Quantum technologies

Quantum technologies and industry

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Quantum technologies

Quantum technologies might be subdivided in four type of applications

- quantum computers;
- quantum simulators;
- quantum communications;
- quantum sensors and metrology.

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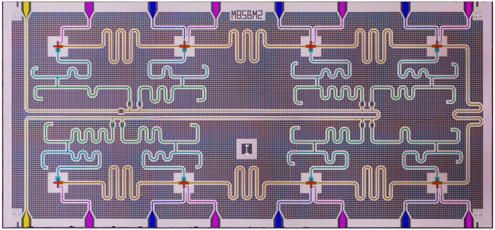
Quantum computers are expected to have a number of significant applications in computing fields such as optimization and machine learning. The most famous application is Shor's algorithm, which can be used to factorise large numbers which are mathematically important to secure data transmission (RSA protocol for encryption).



8-Qubit superconducting quantum processor fabricated at ETH Zurich. Image extracted from `https://qt.eu/discover/technology/`.

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I.1. Quantum computers

Several quantum computers prototypes have been demonstrated over the last two decades. The most advanced ones relies either on trapped ions and superconducting circuits for implementation of qubits.

Typically 10-15 qubits have already run basic algorithms and protocols. More recently, industrial players have reported chips within the 50-72 qubits range (IBM, Rigetti, Intel and Google), all of them based on superconducting qubits.

Other implementations of qubits are also investigated, either in solid-state systems (electrons spins in semiconductors, nuclear spins in solids, Majorana zero modes) or atomic and optical systems (nuclear spins in molecules, hyperfine states and Rydberg states in atoms).

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I.1. Quantum computers

The end of Moore's law, referring to the limit that transistor and processor power seems to reach with standard silicon technologies, make industrial players show interest in quantum computing as **a disruptive technology that could outperform standard silicon transistor technology for computers**.

Most of global IT companies have been taking an increased interest in quantum computing in the last decade, but also start-ups and GAFAM like Google, Microsoft and Amazon.

Recent advances in quantum computer design and development, error correction codes, fault-tolerant algorithms and novel fabrication process are promising milestones towards the achievement with a couple of decades of a prototype that could outperform classical computation in some applications.

The real question is not if there will be a quantum computer, but which market will profit of it within which business model.

- spin qubits in semiconductors: Intel, HRL laboratories, NTT,...
- superconducting qubits chips: IBM, Google, Rigetti, Intel,...
- trapped ions: IonQ,...
- topological qubits: Microsoft.
- superconducting quantum annealer: D-wave.

The most powerful chip available and integrated by IBM is made out of 53 qubits, while Google reported a 72 qubits chips.

Lockheed Martin and Infineon companies are supporting research with trapped ions as qubits, manipulated with lasers beams.

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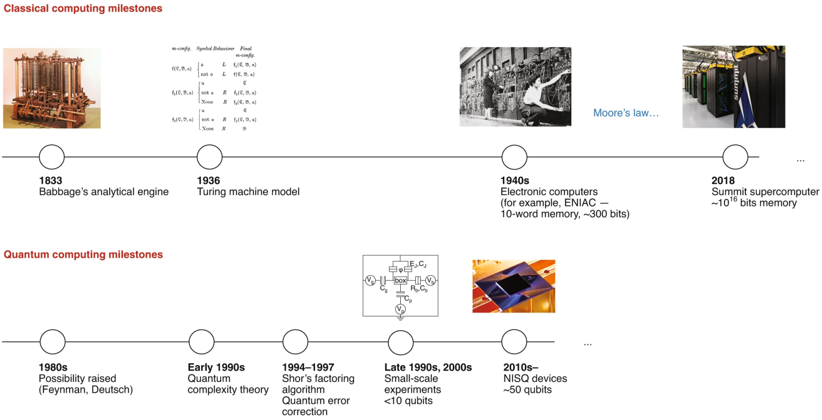

B. Barak, *Work with what you've got*. Nature Physics (2021).
`https://doi.org/10.1038/s41567-020-01126-7`.

I.2. Quantum simulators

Nowadays, industry uses supercomputers facilities in their R&D development. They are particulary useful in the context of complex objects design such as aircrafts, buildings or cars. By contrast, simulating behaviors at microscopic remains an important challenges where supercomputers might be overwhelmed.

