute-force classical computation.”
- Techniques that enabled this milestone represent a “foundational tool for the realization of near-term quantum applications”.
- Eagle Processor used to generate large, entangled states that simulate materials behavior and accurately predict properties such as its magnetisation.
- Paper in Nature:
  - https://www.nature.com/articles/d41586-023-01965-3
- IBM News:
  - https://newsroom.ibm.com/2023-06-14-IBM-Quantum-Computer-Demonstrates-Next-Step-Towards-Moving-Beyond-Classical-Supercomputing
  - https://www.nextbigfuture.com/2023/12/ibm-launches-quantum-system-two-building-block-quantum-centric-supercomputing.html
  - IBM releases first-ever 1,000-qubit quantum chip - https://www.nature.com/articles/d41586-023-03854-1

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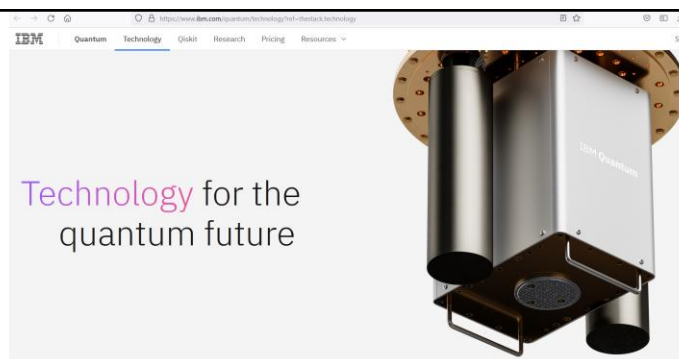
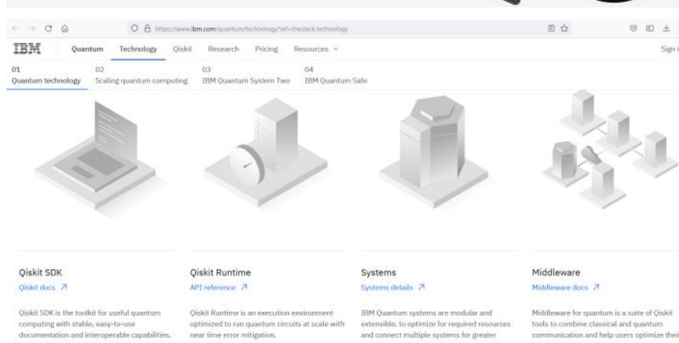
IBM Quantum computing technologies

- https://www.ibm.com/quantum/technology?ref=thestack.technology





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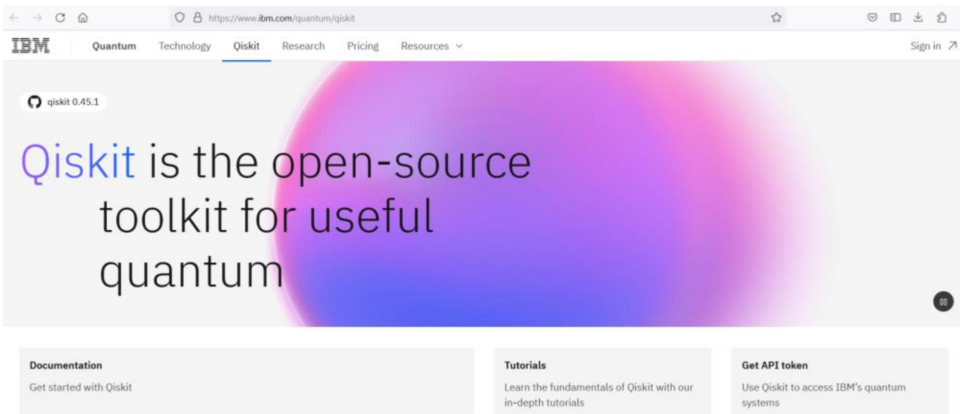
Qiskit

- Qiskit is the open-source toolkit for useful quantum
  - https://www.ibm.com/quantum/qiskit



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Google

- 2019 - Google said its 53-qubit Sycamore quantum processor had surpassed the performance of a conventional computer - on a particular task - for the first time.
  - Sycamore quantum processor was able to perform a specific task in 200 seconds that would take the world's best supercomputer 10,000 years to complete.
  - https://www.nature.com/articles/s41586-019-1666-5

