

Quantum Technologies, risks and prospects

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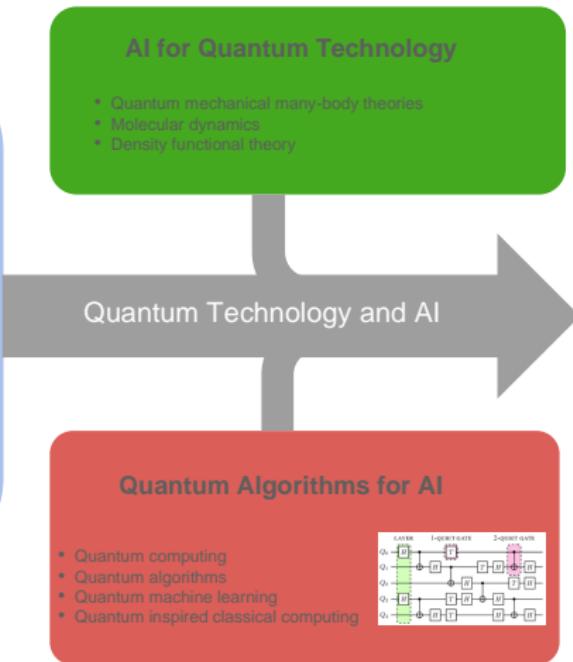
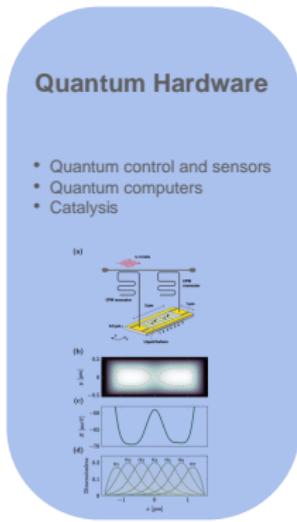
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40th Nordic Conference on Law and IT – Regulating for Complexity,
November 5-7, 2025

What is this talk about?

- I will try to give a pedestrian yet comprehensive overview of the fundamental principles underpinning quantum technologies.
- And how technological advances in quantum technologies are reflected in new investments in the coming years.
- Finally, I will consider a range of ethical and legal challenges that accompany the ongoing expansion of quantum technologies.

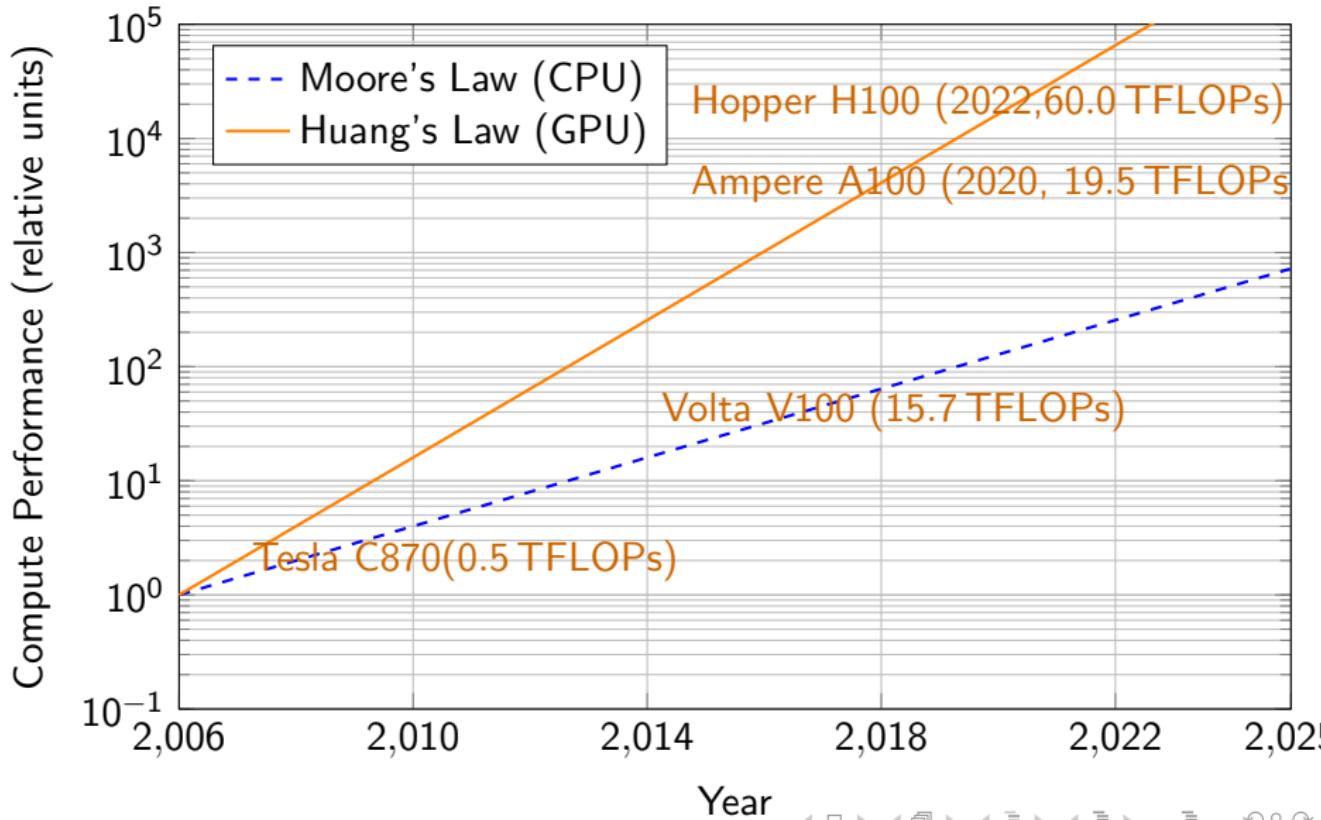
Quantum technologies and machine learning/AI are tightly interwoven



