# Course on Quantum Computing: “Espoo and Aalto University go quantum”

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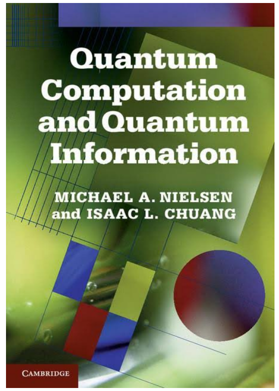
# Some observations that will become clear during the course

- Quantum computers will be in cloud, people may not easily (ever) buy them but use services via internet.
- Programming a quantum computer using a few qubits is not difficult but making a longer logically sensible program in quantum machine language is challenging
- We try to use only that much math that is required to understand the quantum notations

# Course textbooks and materials




- Main book will be Nielsen, Chuang, *Quantum Computation and Quantum Information: 10th Anniversary Edition*, Cambridge UP but we also try to give all basic lecture material in google classroom so that you may not need to buy the book.
- The participating students can all the time express their wishes, but we most likely will use more the IBM Qiskit environment but also take a look at Microsoft Q# system
- Concepts and tools that are needed: jupyter notebook, python, anaconda, registration to at least to IBM in order to get the personal token

# What is meant by quantum computing?

- In classical physics we use bits 0 and 1 that are physically separated from each other usually by a voltage (for example 5V)
- In quantum computing, instead of bits we use quantum bits that are called qubits, the difference may sound really minor, but the calculation philosophy changes $|\varphi\rangle = \varphi_0|0\rangle + \varphi_1|1\rangle$,

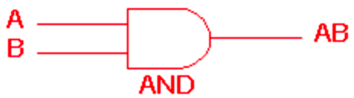
  qubit is actually a superposition of simple bits

The time evolution of the calculation means that we apply certain quantum gates in some clever order, this finally makes up the whole program

- Measuring the qubit, destroys it and we are left with a classical number
- Running a quantum computer means collecting enough statistics so that we
- can see what are the most likely outcomes of the calculation
- In this course we learn what the most commonly used gates are
- We also will write some (python) code that is sent to some spesific quantum computers in a cloud, remember if the computer has only 5 qubits available, you cannot send there a program with higher number of qubits, this is also different from classical computing, you have know how many qubits there in a machine that is available

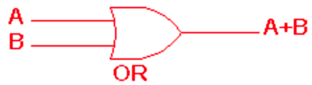
# Examples of classical logic gates

**AND gate**



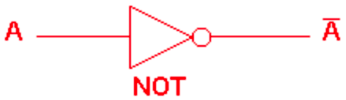

| 2 Input AND gate | | |
|---|---|---|
| A | B | A.B |
| 0 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 1 |

**OR gate**




| 2 Input OR gate | | |
|---|---|---|
| A | B | A+B |
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 1 |

**NOT gate**




| NOT gate | |
|---|---|
| A | $\overline{A}$ |
| 0 | 1 |
| 1 | 0 |

**NAND gate**


| 2 Input NAND gate | | |
|---|---|---|
| A | B | $\overline{A.B}$ |
| 0 | 0 | 1 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 0 |

**NOR gate**


| 2 Input NOR gate | | |
|---|---|---|
| A | B | $\overline{A+B}$ |
| 0 | 0 | 1 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 0 |

**EXOR gate**


| 2 Input EXOR gate | | |
|---|---|---|
| A | B | A⊕B |
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 0 |

This will be more or less to the goal of this course!!!!!

Ladataan qiskitiltä varmuuden vuoksi kaikki *

In [1]:
```
from qiskit import *
```

In [2]:
```
qr=QuantumRegister(2)
```

In [3]:
```
cr=ClassicalRegister(2)
```

In [4]:
```
circuit=QuantumCircuit(qr,cr)
```

In [5]:
```
circuit.draw()
```

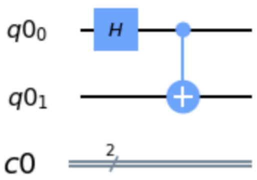
Out[5]:
```
q0_0: |0>

q0_1: |0>

 c0_0: 0

 c0_1: 0
```

In [13]:
```
circuit.h(qr[0])
```

Out[13]:
```
<qiskit.circuit.instructionset.InstructionSet at 0x1a1cc94160>
```

In [16]:
```
circuit.draw(output='mpl')
```

Out[16]:

