

Quantum Technologies, risks and prospects

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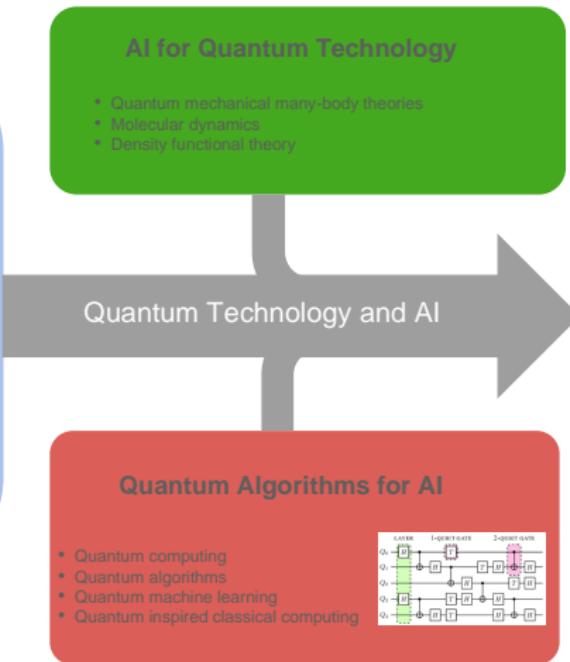
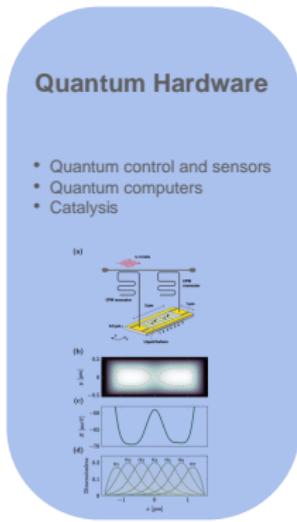
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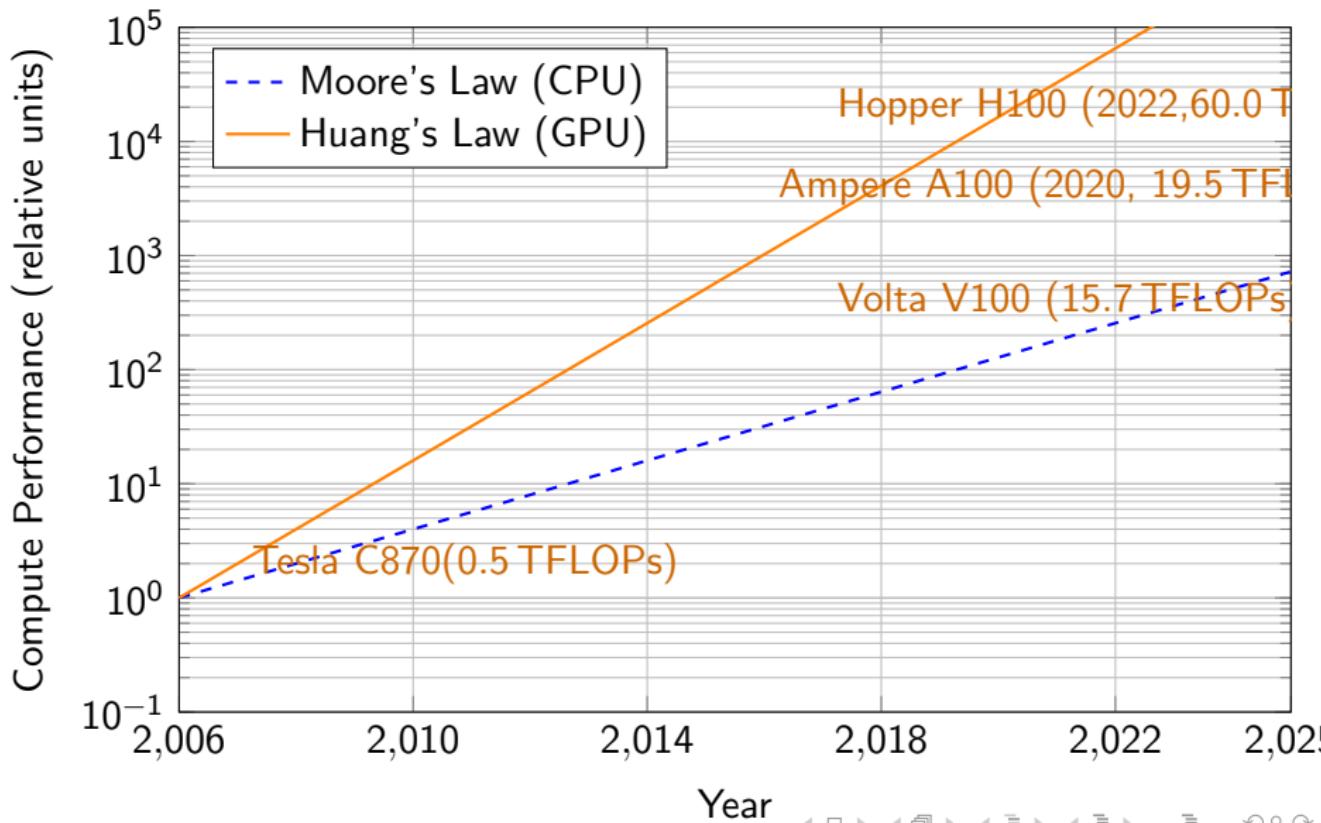
What is this talk about?

In this seminar I will try to give a pedestrian yet comprehensive overview of the fundamental principles underpinning quantum technologies. Beginning with the essential quantum concepts that form their theoretical foundation, I will examine how these ideas are translated into contemporary technological applications. The discussion will further address the interplay between scientific advances and current public and private investments in the field, providing an outlook on prospective developments over the coming decade. Finally, I will consider a range of ethical and legal challenges that accompany the ongoing expansion of quantum technologies. And why this could (or should) be of interest to a society as a whole.

