Quantum Technologies, risks and prospects

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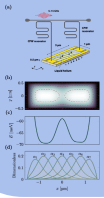
What is this talk about?

The main emphasis is to give you a short and hopefully pedestrian introduction to the whys and hows of AI/machine learning (ML) and quantum technologies. And why this could (or should) be of interest. And how technological advances in quantum technologies are reflected in new investments in the coming years. Finally, I may consider a range of ethical and legal challenges that accompany the ongoing expansion of AI/ML and quantum technologies.

Quantum technologies and machine learning/AI are tightly interwoven

Quantum Hardware

- Quantum control and sensors
- Quantum computers
- Catalysis



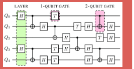
AI for Quantum Technology

- Quantum mechanical many-body theories
- Molecular dynamics
- Density functional theory

Quantum Technology and AI

Quantum Algorithms for AI

- Quantum computing
- Quantum algorithms
- Quantum machine learning
- Quantum inspired classical computing

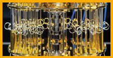


Societal impact and products

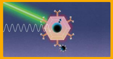
New medicines

Better shipping

Financial innovation



Quantum readiness



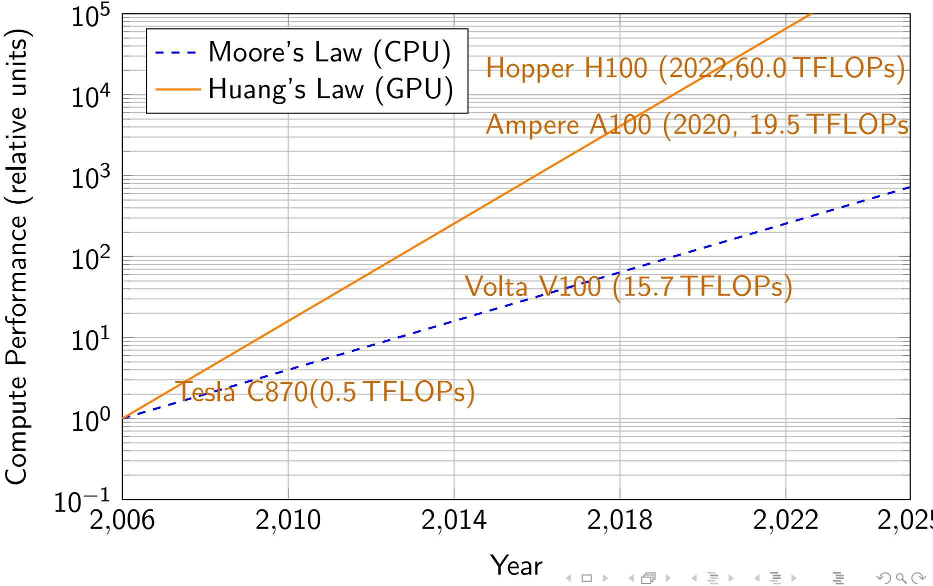
Quantum sensors and computers

- Drug discovery
- Quantum sensing
- Supply chain optimization
- Financial market modelling and risk analysis
- Material discovery

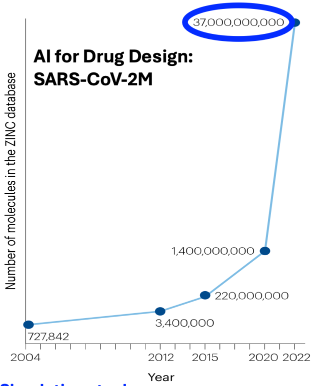
But there are some important differences

- 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
		76	1,353.00	2,055.72	24,607
	Max, Slingshot-11, Intel DOE/SC/Argonne National Laboratory United States				
4	**Eagle** - Microsoft NDv5, Xeon Platinum 8480C 48C 2GHz, NVIDIA H100, NVIDIA Infiniband NDR, Microsoft Azure Microsoft Azure United States	2,073,600	561.20	846.84	

Advance nuclear weapon science and scientific discovery.