One can not yet predict if a chemical reaction will take place between complex molecules. But all those small systems are fundamentally quantum systems.

Difficulties appears when one want to simulate a large quantum system such as a molecule with a classical computer governed by classical physics. If physics is too hard for classical computers, then build a physical computer that exploits that power, *i.e.* a quantum computer.

I.2. Quantum simulators

R. Feynman noticed that *"it does seem to be true that all various field theories have the same kind of behavior, and can be simulated every way."*

And he concluded that *"Nature isn't classical, dammit, and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."*

Quantum simulators are a subclass of quantum computers, less sensitive to decoherence and environmental noise. They are dedicated to physical simulation of systems.

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I.2. Quantum simulators

Quantum simulators based on the laws of quantum physics will allow us to overcome the shortcomings of supercomputers and to simulate materials or chemical compounds, as well as to solve equations in other areas, like high-energy physics.

Quantum simulators can be viewed as analog versions of quantum computers, dedicated to reproducing the behaviour of materials where quantum phenomena arise and give rise to their properties (at low temperature or for chemical reactions).

Their main advantage over all-purpose quantum computers is that **quantum simulators do not require complete control of each individual component, and thus are simpler to build and more tolerant to noise**.

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I.2. Quantum simulators

Several quantum simulators are under development, including ultracold atoms in optical lattices, trapped ions, arrays of superconducting qubits or of quantum dots and photons. First prototypes have already been able to perform simulations on specific problems beyond than what is possible with current supercomputers.

Quantum simulators are expected to impact deeply material science, and for instance help in the understanding of

- high-T_c supraconductivity, with applications in energy storage and distribution and in transportation;
- pharmaceutical, chemical and petrol industries (offering a unique tools to simulate molecules and predict chemical reactions).

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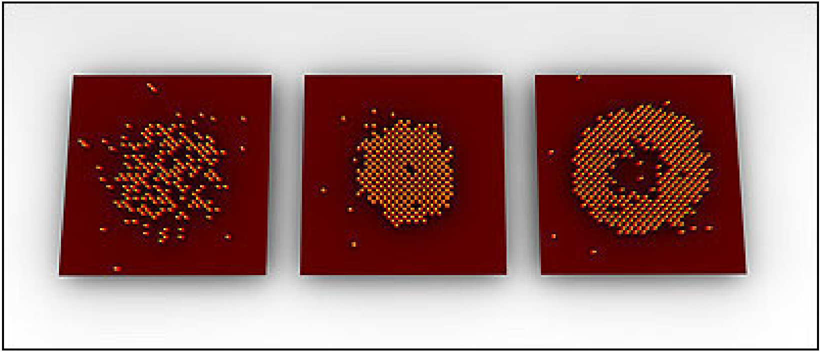

Single atom resolution microscope that permits to accesss directly to information of an atomic system at single atom level. Image from Immanuel Bloch's group at MPQ Munich. Extracted from https://www.photonics.com/Quantum_Particles_in_Perfect_Order_/a43862

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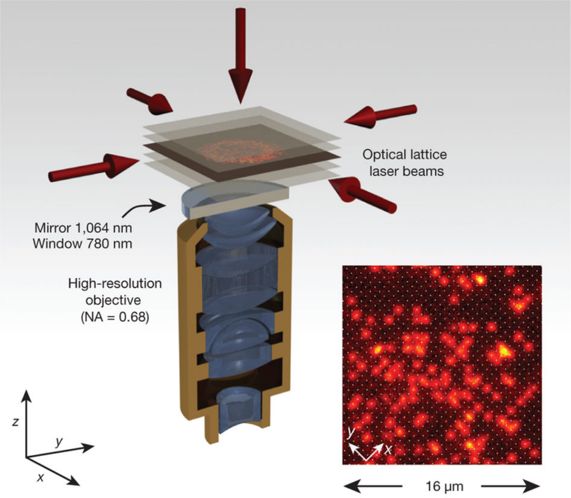
I.2. Quantum simulators



Single atom microscope (I. Bloch).