Quantum technologies and machine learning/AI are tightly interwoven

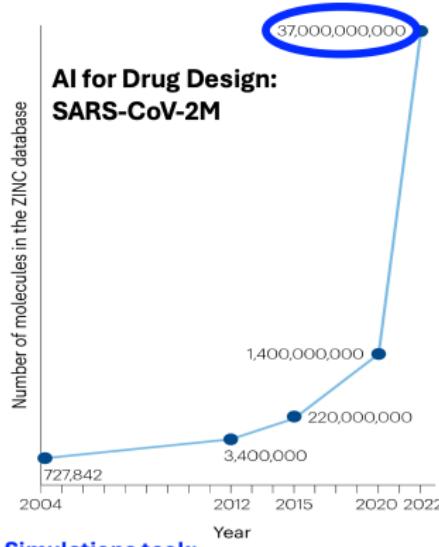


From Moore's law to Huang's law, the race for more performance



e

Machine learning and AI models are computationally expensive



Simulations took:

90 days on 250 GPUs & 640 cpu-core

1 day on 27000 GPU Summit supercomputer

Nature Reviews Drug Discovery 23, 141–155 (2024)

TOP4 Powerful Supercomputers as of Nov 2024

Rank	System	Cores	Rmax (PFlop/s)	Rpeak (PFlop/s)	Power (kW)
1	El Capitan - HPE Cray EX255a, AMD 4th Gen EPYC 24C 1.8GHz, AMD Instinct MI300A, Slingshot-11, TOSS, HPE DOE/NNSA/LLNL United States	11,039,616	1,742.00	2,746.38	29,581

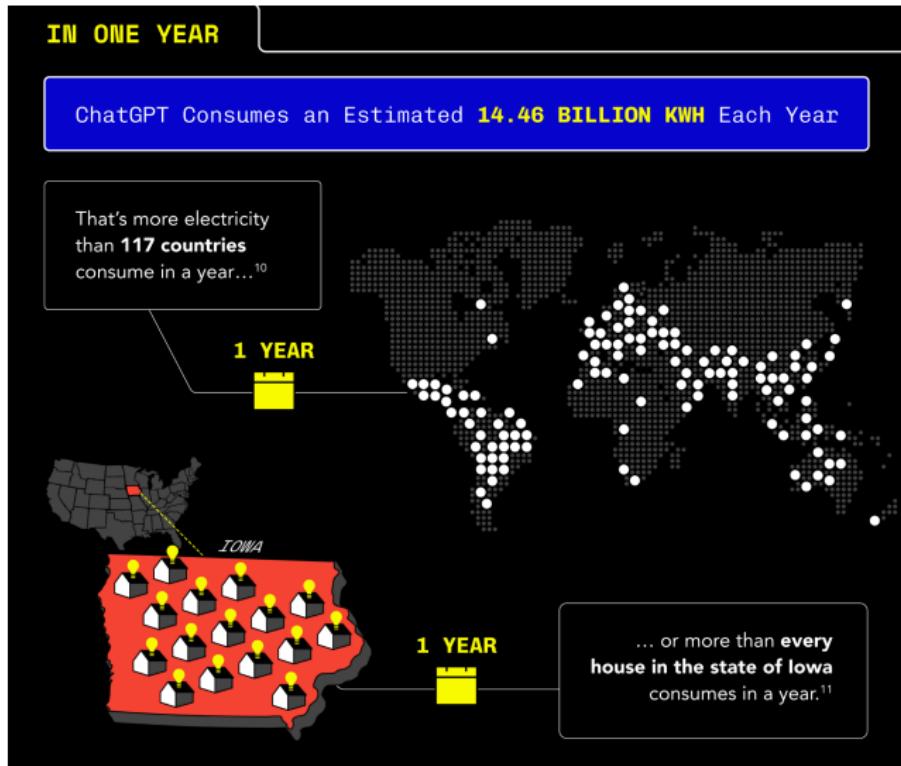
nature reviews drug discovery

Perspective | Published: 08 December 2023

Integrating QSAR modelling and deep learning in drug discovery: the emergence of deep QSAR

	Max, Slingshot-11, Intel DOE/SC/Argonne National Laboratory United States			
4	Eagle - Microsoft NvD5, Xeon Platinum 8480C 48C 2GHz, NVIDIA H100, NVIDIA Infiniband NDR, Microsoft Azure Microsoft Azure United States	2,073,600	561.20	846.84

And power greedy, perhaps quantum computers can reduce the impact?



Taken from <https://www.businessenergyuk.com/knowledge-hub/>

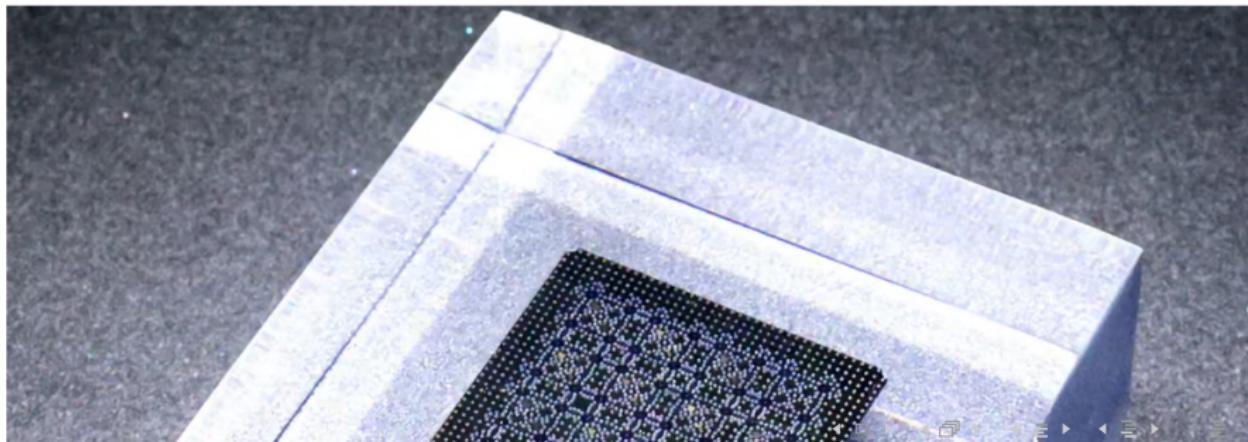
And not exactly environmentally friendly