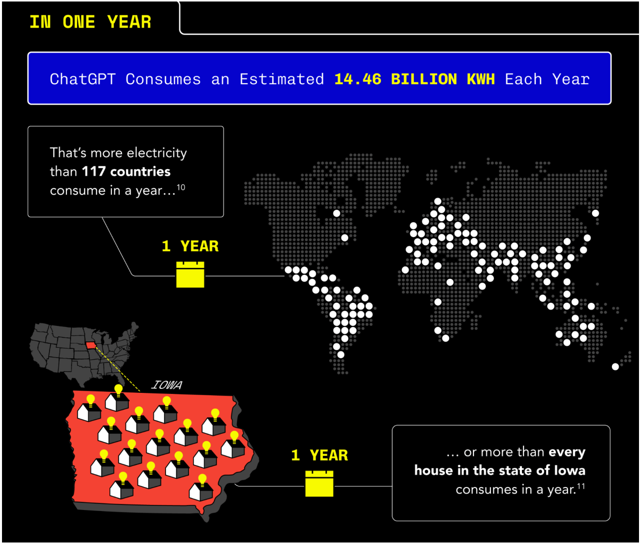
US$600 million

nature reviews drug discovery

Perspective | Published: 08 December 2023

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

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.

H **Hartmut Neven**
Founder and Lead, Google Quantum AI

V **Vadim Smelyanskiy**
Director, Quantum Pathfinding, Google Quantum AI

Share

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 Machine Learning?

Machine Learning (ML) is the study of algorithms that improve through data experience.

Types of Machine Learning:

- **Supervised Learning:** Labeled data for classification or regression.
- **Unsupervised Learning:** No labels; discover hidden patterns.
- **Reinforcement Learning:** Learning through interaction with the environment.

ML Workflow:

$$\text{Data} \rightarrow \text{Model Training} \rightarrow \text{Prediction}$$

AI/ML and some statements you may have heard (and what do they mean?)

1. Fei-Fei Li on ImageNet: **map out the entire world of objects** (The data that transformed AI research)
2. Russell and Norvig in their popular textbook: **relevant to any intellectual task; it is truly a universal field** (Artificial Intelligence, A modern approach)
3. Woody Bledsoe puts it more bluntly: **in the long run, AI is the only science** (quoted in Pamilla McCorduck, Machines who think)

If you wish to have a critical read on AI/ML from a societal point of view, see Kate Crawford's recent text Atlas of AI.
Here: with AI/ML we intend a collection of machine learning methods with an emphasis on statistical learning and data analysis

Main categories of Machine Learning

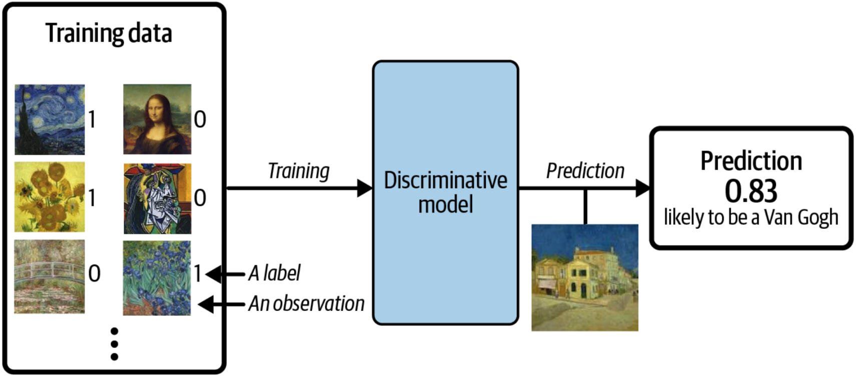
Another way to categorize machine learning tasks is to consider the desired output of a system. Some of the most common tasks are:

- Classification: Outputs are divided into two or more classes. The goal is to produce a model that assigns inputs into one of these classes. An example is to identify digits based on pictures of hand-written ones. Classification is typically supervised learning.
- Regression: Finding a functional relationship between an input data set and a reference data set. The goal is to construct a function that maps input data to continuous output values.
- Clustering: Data are divided into groups with certain common traits, without knowing the different groups beforehand. It is thus a form of unsupervised learning.