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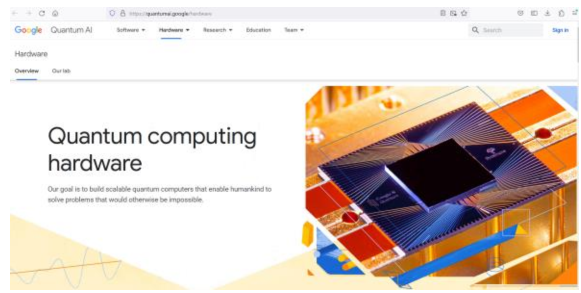
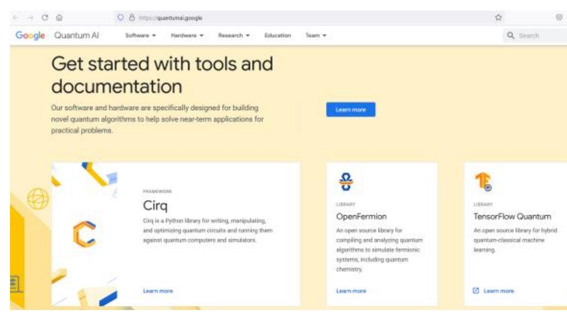
Google Quantum AI

- https://quantumai.google/
- https://quantumai.google/learn/map hardware





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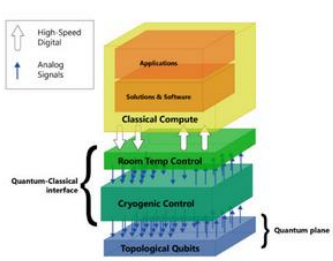
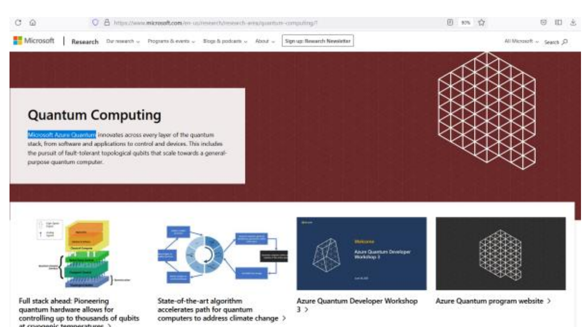
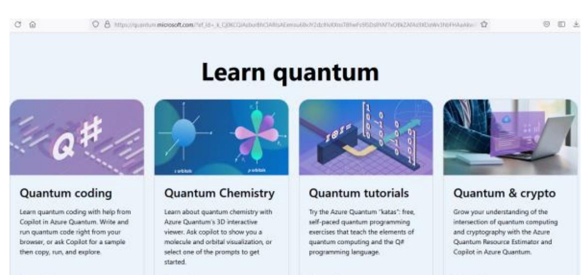
Microsoft Azure Quantum

- https://www.microsoft.com/en-us/research/research-area/quantum-computing/?
- https://quantum.microsoft.com/
- https://quantum.microsoft.com/en-us/our-story/quantum-roadmap







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D-Wave Systems

- D-Wave was the world's first company to sell computers to exploit quantum effects in their operation
  - https://www.dwavesys.com/
- Quantum "Core" Training: Skill Up for the Future Today
  - https://www.dwavesys.com/it-training-savings/?banner=

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Honeywell - Quantinuum

- Quantinuum unites best-in-class software with high-fidelity hardware to accelerate quantum computing. With integrated full-stack technology, our world-class scientists are rapidly scaling quantum computing.
  - https://www.quantinuum.com/about
- Honeywell leverages quantum computing encryption keys from Quantum Origin to bolster utilities' data security against cyber threats

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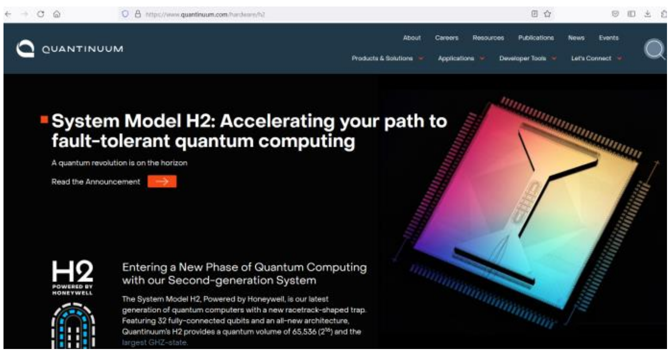
Honeywell - Quantinuum

- System Model H2
  - https://www.quantinuum.com/hardware/h2
  - Powered by Honeywell - latest generation of quantum computers with a new racetrack-shaped trap
  - 32 fully-connected qubits and an all-new architecture
  - Provides a quantum volume of 65,536 (2^16) and the largest GHZ-state.