- In Ireland, data centers consume more than 20 percent of the country's electricity.
- In Chile, precious aquifers are in danger of depletion.
- In South Africa, where blackouts have long been routine, data centers are further taxing the national grid.
- Similar concerns have surfaced in Brazil, Britain, India, Malaysia, the Netherlands, Singapore and Spain

The future is here, sooner than we may think

Google hails breakthrough as quantum computer surpasses ability of supercomputers

Algorithm performed task beyond capability of classical computers, although experts say real-world application still years away



Add info about tech regulations in AI

US-China war on restricting access to sophisticated technologies

- ① TSMC restrictions
- ② Seagate, Micron
- ③ Huawei, Nvidia etc, semiconductor control etc

Mention Alessandro Aresu's book

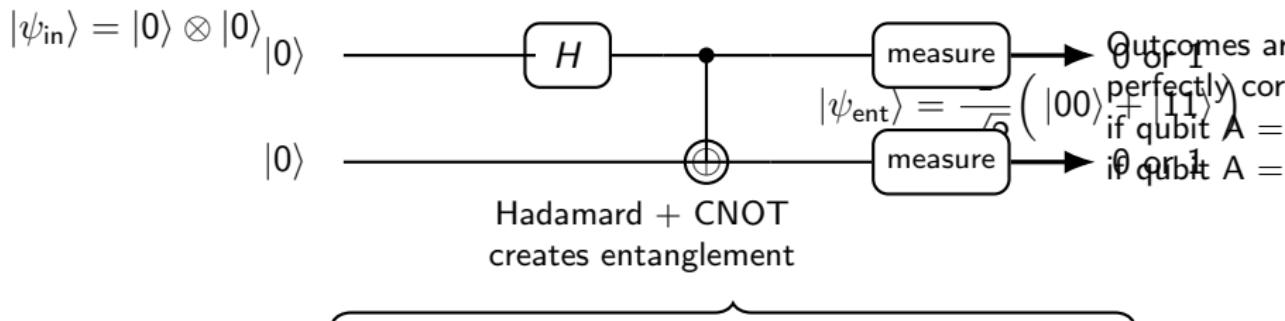
The basis: What is Quantum Computing?

Quantum computing leverages principles of quantum mechanics to perform computations beyond classical capabilities.

Key Concepts:

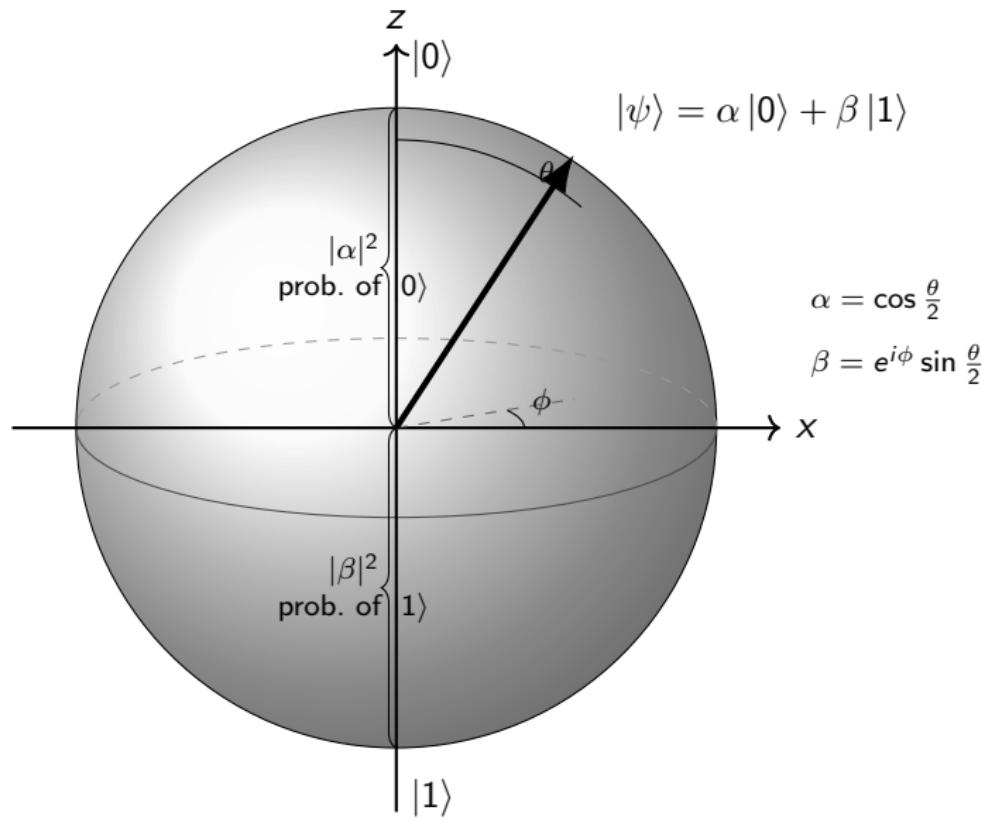
- **Superposition:** Qubits can exist in a combination of states.
- **Entanglement:** Correlation between qubits regardless of distance.
- **Quantum Interference:** Probability amplitudes interfere to solve problems.

Superposition

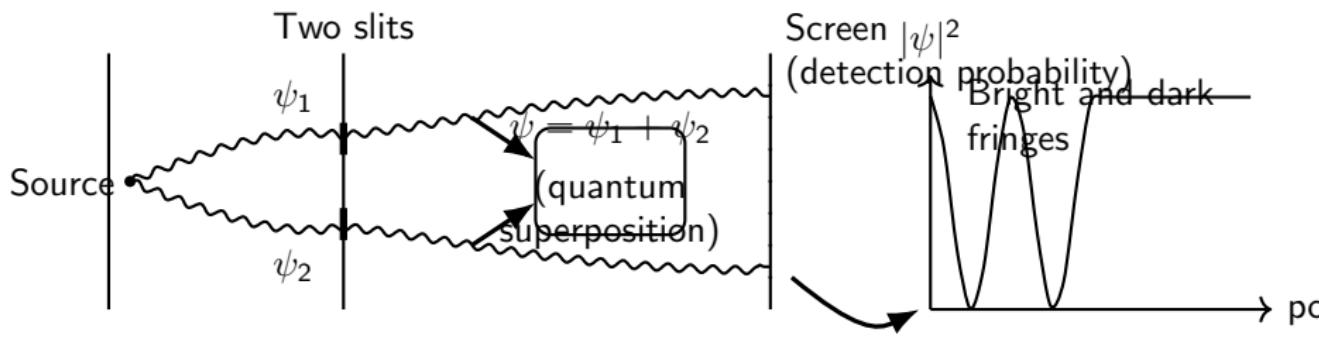


Entanglement: the two-qubit state cannot be written as $|\phi\rangle_A \otimes |\chi\rangle_B$. Measurement on one instantly fixes the other's outcome, even though each result is individual.