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I.3. Quantum communications

The motivation is the development of quantum-safe cryptography, that is encryption methods that quantum computers could not break. Quantum communications relies on the use of entanglement in order to secure communications.

Quantum key distribution (QKD)

Method of transmitting information using entangled light in a way that makes any interception of the transmission obvious to the user.

Entangled states are fundamentally sensitive to measurement. Therefore, if a spy intercepting the message sent, the measurement while project the entangled state on the measured states. If the entanglement is broken by the measurement, it is possible for the sender/reciever to know that it happened. Several protocol might be used to achieved that, such as the BB84 protocol.

I.3. Quantum communications

Quantum Random Number Generator (QRNG)

Generation of random number from fundamental probability nature of quantum states.

Random number are used to secure data encryption, ubt it is not easy to produce random number classically.

But when a quantum system is in a superposition state such as

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right),$$

the probability to measure $|0\rangle$ is fundamentally random, with 0.5 probability of success.

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I.3. Quantum communications

Secure solutions based on quantum encryption are also immune to attacks by quantum computers, and are **commercially available today**, as is quantum random number generation – a key primitive in most cryptographic protocols.

But quantum encryption is based on the transmission of entangled states which are fragile states. Then, theses fragile states might be affected by decoherence (and "accidental" projective measurement) during the propagation in the communication channel.

Currently, quantum communication systems can only function over distances of less than 500 km.

While in classical communication systems repeaters allows amplification of signal, quantum information is secure because it cannot be cloned. But for the same reason it cannot be relayed through conventional repeaters.

I.3. Quantum communications

Repeaters based on trusted nodes or fully quantum devices, possibly involving satellites, are needed to reach global distances. It has been realized in the chinese project called *Quantum Experiments at Space Scale* (QUESS).

The mission cost was around $100 million in total. Secured quantum communication has been demonstrated between the Institute for Quantum Optics and Quantum Information in Beijing (China) and Vienna (Austria), separated by a ground distance of 7,500km, enabling the first quantum secured intercontinental video call in 2016.

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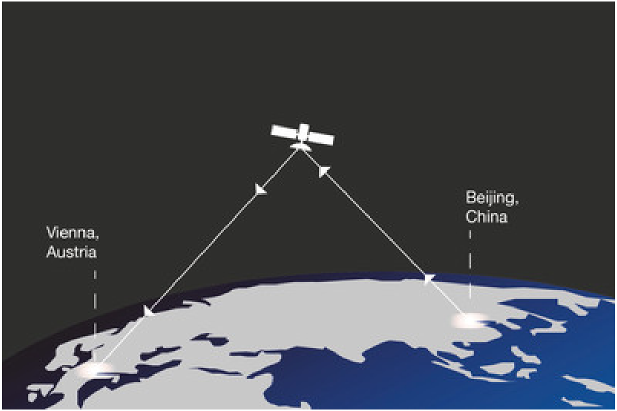
I.3. Quantum communications



Principle of the QUESS project: intercontinental secured quantum communication between China and Austria. Image ©ÖAW. Extracted from https://www.oeaw.ac.at/en/oeaw/press/public-relations-and-communications/pressefotos/first-quantum-satellite-successfully-launched/

I.3. Quantum communications

To reach intercontinental distance, secured quantum communications requires either the use of satellites or quantum repeaters, devices still in the phase of development at the academic level.

The advantage of quantum repeaters lies in extending the distances between trusted nodes. The building blocks for fully quantum repeater schemes are twofold

- a small quantum processor;
- a quantum interface to convert the information into photons similar to the optoelectronics devices used in today's internet, but with quantum functionality.

These building blocks have already been demonstrated in the lab, but years of R&D are still needed for them to reach the market.

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I.4. Quantum sensors and metrology

Quantum superposition states can be very sensitive to a number of external effects, such as electric, magnetic and gravitational fields; rotation, acceleration and time, and therefore can be used to make very accurate sensors.

The most known application of atomic metrology is probably **atomic clock** with precision so high that, for the most performant academic lab atomic clocks, one has an error of 1 second in a span of about one-hundred million years!