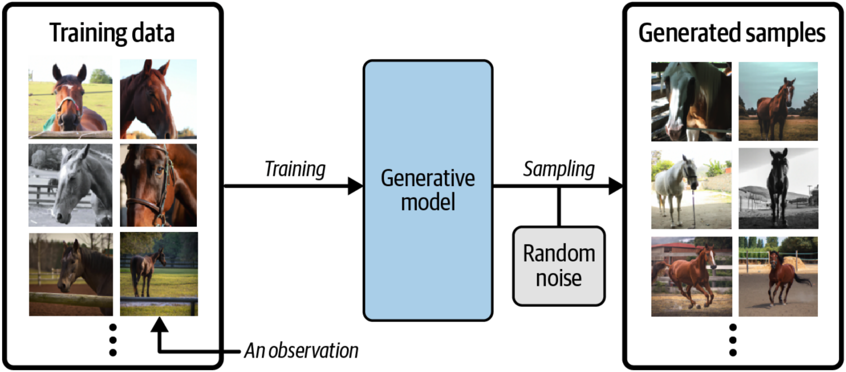
The plethora of machine learning algorithms/methods

1. Deep learning: Neural Networks (NN), Convolutional NN, Recurrent NN, Boltzmann machines, autoencoders and variational autoencoders and generative adversarial networks, stable diffusion and many more generative models
2. Bayesian statistics and Bayesian Machine Learning, Bayesian experimental design, Bayesian Regression models, Bayesian neural networks, Gaussian processes and much more
3. Dimensionality reduction (Principal component analysis), Clustering Methods and more
4. Ensemble Methods, Random forests, bagging and voting methods, gradient boosting approaches
5. Linear and logistic regression, Kernel methods, support vector machines and more
6. Reinforcement Learning; Transfer Learning and more

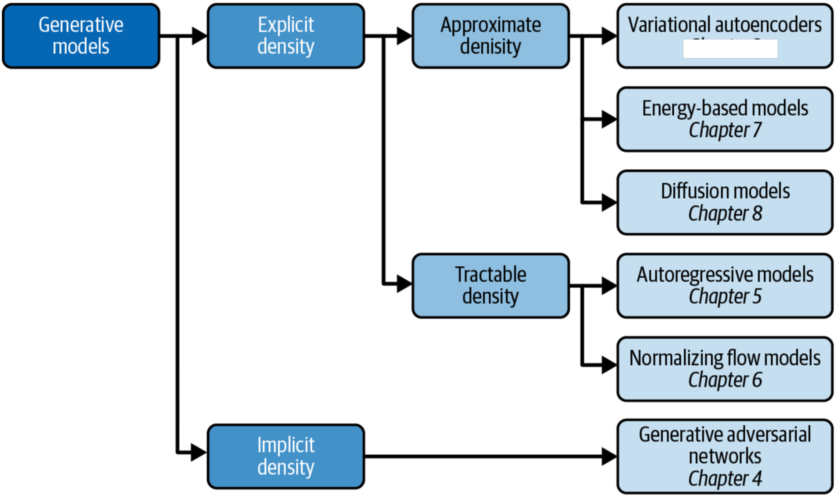
Example of discriminative modeling, taken from Generative Deep Learning by David Foster



Example of generative modeling, taken from Generative Deep Learning by David Foster



Taxonomy of generative deep learning, taken from Generative Deep Learning by David Foster



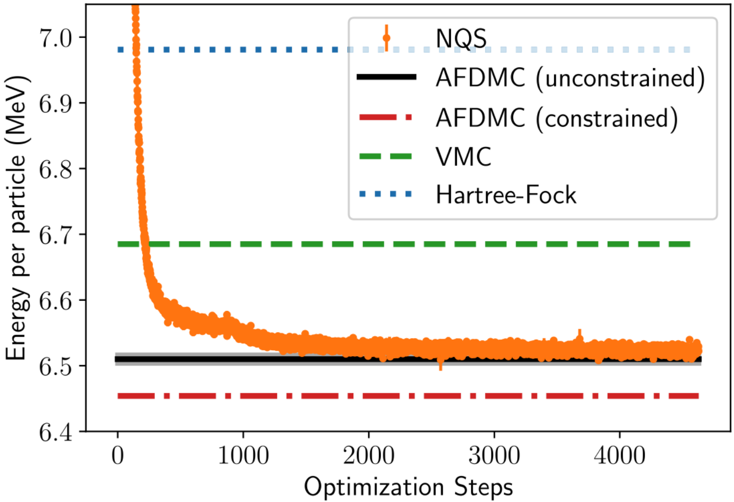
What are the basic Machine Learning ingredients?