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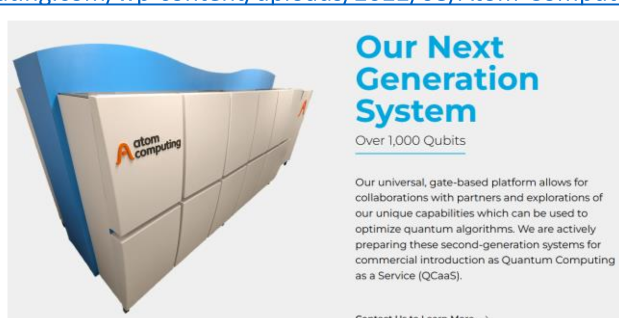
Atom Computing

- Atom Computing is building highly scalable, gate-based quantum computers with atomic arrays of optically-trapped neutral atoms
  - https://atom-computing.com/
- Prototype platform, Phoenix, harnesses the power of 100 qubits
- Actively developing next-generation systems with over 1,000 qubits
  - https://atom-computing.com/wp-content/uploads/2022/08/Atom-Computing-Atomic-Arrays.pdf



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Outline

- Quantum Computing
- Quantum Simulators
- Tech Companies
- More Resources
- More online courses
- More recent research articles
- Books
- Skeptics

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More Resources

- What is Quantum Computing?
  - https://www.ibm.com/topics/quantum-computing
- IBM Quantum Summit
  - https://research.ibm.com/blog/quantum-roadmap-2033
  - https://www.hpcwire.com/2023/12/04/ibm-quantum-summit-two-new-qpus-upgraded-qiskit-10-year-roadmap-and-more/
- Quantum Summit
  - https://www.quantum-summit.com/
- Demystifying Quantum Gates — One Qubit At A Time
  - https://towardsdatascience.com/demystifying-quantum-gates-one-qubit-at-a-time-54404ed80640
- …

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More Online Courses

- “Quantum Computing Fundamentals with Microsoft Azure Quantum” at Udemy (more as well)
  - https://www.udemy.com/topic/quantum-computing/
- MIT - The Quantum Computing Revolution is Here
  - https://xpro.mit.edu/programs/program-v1:xPRO+QCF/
- ...

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More Recent Research Articles

- Topological transitions of the generalized Pancharatnam-Berry phase.
  - Study observes hidden quantum transition, bridges gap between theoretical and practical experimentation
  - https://www.science.org/doi/10.1126/sciadv.adg6810
- Exploring large-scale entanglement in quantum simulation
  - Developed a more efficient description, that allows to extract entanglement information from the system with drastically fewer measurements
  - https://www.nature.com/articles/s41586-023-06768-0
- Quantum storage of entangled photons at telecom wavelengths in a crystal
  - Successful quantum storage of entangled photons at telecom wavelengths within a crystal
  - https://www.nature.com/articles/s41467-023-42741-1
- IBM Offers Quantum Error Suppression Out Of The Box - Software from Q-CTRL can boost performance by up to 1000 times
  - https://spectrum.ieee.org/quantum-error-correction-ibm
- InAs-Al hybrid devices passing the topological gap protocol
  - https://journals.aps.org/prb/abstract/10.1103/PhysRevB.107.245423
- ...

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More Recent Online Articles

- From Cancer Detection to Disaster Response: NQCC Announces Quantum Computing Projects to Receive 2025 SparQ Grants
  - https://thequantuminsider.com/2024/11/30/from-cancer-detection-to-disaster-response-nqcc-announces-quantum-computing-projects-to-receive-2025-sparq-grants/
- Scientists Discover a Way to Shrink Quantum Computer Components by 1,000x
  - https://scitechdaily.com/scientists-discover-a-way-to-shrink-quantum-computer-components-by-1000x/

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Books

- Quantum Supremacy: How the Quantum Computer Revolution Will Change Everything
  - https://www.amazon.com/Quantum-Supremacy-Computer-Revolution-Everything/dp/0385548362
- Quantum Computing: An Applied Approach, 2nd ed., 2021.
  - https://www.amazon.com/Quantum-Computing-An-Applied-Approach-dp-3030832732/dp/3030832732/ref=dp_ob_title_bk
- …

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And…, the Other Side

- Meta’s AI chief doesn’t think AI super intelligence is coming anytime soon, and is skeptical on quantum computing
  - “The number of problems you can solve with quantum computing, you can solve way more efficiently with classical computers,” LeCun said.
  - “Quantum computing is a fascinating scientific topic,” LeCun said. It’s less clear about the “practical relevance and the possibility of actually fabricating quantum computers that are actually useful.”
  - https://www.cnbc.com/2023/12/03/meta-ai-chief-yann-lecun-skeptical-about-agi-quantum-computing.html
- …

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