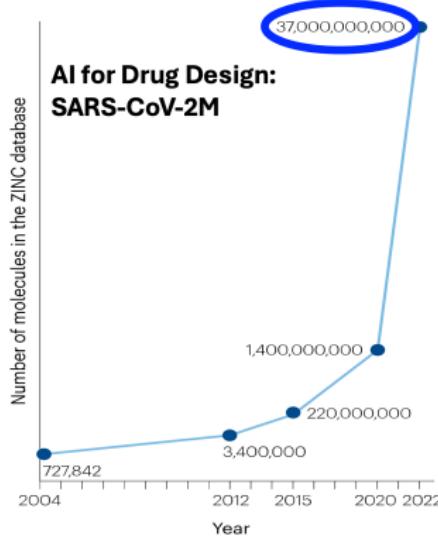
But there are some important differences

- Many startups in the AI/ML are low-cost w.r.t. equipment (software development), this may change due to needs for more high-performance computing resources. Own research example: One GPU-hour costs 5.60 NOK while a CPU-hour costs 0.06 NOK via **Sigma2**.
- Quantum technology research requires (hardware side) considerable investments. A dilution refrigerator from say the Finnish company Bluefors costs approx 1 MUSD or more.

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



Machine learning and AI models are computationally expensive



Simulations took:

90 days on 250 GPUs & 640 cpu-core

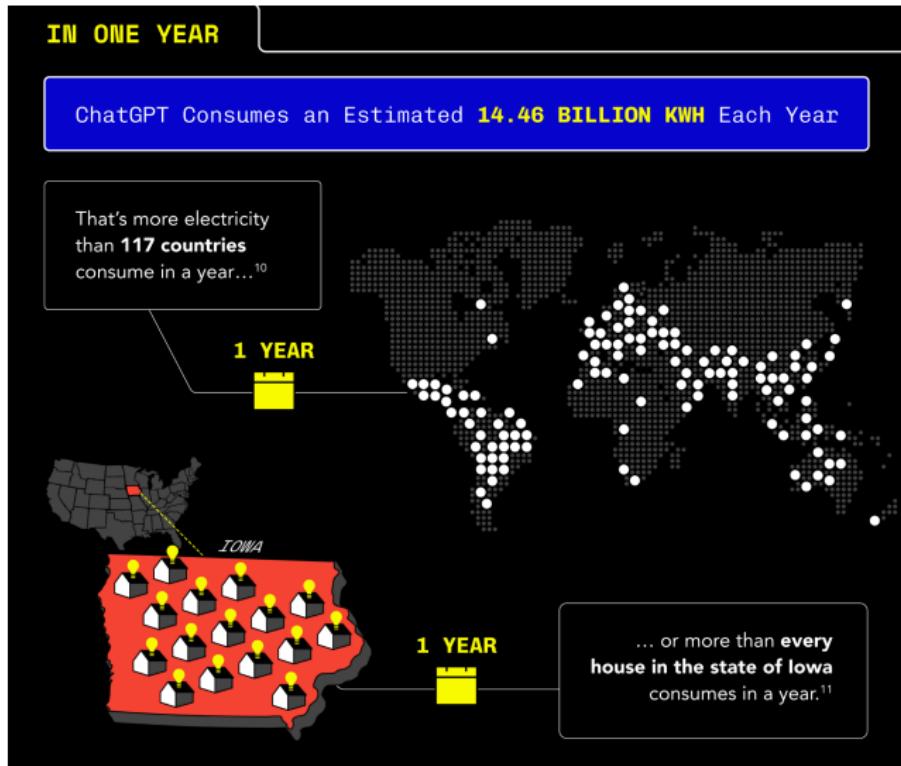
1 day on 27000 GPU Summit supercomputer

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	
			Advance nuclear weapon science and scientific discovery			
			US\$600 million			
76	nature reviews drug discovery	1,353.00	2,055.72	24,607		
	Perspective Published: 08 December 2023					
4	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	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 perhaps not 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 and other countries.