Quantum interference



Entanglement



Two coherent paths
Interference pattern arises from **phase-coherent** addition of amplitudes.
Classical probabilities would *add*; quantum amplitudes *interfere*.

Quantum Speedups

Why Quantum?

- **Quantum Parallelism:** Process multiple states simultaneously.
- **Quantum Entanglement:** Correlated states for richer information.
- **Quantum Interference:** Constructive and destructive interference to enhance solutions.

Example - Grover's Algorithm:

Quantum Search Complexity: $O(\sqrt{N})$ vs. $O(N)$

Advantage: - Speedups in high-dimensional optimization and linear algebra problems.

Challenges and Limitations

1. Quantum Hardware Limitations:

- Noisy Intermediate-Scale Quantum (NISQ) devices.
- Decoherence and limited qubit coherence times.

2. Data Encoding:

- Efficient embedding of classical data into quantum states.

3. Scalability:

- Difficult to scale circuits to large datasets.

What is Quantum Entanglement?

Quantum Entanglement is a quantum phenomenon where two or more particles become correlated in such a way that the state of one particle directly affects the state of the other, regardless of distance.

Key Features:

- Non-local correlations
- No classical analog
- Violates Bell's inequalities

Entangled State Example:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

1. Quantum Communication

Quantum Teleportation:

- Entanglement enables the transmission of quantum states using classical communication.
- No need to send the physical quantum particle.

Advantage:

- Instantaneous state transfer within quantum mechanics constraints.
- Quantum networks rely on entanglement for secure communication.

2. Quantum Cryptography

Quantum Key Distribution:

- Entanglement ensures secure communication.
- Eavesdropping disturbs quantum states, revealing interception attempts.
- Any measurement by a third party collapses the wavefunction.
- Ensures security based on quantum mechanics, not computational hardness.

Advantage: Unconditional security guaranteed by the laws of physics.

3. Quantum Computing

Speedup in Quantum Algorithms:

- Entanglement provides exponential state space.
- Quantum parallelism arises from entangled qubits.

Grover's Algorithm:

$$\mathcal{O}(\sqrt{N}) \text{ vs. } \mathcal{O}(N)$$

Shor's Algorithm:

$$\text{Factoring in } \mathcal{O}((\log N)^3)$$

4. Quantum Metrology

Quantum Metrology:

- Uses entangled states for ultra-precise measurements.
- Overcomes the classical shot-noise limit.

Heisenberg Limit:

$$\Delta\theta \geq \frac{1}{N},$$

where N is the number of entangled particles.

Advantage:

- Quantum entanglement improves sensitivity beyond classical limits.

Challenges of Quantum Entanglement

Decoherence:

- Entangled states are fragile.
- Interaction with the environment collapses the wavefunction.

Scalability:

- Difficult to entangle large numbers of qubits.
- Error correction requires complex protocols.

Measurement Problem:

- Measurement destroys entanglement.
- Trade-off between information gain and entanglement preservation.

What is Quantum Machine Learning?

Quantum Machine Learning (QML) integrates quantum computing with machine learning algorithms to exploit quantum advantages.

Motivation:

- High-dimensional Hilbert spaces for better feature representation.
- Quantum parallelism for faster computation.
- Quantum entanglement for richer data encoding.

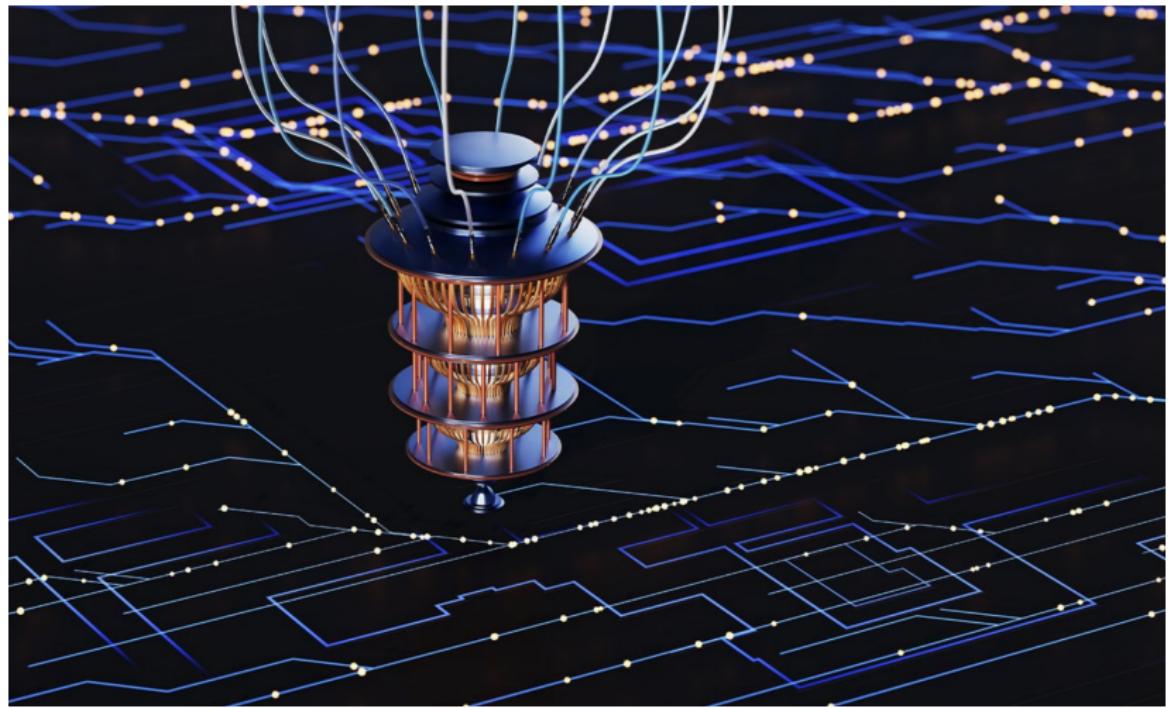
Quantum computing requirements

- ① A scalable physical system with well-characterized qubit
- ② The ability to initialize the state of the qubits to a simple fiducial state
- ③ Long relevant Quantum coherence times longer than the gate operation time
- ④ A **universal** set of quantum gates
- ⑤ A qubit-specific measurement capability