This makes them one of the most accurate devices in human history, at least when it comes to keeping time. The main application of atomic clocks is **geopositioning** and **UTC time** definition.

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I.4. Quantum sensors and metrology

The Global Positioning System (GPS) operated by the US Air Force Space Command provides very accurate timing and frequency signals. GPS satellites, each of which has at least two onboard caesium and as many as two rubidium atomic clocks.

GPS Time (GPST) is a continuous time scale and theoretically accurate to about 14 ns. However, most receivers lose accuracy in the interpretation of the signals and are only accurate to 100 ns.

The Galileo Global Navigation Satellite System is operated by the European GNSS Agency and European Space Agency and is expected to achieving full operating global coverage soon. It should offers 30 ns timing accuracy, equipped with two passive hydrogen maser and two rubidium atomic clocks for onboard timing.

I.5. Applications of quantum technologies

- Clocks and network synchronisation;
- Quantum communications;
- Quantum-optical metrology and imaging;
- Sensing with NV centers;

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II.1. From invention to innovation

Research, development and industrialisation are three aspects inherent to the development of new products and technologies.

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Research is dedicated to the study of the feasibility of a concept or fundamental studies.

Fundamental studies may permit to discover a phenomena that nobody expected, which will then result in a technological innovation.

Sometimes, fundamental researches requires technological development that found applications in industry or for the development of new commercial products. That is the case of the World Wide Web, which has been invented in 1989 by Tim Berners-Lee, a british research of CERN, the european center for subatomic physics research.

II.1. From invention to innovation

Development is another step of technological innovation process. Once a physical phenomena has been demonstrated, most of times the first prototype is not useable directly. The development phase consists in the optimization of the invention, improving the corresponding technology, the overall performances so that a useable prototype might be obtained.

An interesting example are semiconductor lasers.

- 1962: coherent light emission from a gallium arsenide (GaAs) semiconductor diode (a laser diode) was demonstrated by two US groups led by Robert N. Hall at the General Electric research center and by Marshall Nathan at the IBM T.J. Watson Research Center, based on theoretical work by William P. Dumke at IBM's Kitchawan Lab.

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II.1. From invention to innovation

- Diode lasers of that era operated with threshold current densities of 1000 A/cm^2 at 77 K temperatures. Such performance enabled continuous-lasing to be demonstrated in the earliest days.
- When operated at room temperature, threshold current densities were two orders of magnitude greater, or 100,000 A/cm^2 in the best devices.
- The dominant challenge was to obtain low threshold current density at 300 K and thereby to demonstrate continuous-wave lasing at room temperature from a diode laser.
- The innovation that met the room temperature challenge was the double heterostructure laser (awarded by the 2000 Nobel prize in Physics).

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II.1. From invention to innovation

Once the development has permit to obtained a prototype of a devices with performances good enough and size acceptable for commercialization, the last step is industrialisation.

It consists in the development of a fabrication process compatible with factory mass production, with reasonable cost so that the produced device could be sold at a competitive price regarding its application.

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II.2. Technology readiness level

In recent years, the public has often associated technological innovation with the most successful private companies in the world, such as Apple, Google, and Microsoft.

But a significant portion of the technologies leveraged by the iPhone, for example, was originally conceived in research conducted by the public sector. The journey of new technology from research to commercialization goes through a number of so-called technology readiness levels (TRLs).

TRL levels are a method for understanding the maturity of a technology. These levels were first developed at NASA between the 1970s and the 1990s. The latest version of the scale from NASA includes nine TRLs and has gained widespread acceptance across governments, academia, and industry.

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II.2. Technology readiness level

Technology readiness level (TRL).

II.2. Technology readiness level

Some tech giants are large enough to fund research units and work at all levels of this scale, but most companies cannot afford the high investments and specialized competencies this approach requires. Either way, in today's dynamic and volatile markets they have to aim at doing the disrupting in order to avoid being disrupted. Companies that cannot afford research units have to innovate by relying on research conducted elsewhere, and the natural candidate is academia. Academia tends to focus on TRLs

1–4, whereas industry prefers to work with TRLs 7–9, rarely 6. The term *Valley of Death* represents the often neglected addressing of TRLs 4 through to 7, where neither academia nor the private sector prioritise investment. Consequently, many technologies, even if they are promising, reach TRLs 4–6 and die there.