The future is here, sooner than we may think

Our Quantum Echoes algorithm is a big step toward real-world applications for quantum computing

Oct 22, 2025
5 min read

Our Willow quantum chip demonstrates the first-ever algorithm to achieve verifiable quantum advantage on hardware.



Hartmut Neven
Founder and Lead,
Google Quantum AI



Vadim Smelyanskiy
Director, Quantum
Pathfinding, Google
Quantum AI

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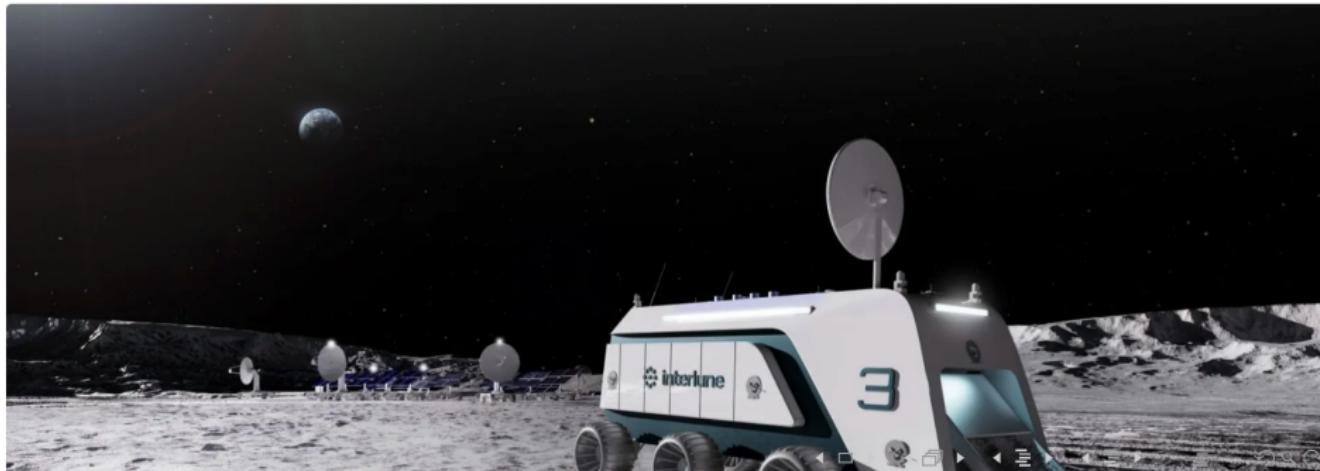


Modern quantum platforms require cooling down to extremely low temperatures

Bluefors to Source Helium-3 from the Moon with Interlune to Power Next Phase of Quantum Industry Growth

3 min read

September 16, 2025



What is quantum technology? Three main fields

Quantum computing

is a new computing paradigm that capitalizes on the laws of quantum mechanics to provide significant performance improvement for certain applications, and to enable new territories of computing beyond existing classical computing.

Quantum communication

is the secure transfer of quantum information across distances and could ensure security of communication even in the face of unlimited quantum computing power.

Quantum sensing

includes a new generation of sensors, based on quantum systems, that provide measurements of various quantities (for example, electromagnetic fields, gravity, or time) and that are orders of magnitude more sensitive than classical sensors.

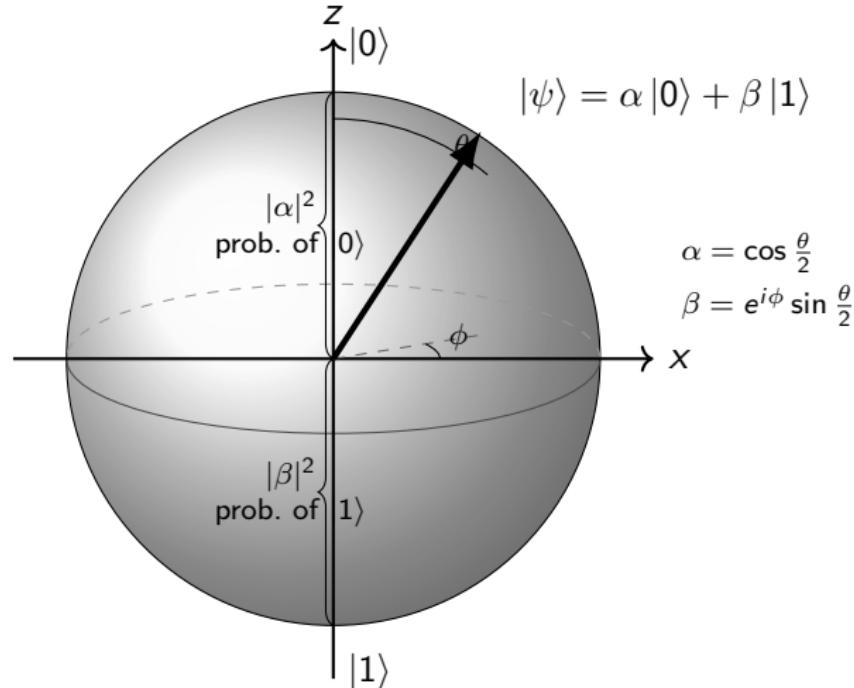
The basic concepts

Quantum technologies leverage 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. Is a core tool in quantum algorithms. It is used to amplify the probability of finding the correct answer while suppressing incorrect ones.