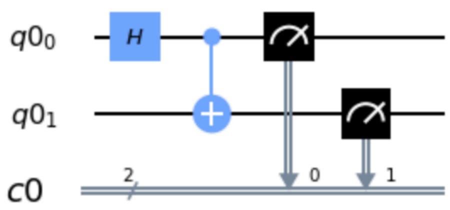


In [15]:
```python
circuit.cx(qr[0],qr[1])
```
Out[15]:
```
<qiskit.circuit.instructionset.InstructionSet at 0x1a1cf599e8>
```

In [19]:
```python
circuit.draw
```
Out[19]:
```
<bound method QuantumCircuit.draw of <qiskit.circuit.quantumcircuit.QuantumCircuit object at 0x1a1cc94898>>
```

In [18]:
```python
circuit.measure(qr,cr)
```
Out[18]:
```
<qiskit.circuit.instructionset.InstructionSet at 0x1a1cf16470>
```

In [21]:
```python
circuit.draw(output='mpl')
```
Out[21]:

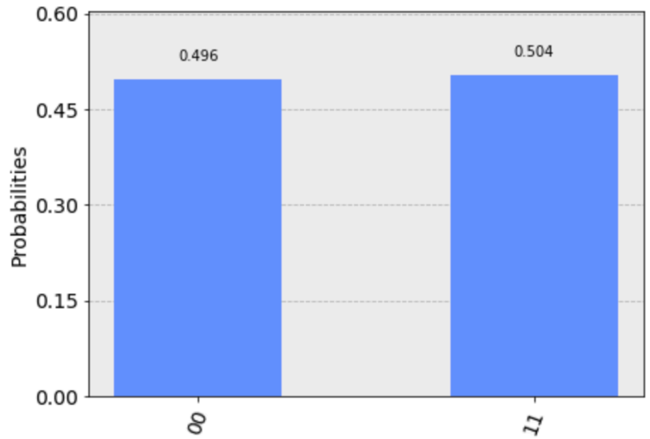



In [22]:
```python
simulator=Aer.get_backend('qasm_simulator')
```

In [40]:
```python
result=execute(circuit,backend=simulator).result()
```

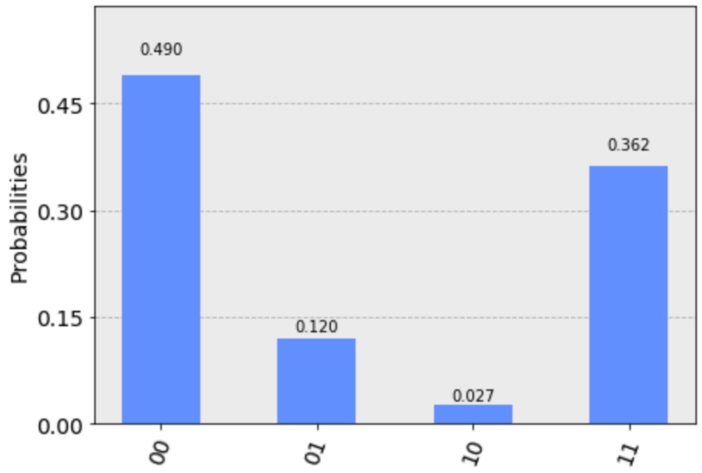
In [41]:
```python
from qiskit.tools.visualization import plot_histogram
```

```
In [22]: simulator=Aer.get_backend('qasm_simulator')

In [40]: result=execute(circuit,backend=simulator).result()

In [41]: from qiskit.tools.visualization import plot_histogram

In [42]: plot_histogram(result.get_counts(circuit))
Out[42]:
```




Klassinen simulaattori antoi siis melko tarkkaan tuloksen, että puolet mittauksista tuottaa tuloksen |00> ja puolet |11>, sen sijaan |01> ja |10> ei tule tulokseksi ikinä, vielä ei olla siis käytetty oikeaa kvanttitietokonetta, tehdään se seuraavaksi!!!
Tulokset on tietty sitä mitä pitikin tulla.

```
In [43]: IBMQ.load_account()
Out[43]: <AccountProvider for IBMQ(hub='ibm-q', group='open', project='main')>

In [44]: provider=IBMQ.get_provider('ibm-q')

In [45]: qcomp=provider.get_backend('ibmq_16_melbourne')

In [46]: job=execute(circuit, backend=qcomp)

In [47]: from qiskit.tools.monitor import job_monitor

In [48]: job_monitor(job)
         Job Status: job has successfully run

In [49]: result=job.result()

In [50]: plot_histogram(result.get_counts(circuit))
Out[50]:
```