Quantum platforms

- ① Superconduting qubits
- ② Ion traps
- ③ Quantum dot systems (in semiconductors)
- ④ more text to come

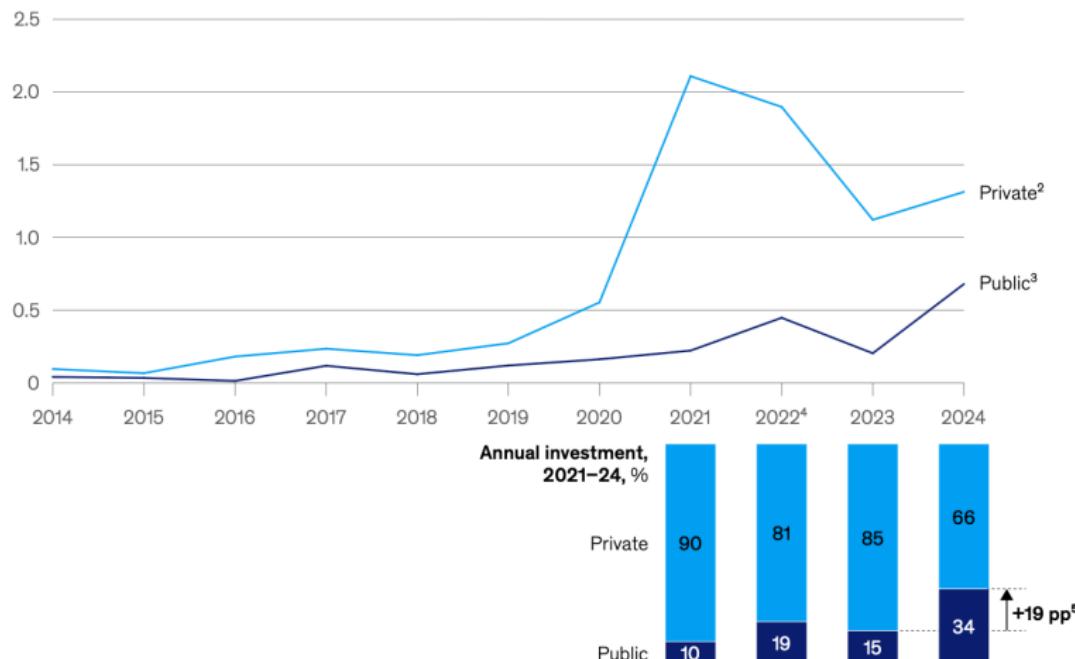
Considerable investments (add source)



Considerable investments (add source)

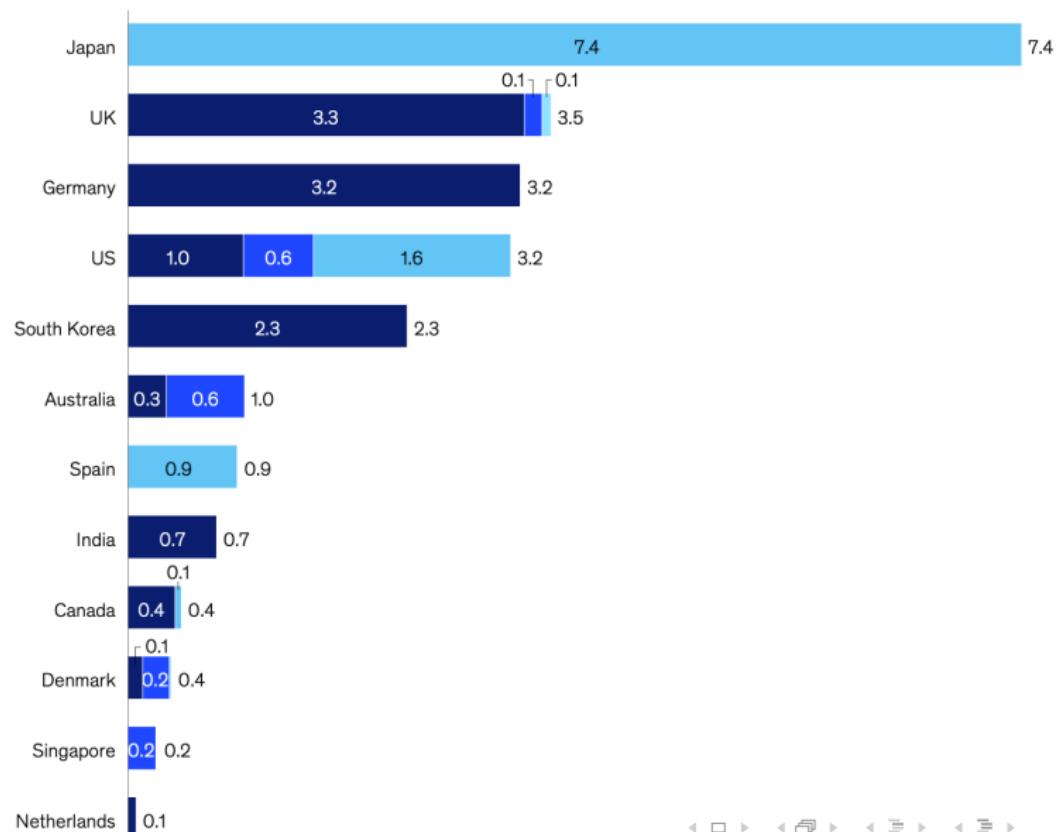
Public investment in quantum technology start-ups increased 19 percentage points from 2023 to 2024.