Superposition



Quantum superposition of a single qubit:
the same physical state $|\psi\rangle$ is a coherent combination of $|0\rangle$ and $|1\rangle$.

What is Quantum Entanglement?

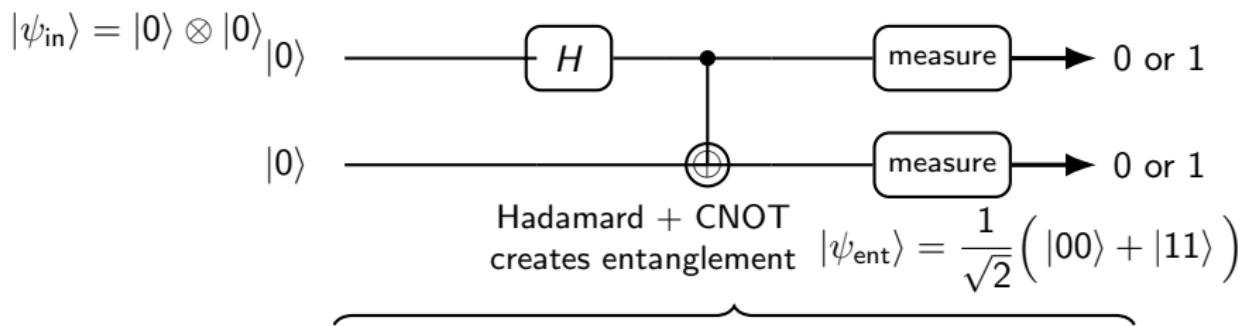
Quantum Entanglement is a quantum phenomenon where two or more particles become correlated in such a way that the state of one particle directly affects the state of the other, regardless of distance. Fundamental for making quantum gates, quantum sensors and much more.

Key Features:

- Non-local correlations
- No classical analog

Entanglement

Outcomes are perfectly correlated:
if qubit A = 0, qubit B = 0;
if qubit A = 1, qubit B = 1.



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.

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, is a core tool in quantum algorithms.

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.

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.