Nyt on siis käyty Melbournessa tekemässä oikealla julkisesti käytettävissä olevalla 16 qubitin koneella ensimmäinen ihka oikea kvanttilaskenta. Vautsi vau vau! Ei mennyt montaa sekuntia, itse asiassa laskenta meni nopeasti, mutta oltiin muutama sekunti ensin jonossa. Job monitor päivittyy automaattisesti, kun on saatu oikeeta peliaikaa! Tein tän 19.1.2020 klo 19 Suomen aikaa. Jonossa ei ollut kuin 1 työ ennen tätä koodia. Tulokset on paljon huonompia kuin klassisella koneella, miksi? Mikä valtava ero on kvanttilaskennalla verrattuna klassiseen käpistelyyn?

# WTF?

A classical computer solves way better than a real quantum computer this very simple problem.

What’s the fuzz of all quantum things?

Are we saying that quantum gadgets are obviously useless?

Obviously, a quantum algorithm needs to be run many times in order to collect statistical result which at least so far contains some experimental noise.

Noise levels will go down as technologies are improved in the future

Finally, quantum computing has a different philosophy, results are statistical but computation is massively parallel

A kind of rule of thumb is that a quantum register of N qubits may be compared to a classical one so that $2^N$ equals the amount of corresponding classical bits

If  for example N= 15, we get huge numbers…

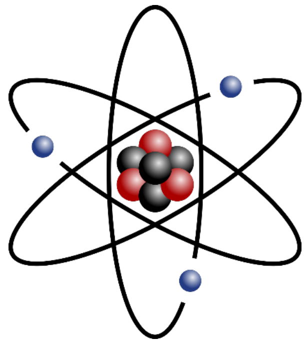
| Company | Type | Technology | Now | Next Goal |
|---|---|---|---|---|
| Intel | Gate | Superconducting | 49 | TBD |
| Google | Gate | Superconducting | 72 | TBD |
| IBM | Gate | Superconducting | 53 | TBD |
| Rigetti | Gate | Superconducting | 16 | 128 |
| USTC (China) | Gate | Superconducting | 10 | 20 |
| IonQ | Gate | Ion Trap | 11 | 79 |
| IQOQI/Univ. Ulm/Univ. Innsbruck | Gate | Ion Trap | 20 | TBD |
| NSF STAQ Project | Gate | Ion Trap | N/A | ≥64 |
| Intel | Gate | Spin | 26 | TBD |
| Silicon Quantum Computing | Gate | Spin | N/A | 10 |
| CEA-Leti/INAC/Institut Néel | Gate | Spin | N/A | 100 |
| Univ. of Wisconsin | Gate | Neutral Atoms | 49 | TBD |
| Harvard/MIT | Quantum Simulator | Rydberg Atoms | 51 | TBD |
| Univ. of Maryland / NIST | Quantum Simulator | Ion Trap | 53 | TBD |
| D-Wave | Annealing | Superconducting | 2048 | 5000 |
| iARPA QEO Research Program | Annealing | Superconducting | N/A | 100 |
| NTT/Univ. of Tokyo/Japan NII | Qtm Neural Network | Photonic | 2048 | >20,000 |

Updated September 18, 2019

2^53 9.0071993e+15

# Overview of Quantum Technologies

# What is “quantum technology”?



“Quantum technology” = technology based on the quantum behavior of radiation and matter

**The point:** Quantum systems behave in some situations very differently from macroscopic “classical” systems as described by classical physics.

=> Quantum behavior of matter offers **new kind of resources** for technological applications than what is classically possible/allowed.