Almost every problem in ML and data science starts with the same ingredients:

- The dataset $\boldsymbol{x}$ (could be some observable quantity of the system we are studying)
- A model which is a function of a set of parameters $\boldsymbol{\alpha}$ that relates to the dataset, say a likelihood function $p(\boldsymbol{x}|\boldsymbol{\alpha})$ or just a simple model $f(\boldsymbol{\alpha})$
- A so-called **loss/cost/risk** function $\mathcal{C}(\boldsymbol{x}, f(\boldsymbol{\alpha}))$ which allows us to decide how well our model represents the dataset.

We seek to minimize the function $\mathcal{C}(\boldsymbol{x}, f(\boldsymbol{\alpha}))$ by finding the parameter values which minimize $\mathcal{C}$. This leads to various minimization algorithms. It may surprise many, but at the heart of all machine learning algortihms there is an optimization problem.

Dilute neutron star matter from neural-network quantum states by Fore *et al.*, Physical Review Research 5, 033062 (2023) at density $\rho = 0.04\ \mathrm{fm}^{-3}$



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 ofcommunication 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.

Where are we?


HOW'S YOUR QUANTUM COMPUTER PROTOTYPE COMING ALONG?
GREAT!
DilbertCartoonist@gmail.com
Dilbert.com
THE PROJECT EXISTS IN A SIMULTANEOUS STATE OF BEING BOTH TOTALLY SUCCESSFUL AND NOT EVEN STARTED.
4-17-12 ©2012 Scott Adams, Inc./Dist. by Universal Uclick
CAN I OBSERVE IT?
THAT'S A TRICKY QUESTION.

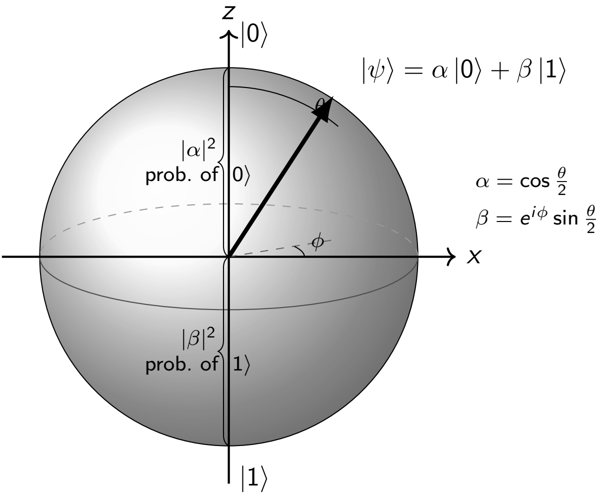
The basic concepts

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 $|1\rangle$.

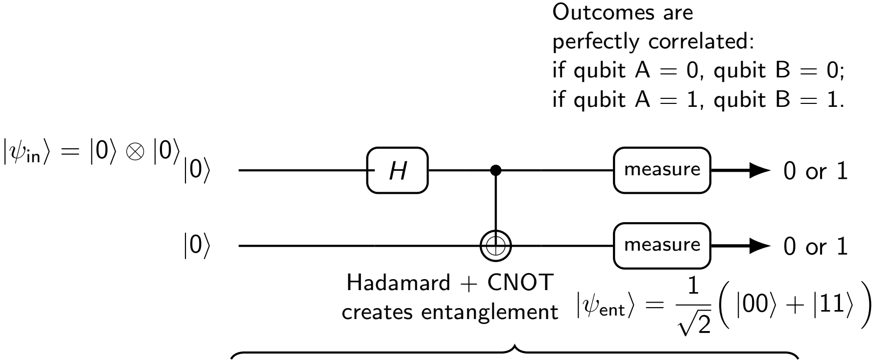
What is Quantum Entanglement?

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

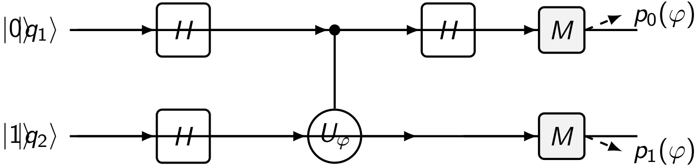


Entanglement: the two-qubit state cannot be written as $|\phi\rangle_A \otimes |\chi\rangle_B$.
Measurement on one instantly fixes the other's outcome.

Interference

Final H on q_1 converts phase into interference in $p_0(\varphi), p_1(\varphi)$

$|0\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$



$|1\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$

Controlled phase $U_\varphi = \mathrm{diag}(1, e^{i\varphi})$
adds a relative phase on the $|11\rangle$ component

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:

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

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.