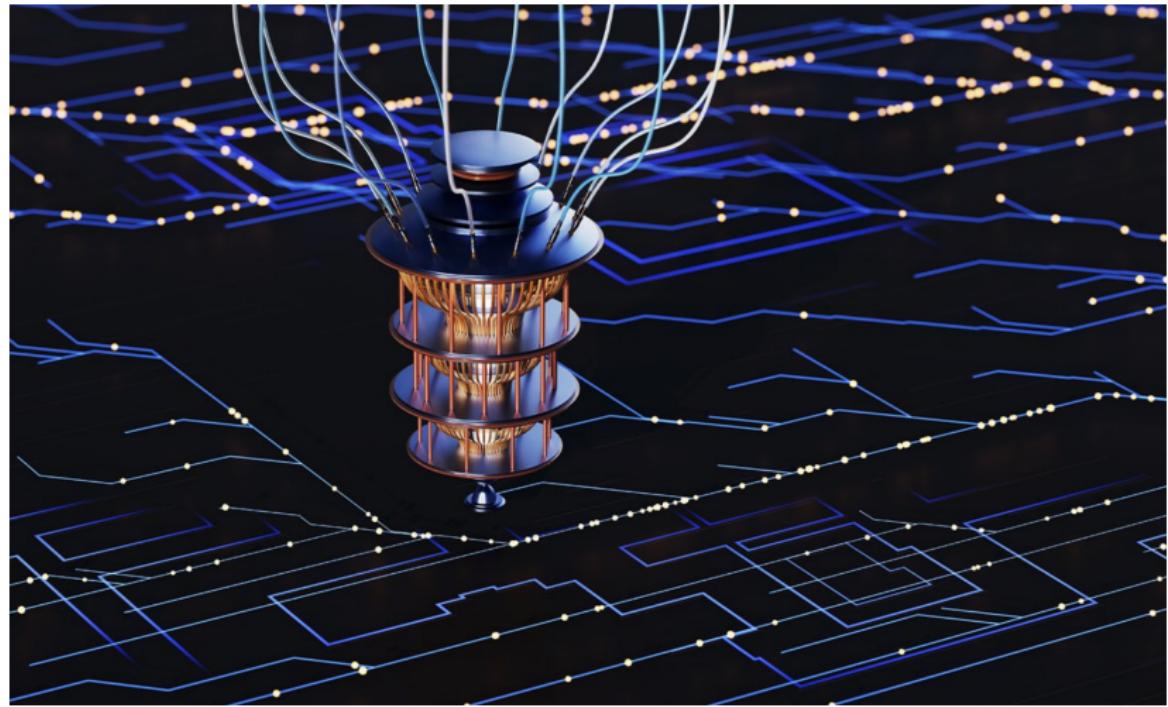
Quantum computing requirements

- 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 Superconducting qubits use Josephson junction circuits operated at millikelvin temperatures
- ② Trapped-ion computers confine ions (e.g. $^{171}\text{Yb}^+$, $^{40}\text{Ca}^+$) in electromagnetic traps, encoding qubits in internal electronic states. Gates are implemented with laser or microwave fields coupling to vibrational modes.
- ③ Photonic quantum computing employs photons (in dual-rail or continuous-variable encodings) as qubits
- ④ Spin qubits—realized in silicon quantum dots, donor atoms, or color centers—encode information in electron or nuclear spin states.
- ⑤ Electrons on helium/neon (more on this below, own research)

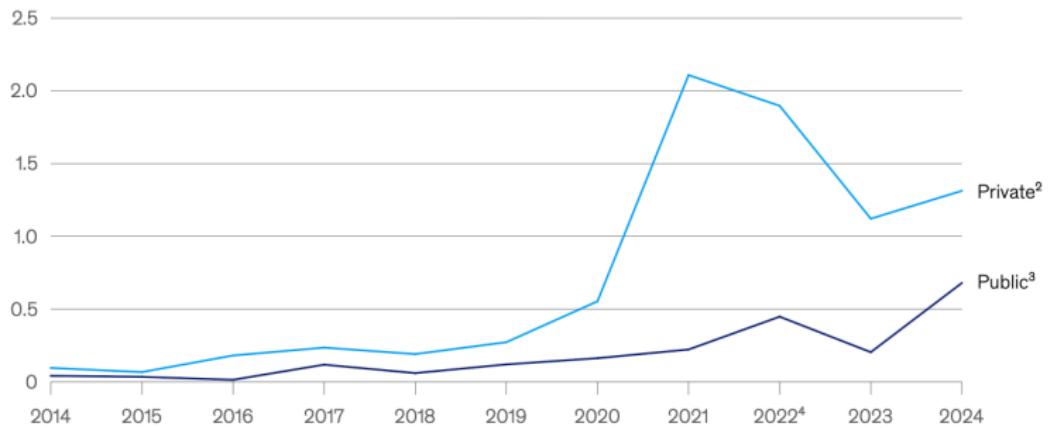
Considerable investments (McKinsey Quantum Technology Monitor, June 2025)



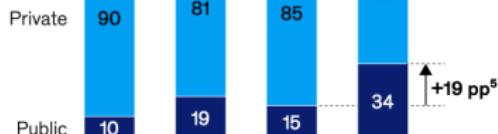
Quantum technology (QT) investments by funding type, 2014–24