# Different levels of quantum technology

Applications of quantum physics can be sorted into two levels:

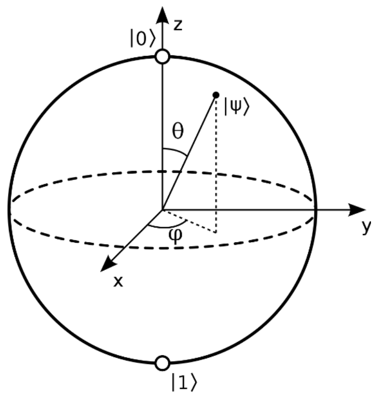
1. "Quantum 1.0":
   - Based on the **collective** behavior of a large number of quantum objects
   - Cannot control the quantum objects individually
   - E.g., LASER, semiconductors, superconducting circuits/magnets,…
2. "Quantum 2.0":
   - Based on the exact behavior of **individual** quantum systems
   - Component quantum systems are individually and accurately controlled
   - E.g., quantum computer, few-photon quantum optics, quantum crypto,...

The second level requires highly sophisticated technology, and therefore is only now becoming possible.

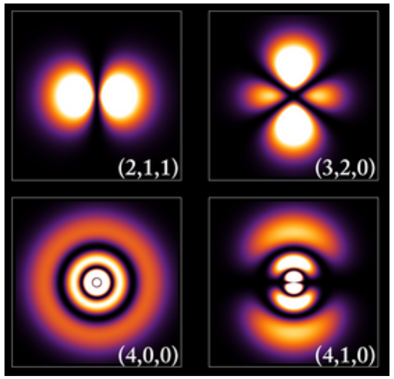
# Some new quantum resources for technology

1. Quantum **superposition**:
   - A quantum system can be in a **mixture** of classically allowed states. Therefore, a quantum system has many more states than its classical counter part.
   - For example, a classical bit has only states 0 and 1. A quantum bit can be in a "**superposition**" of 0 and 1, where both states are possible at the same time.
   - A classical particle can be only in one place at once, while a quantum particle can be (and usually is) in a mixture/superposition of different positions. => Wave-like behavior of particles, "wave-particle duality".

Superpositions of the states 0 and 1, i.e., states of a qubit live on the Bloch sphere.




Energy states of an electron in a hydrogen atom are superpositions of different electron locations.

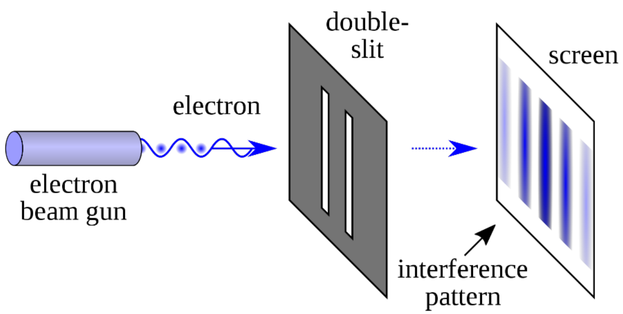


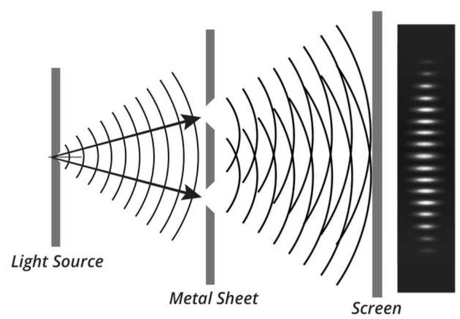
# Some new quantum resources for technology

2. Quantum **interference**:

- Different components of a superposition can **interfere** with each other.
  - Constructive interference: components amplify each other
  - Destructive interference: components cancel each other (either completely or partially)
- NOTE: Works for **individual** quantum systems/particles!
- For example, in quantum algorithms interference can be used to amplify the correct solutions and to cancel out the wrong solutions to a problem. When the system is measured, the superposition collapses to one component.

In the double slit experiment different components of the electron/photon state interfere. An interference pattern is produced.