Quantum technology (QT) investments by funding type, 2014–24,¹ \$ billion



Considerable investments (add source)

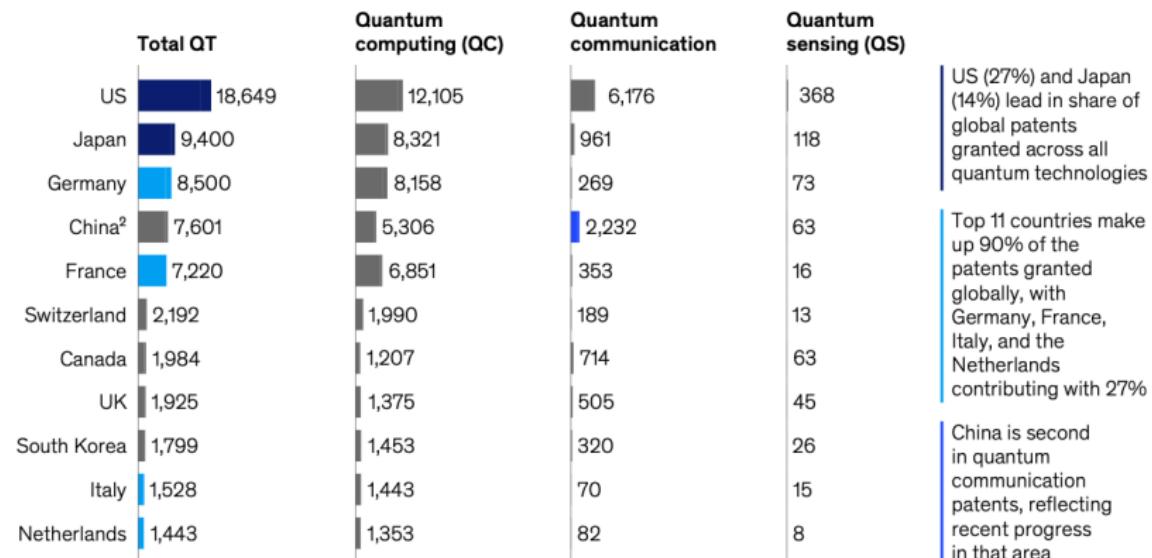
Announced government investments in quantum technology (QT),
Jan 2023–Apr 2025, \$ billion



Considerable investments (add source)

The United States and Japan lead other countries in the number of patents granted for quantum technology.

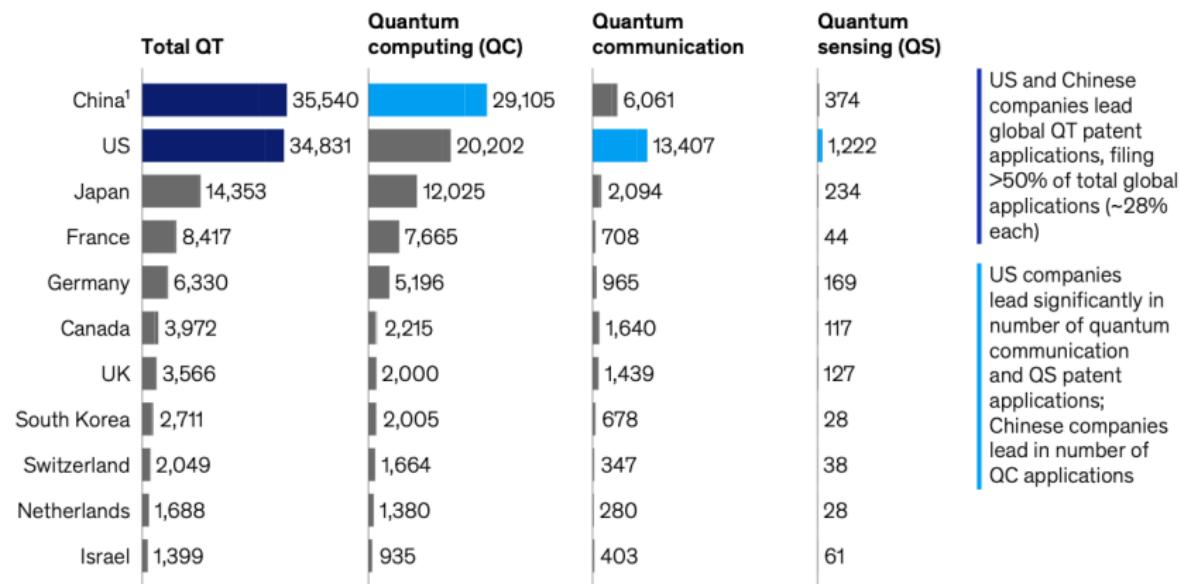
Quantum technology (QT) patents granted, by company HQ location, 2000–24¹



Considerable investments (add source)

The United States and China lead other countries in the number of quantum technology patent requests filed.

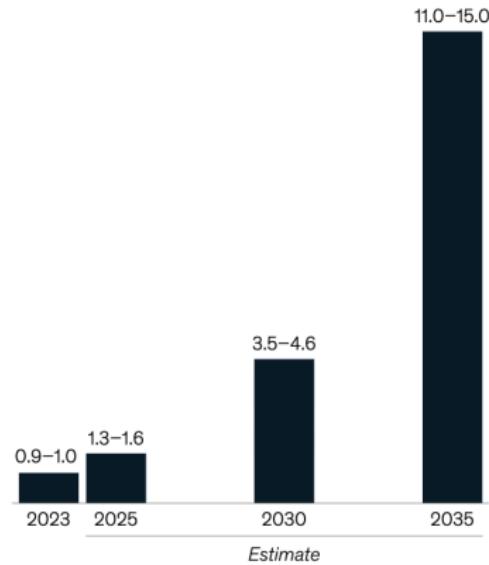
Quantum technology (QT) patent applications, by company HQ location, 2000–24



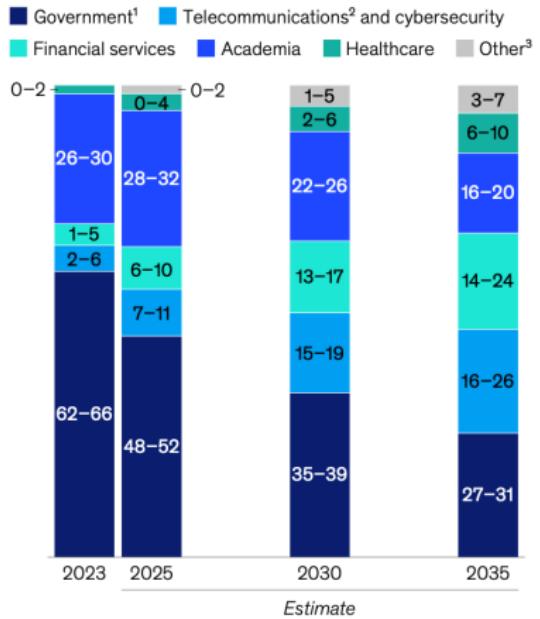
Considerable investments (add source)

The quantum communication market is projected to reach \$11 billion to \$15 billion by 2035.