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



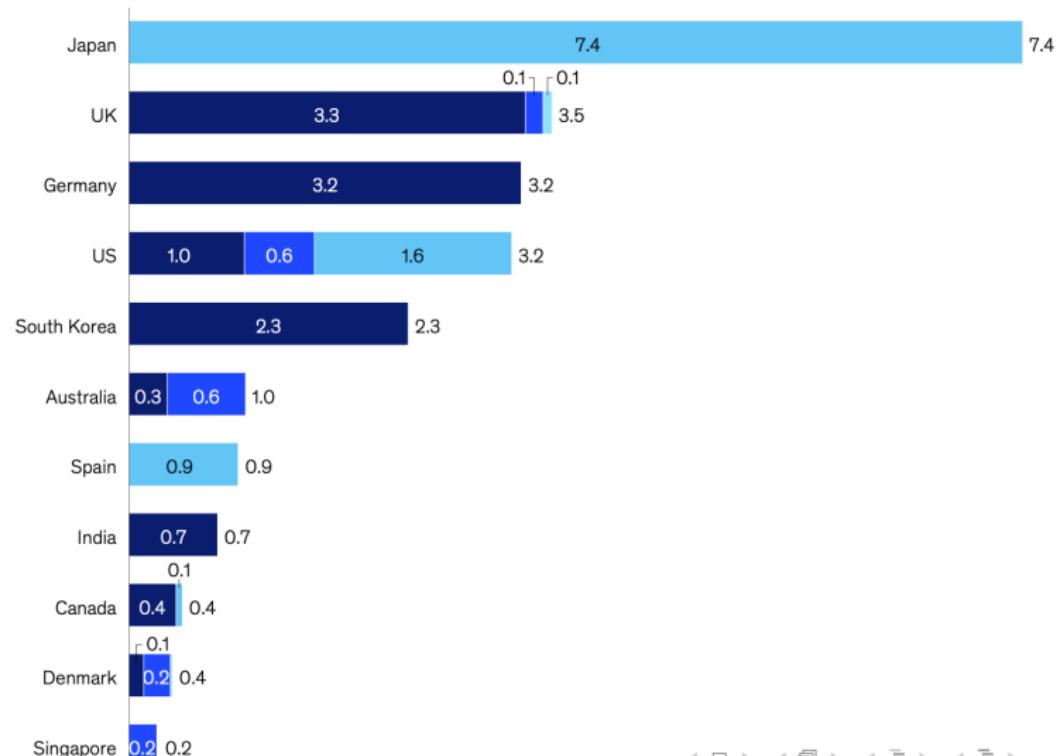
Annual investment,
2021–24, %



Announcements of public investments in quantum technology

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

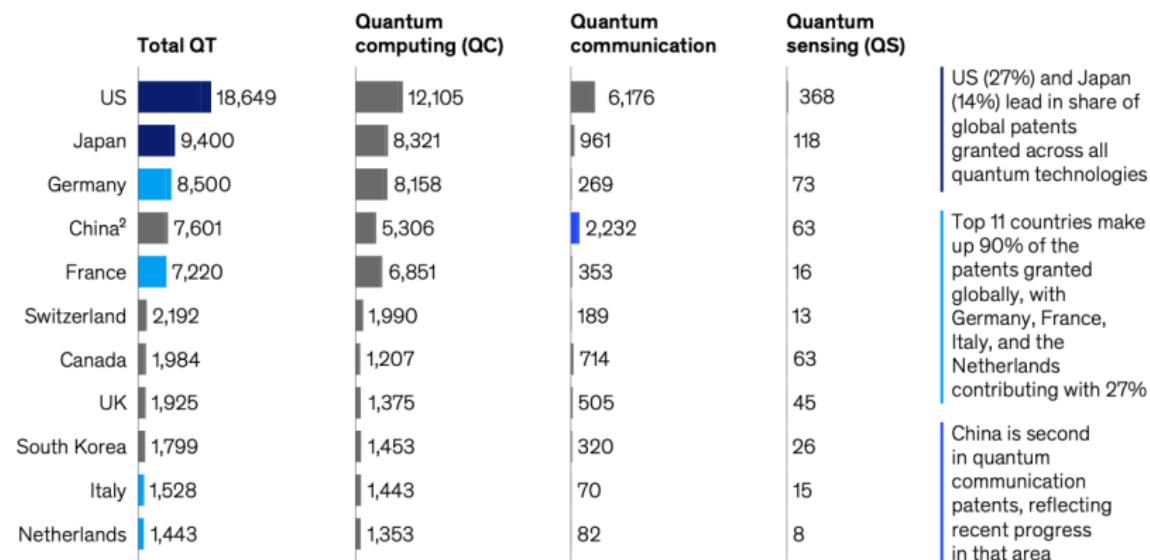
Year announced:
2023 2024 2025 (Jan–Apr)



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

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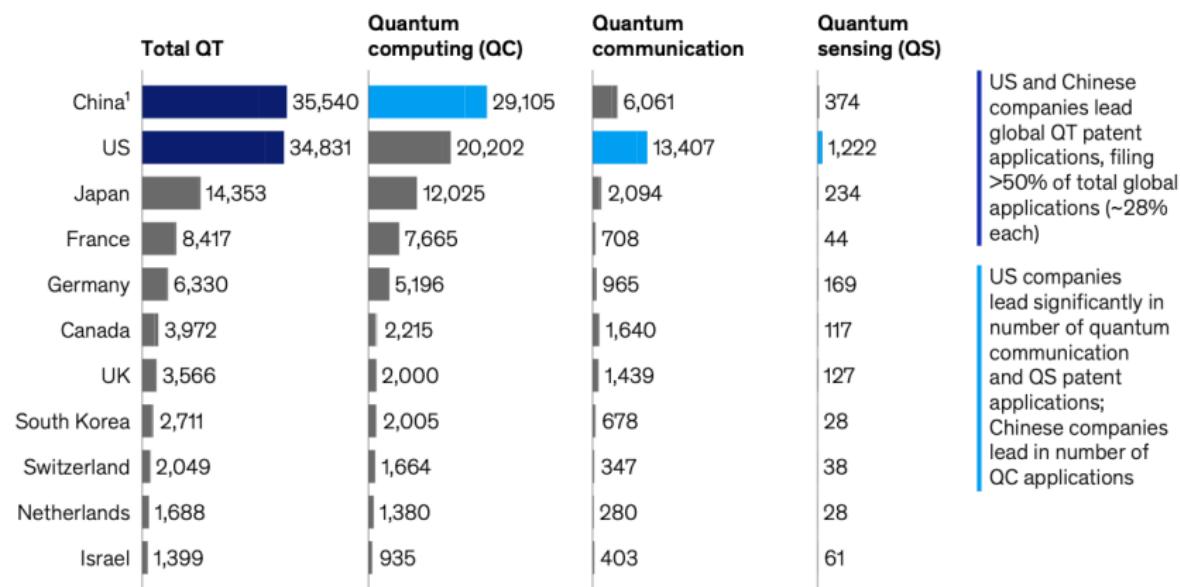
Quantum technology (QT) patents granted, by company HQ location, 2000–24¹