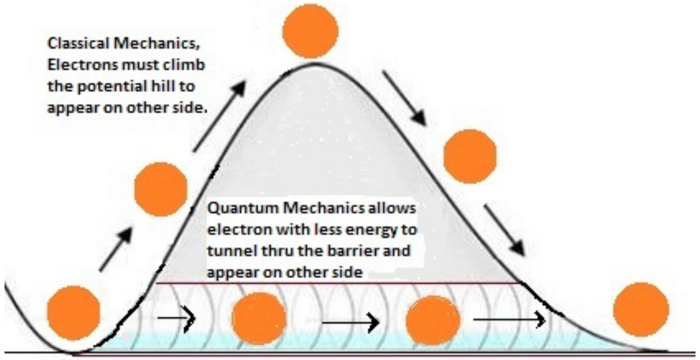


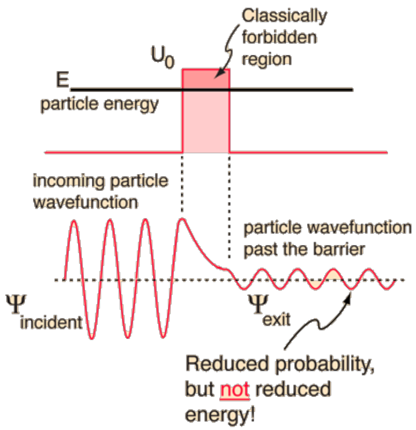



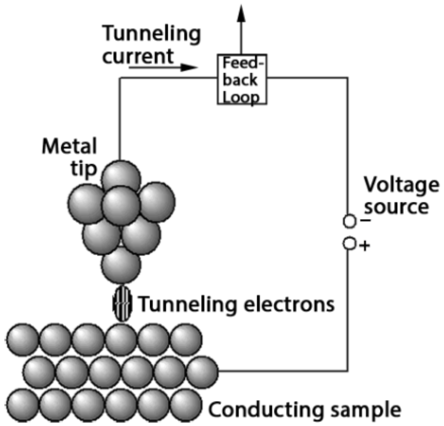
# Some new quantum resources for technology

3. Quantum **tunneling**:

- Quantum particles can travel through energetically forbidden regions due to uncertainty in their position.
- For example, the tunneling of electrons is used in a scanning tunneling microscope (STM) to probe the surface of a material.



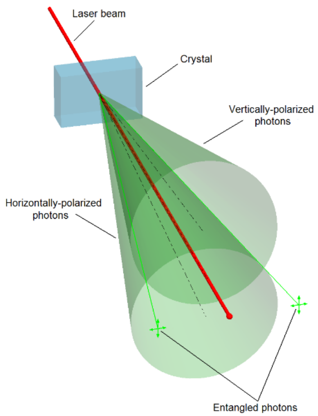



# Some new quantum resources for technology

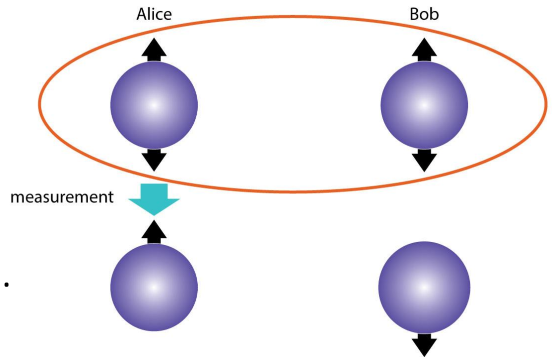
4. Quantum **entanglement**:

- Parts of a quantum system can be more **strongly correlated** than what is classically possible.
- Some operation on one part of a system can also change the other parts.
- For example, the entanglement of photon polarization can be used for secure communication between two parties ("Alice" and "Bob").

Pairs of entangled photons can be produced by shooting a laser at a nonlinear crystal.

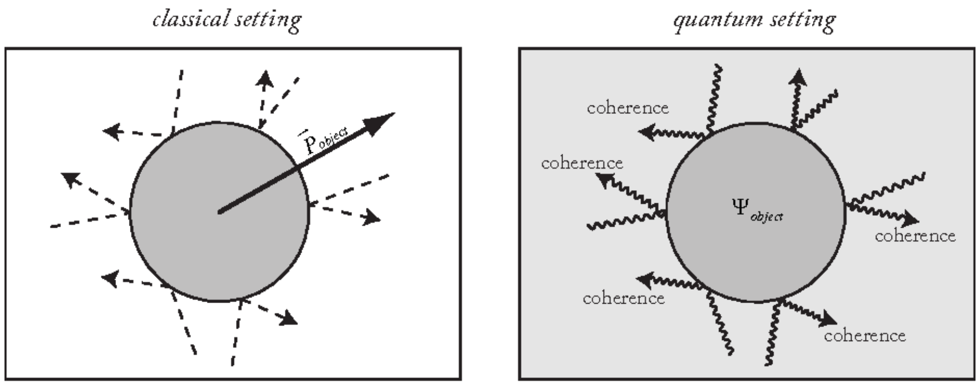



When Alice measures her photon's polarization, the quantum superposition collapses, and also Bob's photon's polarization is fixed.