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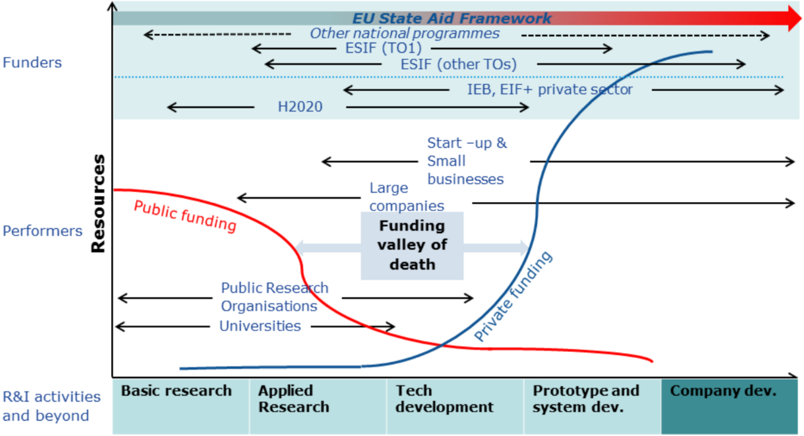
Figure 1 General overview of funding and Stakeholders type according to R&I activities and beyond



II.2. Technology readiness level

The issue of the valley of death has been studied extensively, and the scientific literature offers several proposals for bridging the gap. Alessandro Rossini, senior manager at PWC, has summarized the results of these studies in five recommandations

1. Academia and industry should better understand each other's culture;
2. Academics should better understand real-world industrial challenges;
3. Practitioners should stay up-to-date with the state-of-the-art;
4. Industry should hire more PhDs;
5. Academia and industry should conduct more joint research projects.

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II.3. Getting out of the lab: miniaturization

Semiconductor devices have stimulated the technological development of microfabrication techniques in clean room facilities, such as photolithography, molecular beam expitaxy,... These technological developments have been used in other fields for miniaturization of lab experimental setup.

- **lasers**;
- **microfluidics**, which refers to the behaviour, precise control, and manipulation of fluids that are geometrically constrained to a small scale;
- **atomchips**, miniaturization of ultracold atoms systems (Cold Quanta, IonQ).
- solid-state solutions for quantum technologies, such as **semiconductor base single photon emitters** (Quandela);
- **Quantum Processor** Chips (IBM, Google, Rigetti, D-Wave, Intel,...).

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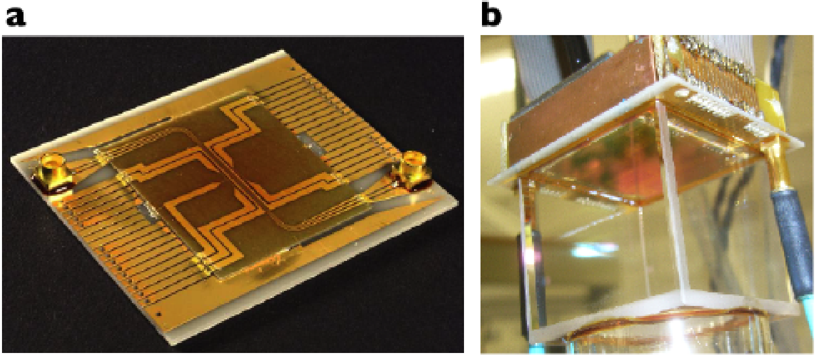
II.3. Getting out of the lab: miniaturization



Atomchip DOI:10.1103/PhysRevA.92.012106

II.3. Getting out of the lab: miniaturization

Most of quantum technologies basic elements have been miniaturized, making them ready for integration to develop commercial devices.

A constraint remains for superconducting qubits which requires subKelvin temperature, and the use of a diluation helium cryostat.

But most of industrial players have chosen this technology anyways. The business model consists not in selling the computer but selling the quantum calculation. The client has a cloud access to the quantum computer which physically remains the property of the company (like IBM or Rigetti). It is the most common business model for the moment, even if D-wave has sold quantum annealing computers.