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.

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:

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

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.

Di Vincenzo criteria

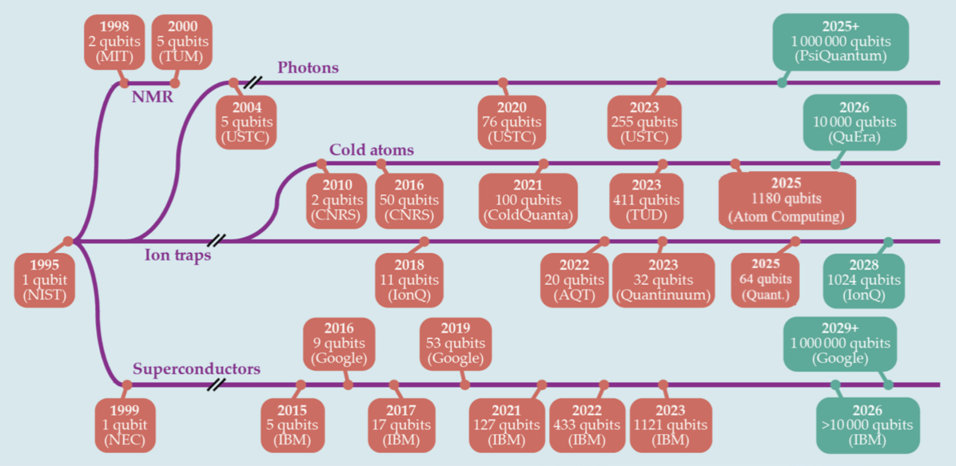
Quantum computing requirements

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

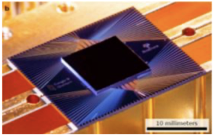
1. Superconducting qubits use Josephson junction circuits operated at millikelvin temperatures
2. Trapped-ion computers confine ions (e.g. $^{171}\text{Yb}^{+}$, $^{40}\text{Ca}^{+}$) in electromagnetic traps, encoding qubits in internal electronic states. Gates are implemented with laser or microwave 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)

Where are we? More seriously

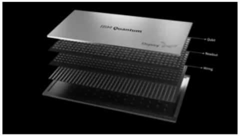


Where are we? More seriously

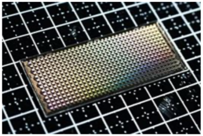
Google AI



IBM



CAS

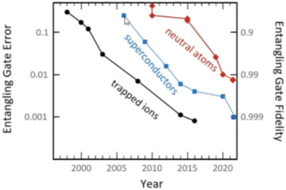


Qubit numbers increase yearly:

- 2019: 53 qubits (Google Sycamore)
- 2022: 433 qubits (IBM Osprey)
- 2023: 70 qubits w/ tunable couplers (Google Sycamore v2) [1]
- 2023: 1.121 qubits (IBM Condor) [2]
- 2023: 133 qubits w/ tunable couplers (IBM Heron)
- 2024: 504 qubits (China CAS Xiaohong) [3]
- 2024: 105 qubits (Google Willow)
- 2030+: IBM wants to break >2.000 qubit[4]

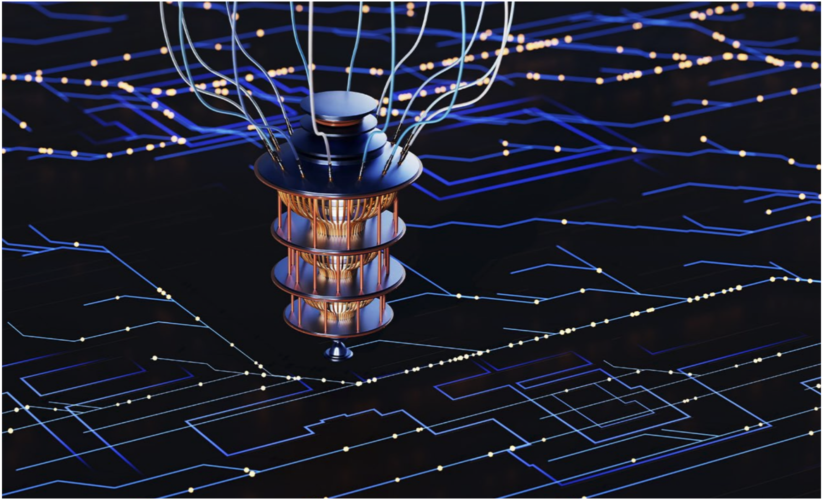
Novel applications showcase the capabilities of superconducting qubit devices