Quantum communication market size,
\$ billion

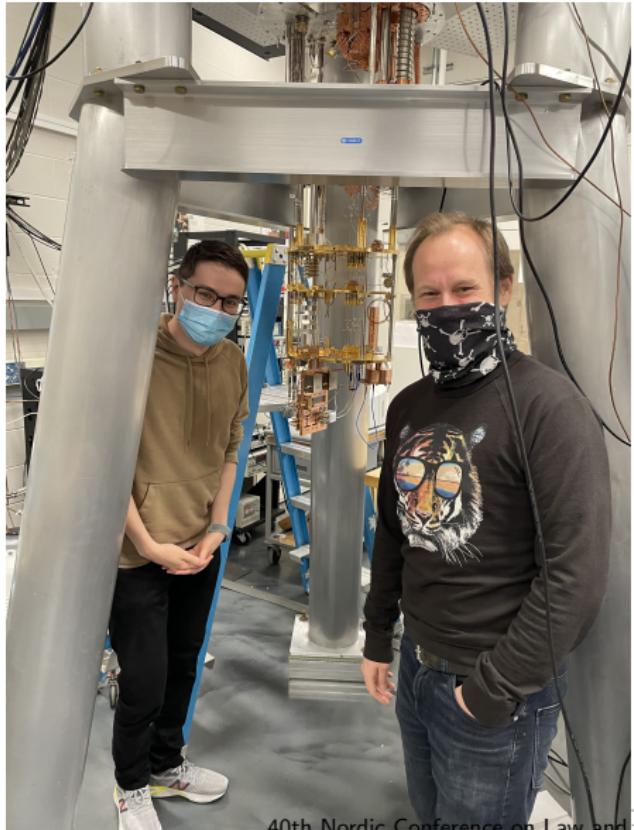


Quantum communication market breakdown by customer type, %



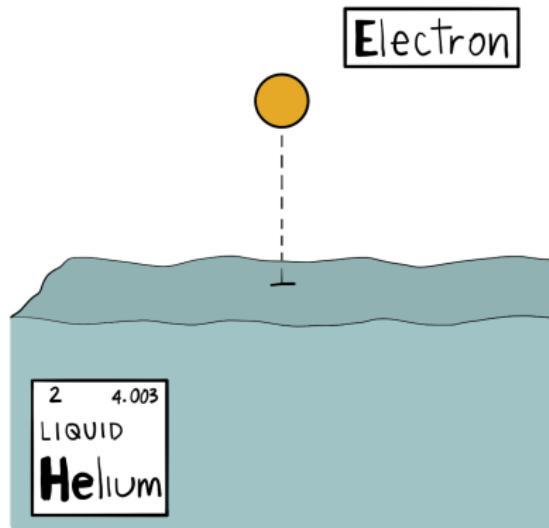
Important properties, electrons on helium

- ① Long coherence times
- ② Highly connect qubits
- ③ Many qubits in a small area
- ④ CMOS compatible
- ⑤ Fast gates



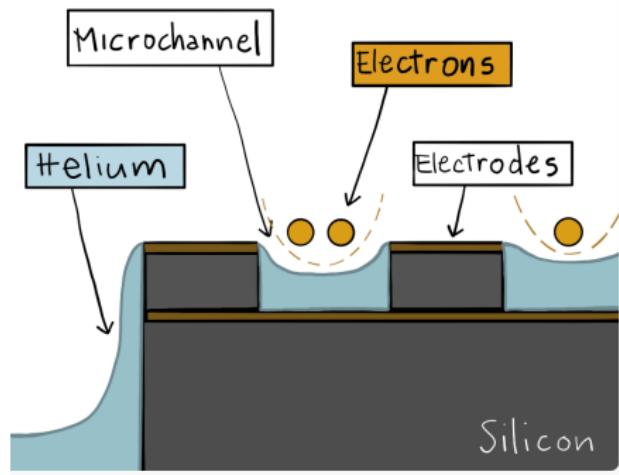
Single electrons can make great qubits

At the heart is the trapping and control of individual electrons floating above pools of superfluid helium. These electrons form the qubits of our quantum computer, and the purity of the superfluid helium protects the intrinsic quantum properties of each electron. The ultimate goal is to build a large-scale quantum computer based on quantum magnetic (spin) state of these trapped electrons.



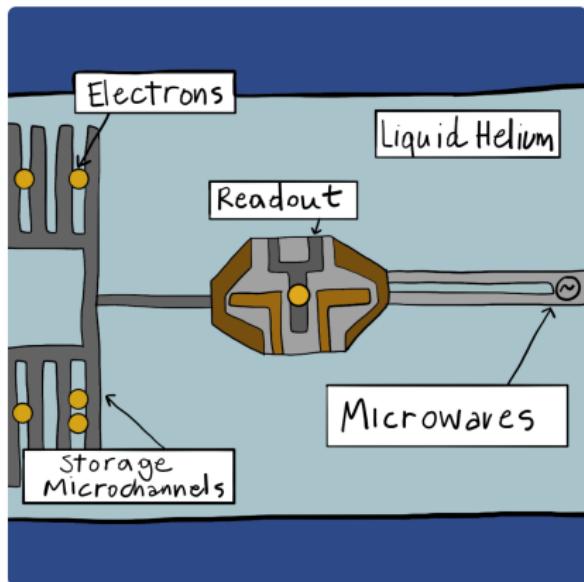
Trapping electrons in microchannels

Microchannels fabricated into silicon wafers are filled with superfluid helium and energized electrodes. Together with the natural electron trapping properties of superfluid helium, these allow for the precision trapping of individual or multiple electrons. The microchannels are only a few micrometers in size, or about five times smaller than the diameter of a human hair.