The United States and China lead other countries in the number of filed patents

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

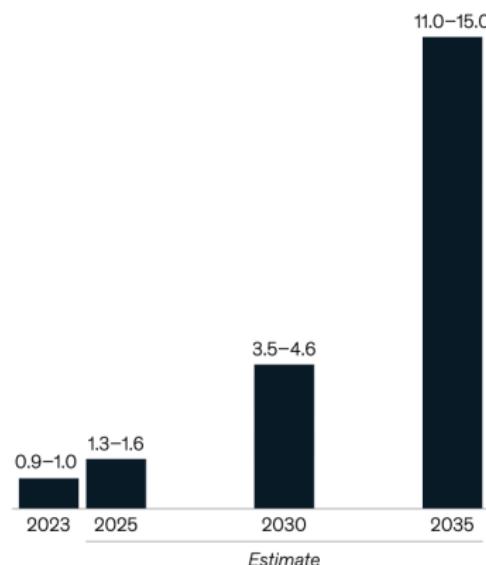
Quantum technology (QT) patent applications, by company HQ location, 2000–24



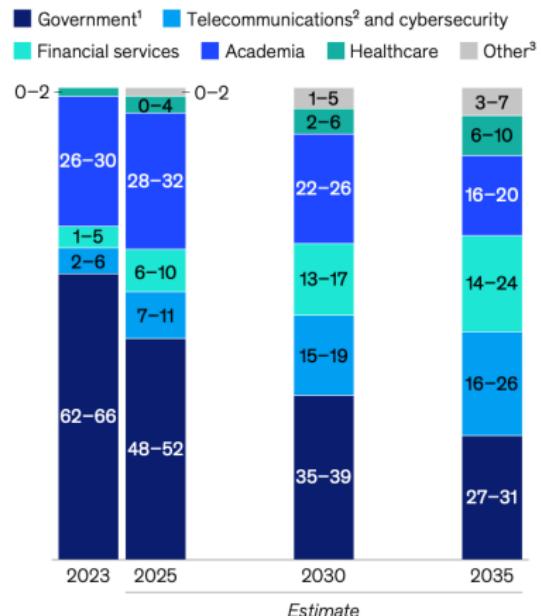
The quantum communication market is projected to reach 11 billion to 15 billion USD by 2035.

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Quantum communication market size,
\$ billion



Quantum communication market breakdown by customer type, %



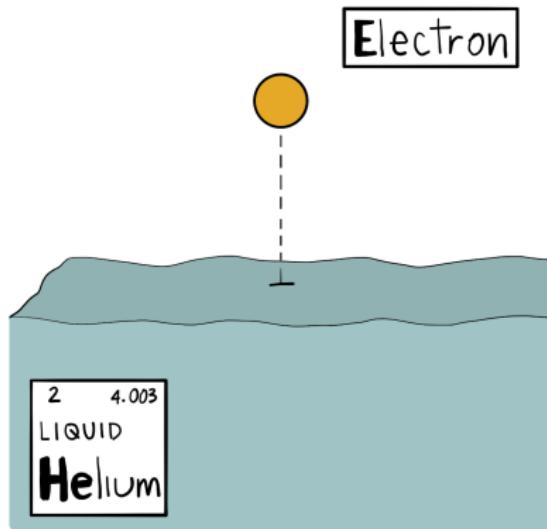
New platform: electrons on helium, <https://eeroq.com/>

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



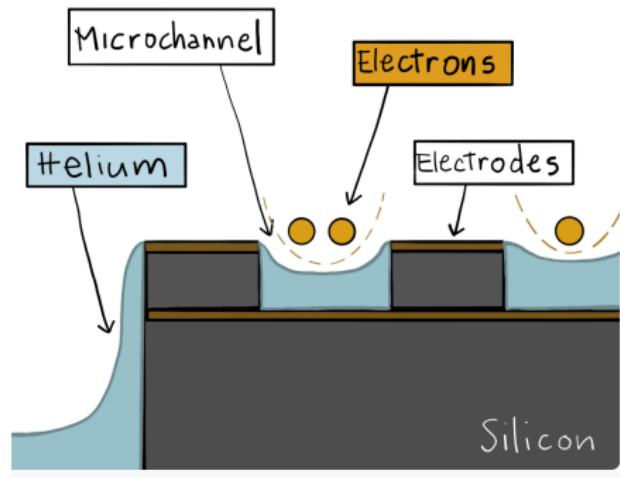
Single electrons can make great qubits

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.