- 2023: Google implements distance 3 and 5 error correction on 50 phys. qubits[5]
- 2023: IBM simulates 2D Ising model on 127 qubits[6]



1: https://thequantuminsider.com/2023/07/04/google-claims-latest-quantum-experiment-would-take-decades-on-classical-computer/
2: https://www.ibm.com/quantum/blog/quantum-roadmap-2033
3: https://www.chinadaily.com.cn/a/202404/26/WS662b15dfa31082fc043c431e.html
4: https://www.ibm.com/roadmaps/quantum/
5: https://research.google/blog/suppressing-quantum-errors-by-scaling-a-surface-code-logical-qubit/
6: https://www.ibm.com/quantum/blog/utility-toward-useful-quantum:

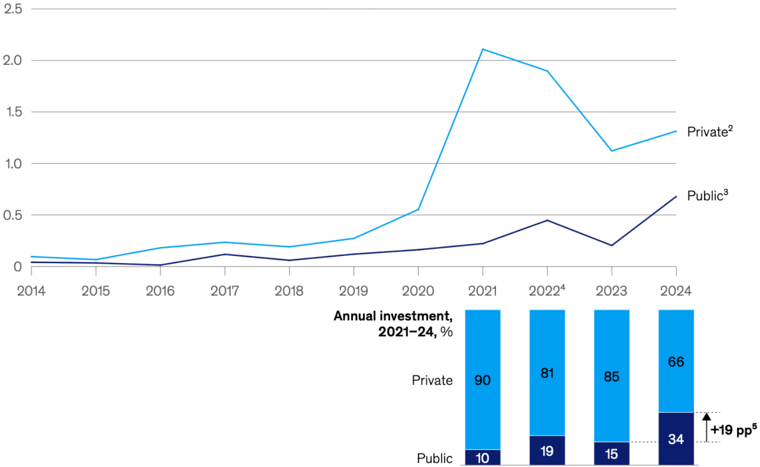
Considerable investements (McKinsey Quantum Technology Monitor, June 2025)



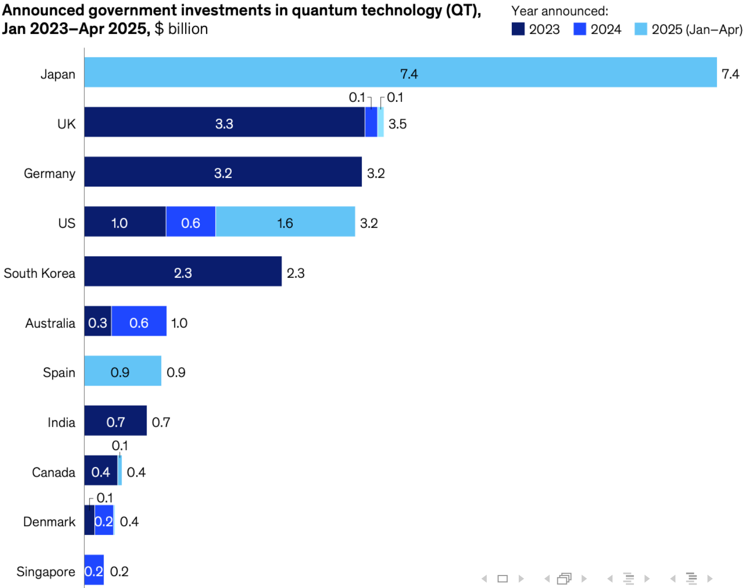
Quantum technology (QT) investments by funding type, 2014–24