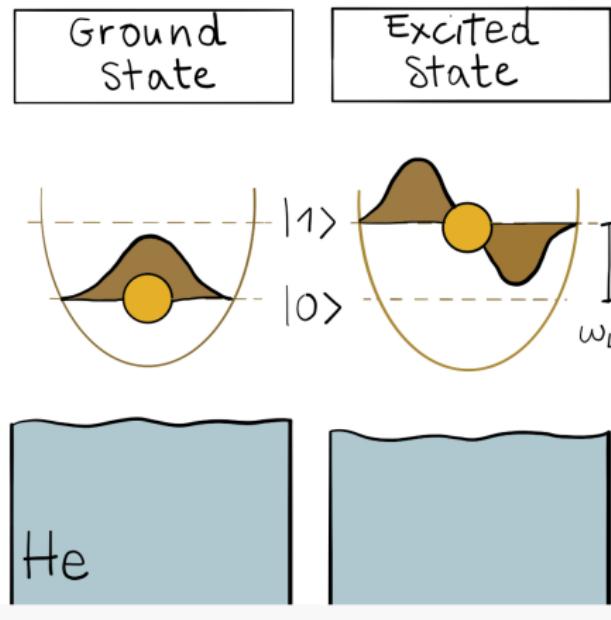
Control and readout

Microchannel regions can store thousands of electrons, from which one can be plucked and transported to the single electron control and readout area. In this region, microwave signals will interact with the electron to perform quantum logic gate operations, which will be readout via extremely fast electronics.



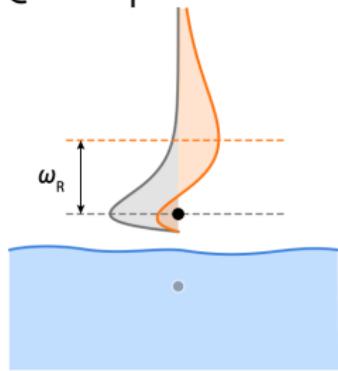
Operations for quantum computing

Quantum information can be encoded in a number of ways using single electrons. Currently, we are working with the side-to-side(lateral) quantum motion of the electron in the engineered trap. This motion can either be in its lowest energy state, the ground state, or in a number of higher-energy excited states. This electron motion also provides the readout capabilities for the ultimate goal of building a large-scale quantum computer based on the electron's magnetic moment (spin).



Qubit platforms

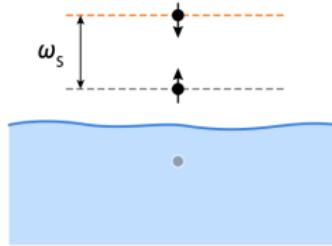
Qubit platforms with electrons on helium



Rydberg states

$$\omega_R/2\pi = 120 \text{ GHz}$$

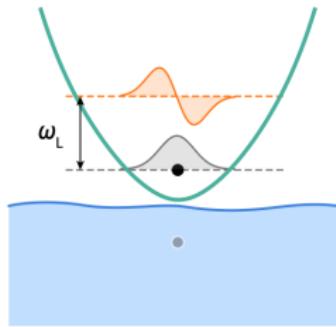
P.M. Platzman and M.I. Dykman
Science **284**(5422), pp.1967 (1999)



Spin states

$$\omega_s/2\pi = 5 \text{ GHz} \text{ at } B = 0.2 \text{ T} \\ (T_2 \approx 1.5 \text{ s})$$

S. A. Lyon, *Phys. Rev. A* **74**, 052338 (2006)



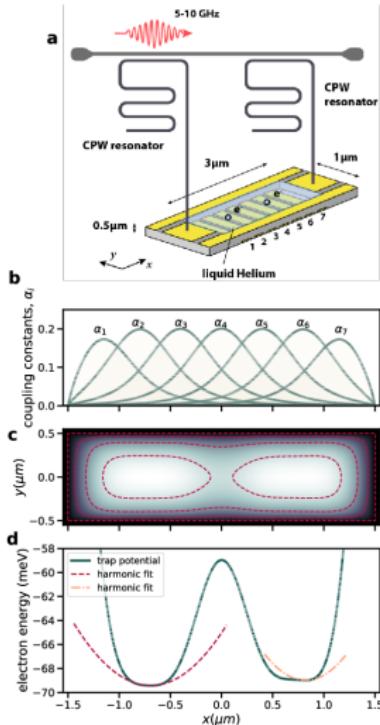
Lateral motional states

$$\omega_s/2\pi = 5 \text{ GHz}$$

D.I. Schuster et al., *Phys. Rev. Lett.* **105**, 040503 (2005)

Final experimental setup

- ① (a) Microdevice where two electrons are trapped in a double-well potential created by electrodes 1-7. The read-out is provided by two superconducting resonators dispersively coupled to electron's in-plane motional states.
- ② (b) Coupling constants from each individual electrode beneath the helium layer.
- ③ (c+d) The electron's energy in a double-well electrostatic potential.



Export control

Technology/Component	Export Sensitivity Category	Reason for Sensitivity
Superconducting CPW resonator (6.04 GHz)	Dual-Use (Quantum computing/EAR)	High-frequency superconducting
Single-electron trap (gated microchannel)	Dual-Use (Quantum hardware/EAR)	Precision single-electron
Superconducting electrodes (Nb films)	Dual-Use (Superconducting electronics/EAR)	Superconducting materials
Pumped ⁴ He cryostat (1.1 K)	Dual-Use (Cryogenic systems/EAR)	High-capacity cryogenic
Superfluid ⁴ He substrate	Dual-Use (Cryogenic medium/EAR)	Specialized cryogenic
Cryogenic RF components	Dual-Use (RF electronics/EAR)	GHz-range passive components
Low-noise RF amplifiers		Specialized amplifiers
On-chip LC filters	Dual-Use (RF filter technology/EAR)	Engineered filtering technologies
Electron-on-helium qubit platform	Dual-Use (Quantum computing/EAR)	Emerging quantum information