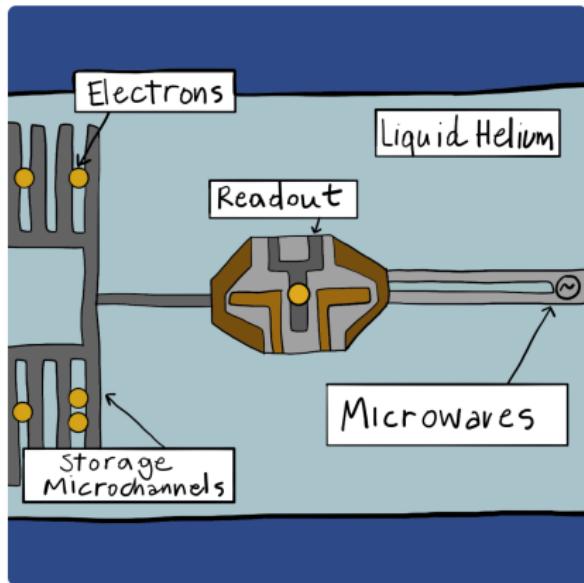
Trapping electrons in microchannels

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.



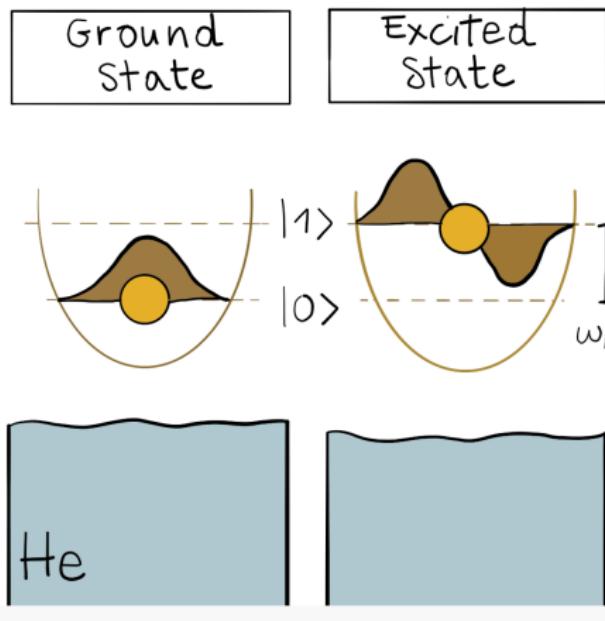
Control and readout

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).



New export control rules

The US Bureau of Industry and Security (BIS) rules are new export controls on certain quantum computing items, implemented through an Interim Final Rule (IFR) on September 6, 2024. These rules add worldwide licensing requirements for items on the Commerce Control List (CCL), create a new license exception for allied countries, and establish reporting requirements. The aim is to control the export of advanced technologies, including quantum computing components, software, and equipment, for national security and foreign policy reasons.

What is controlled

- Quantum computing items: This includes computers, software, components, materials, and related equipment used in their development and maintenance.
- Advanced semiconductor manufacturing equipment: Tools and machines for producing advanced chips.
- Technology: Technology for high-performance computing chips.
Additive manufacturing items: Equipment for producing metal components.

Export control, selected list from own collaborations

Technology/Component and Reason for Sensitivity

- Superconducting CPW resonator: Advanced quantum sensor with potential defense/communications applications.
- Single-electron trap (gated microchannel): Specialized microelectronic architecture for quantum computing.
- Superconducting electrodes (Nb films): Superconducting materials in high-Q resonators and quantum circuits.
- Superfluid ^4He substrate: Specialized cryogenic environment and novel quantum materials.
- Cryogenic RF components: Similar hardware is used in radar and communications systems.
- Electron-on-helium qubit platform: Emerging quantum information platform targeted by new export controls; potential secure/advanced computation application.

Instead of conclusions: Other topics to discuss

- Quantum Technologies and International Treaties
- Quantum computing raises questions about whether existing statutes on intellectual property, liability, privacy, and even antitrust are adequate
- Cybersecurity in the Quantum Era: Threats and Legal Responses – How quantum computing jeopardizes current cryptography and what laws can do about it
- Quantum Communication and Privacy
- Quantum Sensing and Surveillance: Privacy and National Security Implications
- Export Controls and Quantum Tech: Balancing Security and Innovation
- Patents and IP in the Quantum Era: Innovation vs. Open Science
- Geopolitics of Quantum: The New Tech Arms Race and Legal Strategy
- Ethical Quantum Technologies: Ensuring Responsible Innovation and many more