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

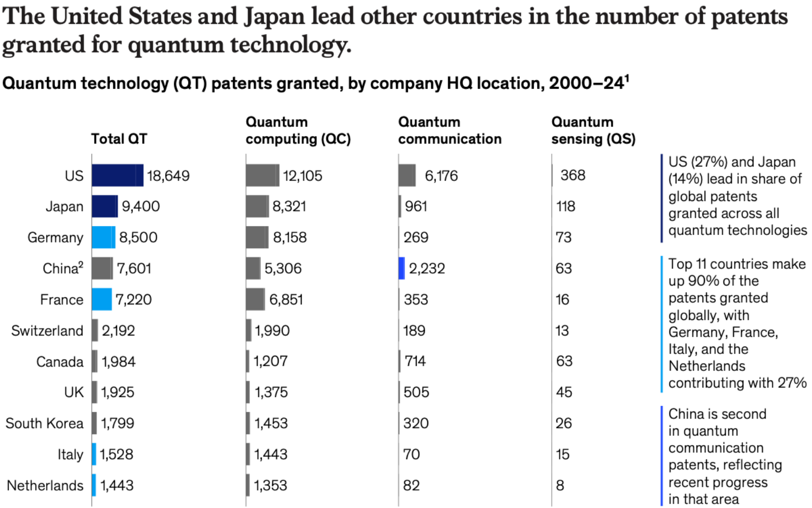
Quantum technology (QT) investments by funding type, 2014–24,[1] $ billion



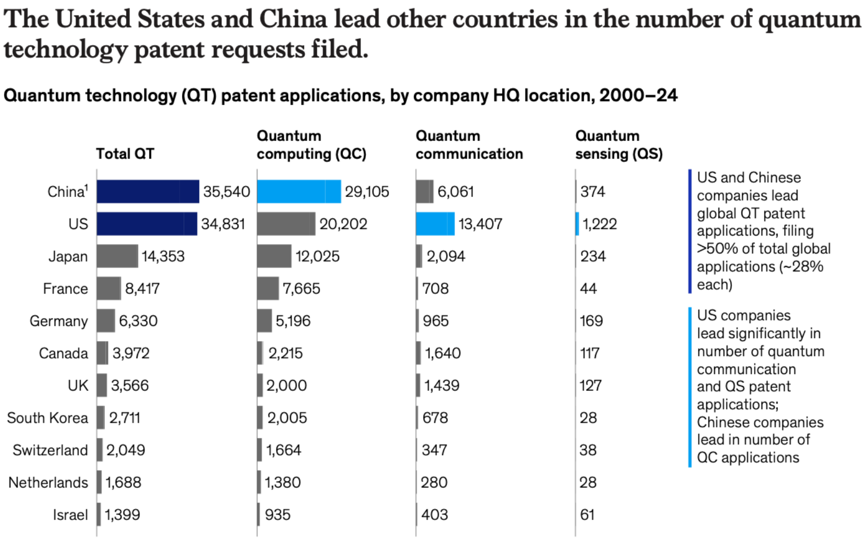
Announcements of public investments in quantum technology



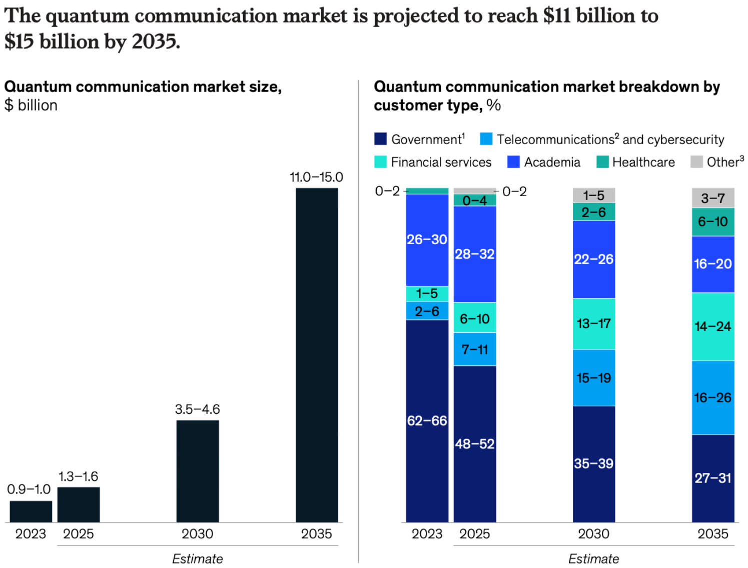
The United States and Japan lead other countries in the number of patents granted for quantum technology



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

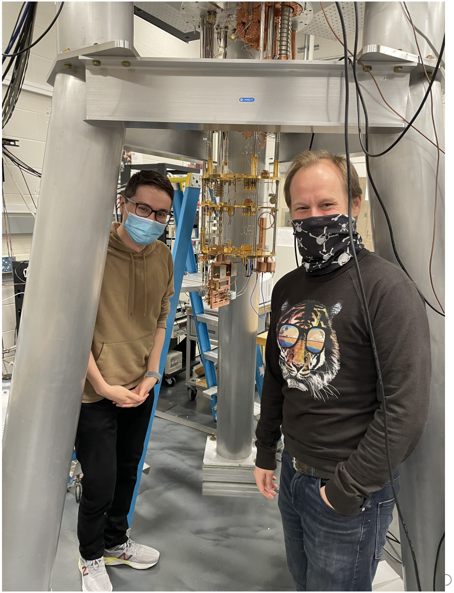


The quantum communication market is projected to reach 11 billion to 15 billion USD by 2035.



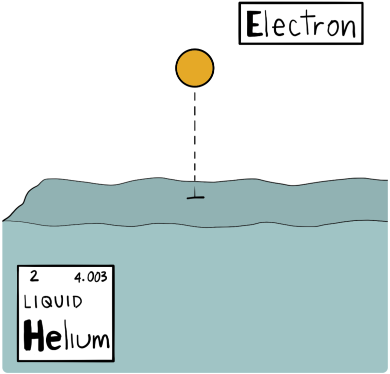
New platform: electrons on helium, `https://eeroq.com/`

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



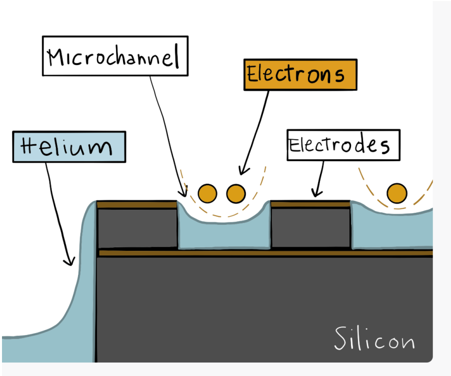
Single electrons can make great qubits

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.



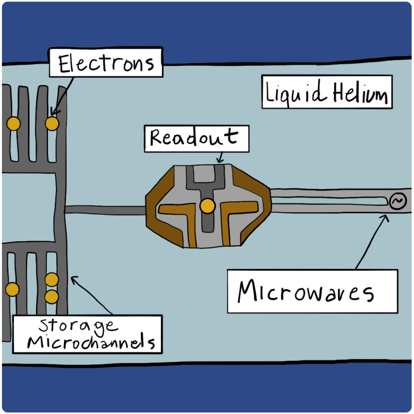
Trapping electrons in microchannels

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.



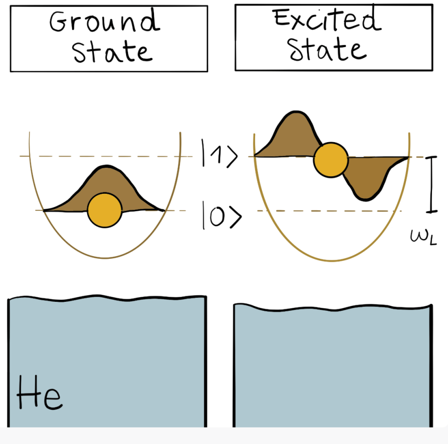
Control and readout

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 ^{4}He 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.

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

Observations (or conclusions if you prefer)

- How do we develop insights, competences, knowledge in AI and quantum technologies that can advance a given field?
  - For example: Can we use ML to find out which correlations are relevant and thereby diminish the dimensionality problem in complex interacting many-particle systems?
  - Can we use AI/ML in detector analysis, accelerator design, analysis of experimental data and more?
  - Can we use AL/ML to carry out reliable extrapolations by using current experimental knowledge and current theoretical models?
  - How do we study entanglement in various quantum platforms? Can we use AI/ML for better design?
- The community needs to invest in relevant educational efforts and training of scientists with knowledge in AI/ML and quantum technologies
- Most likely tons of things I have forgotten

Selected applications of Quantum Machine Learning

1. **Quantum mechanical many-particle systems:**
   - Simulate structures in nuclei, atoms, moleculs etc with QML.
2. **Finance:**
   - Quantum optimization for portfolio management.
3. **Image Recognition:**
   - Quantum-enhanced convolutional neural networks.

Future Perspectives

Quantum Internet:

- Entanglement as a resource for global quantum networks.

Fault-Tolerant Quantum Computing:

- Quantum error correction leveraging entanglement.

Advanced Quantum Sensors:

- Improved sensitivity for medical and scientific applications.