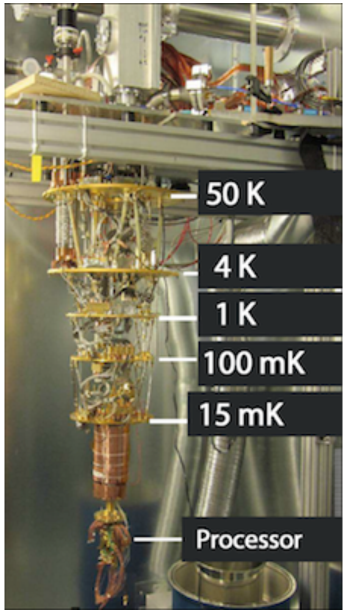
# The challenges of quantum technology

- Quantum states are **extremely delicate**. Weak interaction with the environment entangles the system with the environment and tends to destroy coherence.
- E.g., the longest achieved lifetime of a physical qubit state about $50 - 100\ \mu\mathrm{s}$.
- Quantum states must be protected from the environment: high vacuum, low temperature, quantum error correction,…




$$\vec{P}_{object} \to \vec{P}_{object} + \langle \Delta \vec{p}_{photons} \rangle = \vec{P}_{object}$$

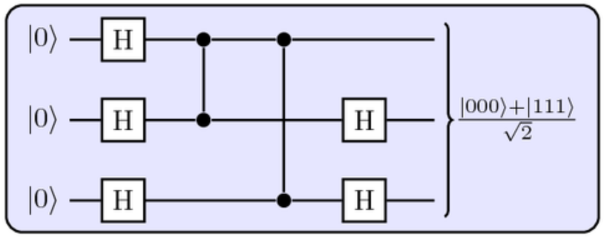
$$\Psi_{object} \to \Phi_{object+photons} \neq \Psi_{object} \otimes \Phi_{photons}$$



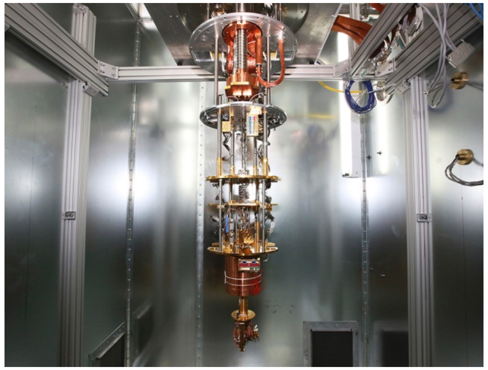
# The many faces of quantum technology

**Quantum computing:**

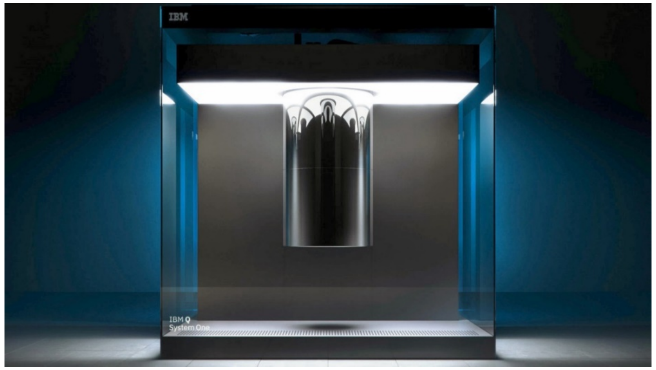
- Application of quantum systems to solve computational tasks
- Several big companies (IBM, Microsoft, Intel,…) and startups (IQM, D-Wave,…) involved
  https://en.wikipedia.org/wiki/List_of_companies_involved_in_quantum_computing_or_communication
- Work to be done both on the hardware and the software
- Today, IBM's 20-qubit processor is the largest universal quantum computer (that I know of)
- IBM predicts quantum computers to surpass classical computers in some tasks in 5 years




a quantum circuit schematic



D-Wave systems quantum annealer



IBM Q quantum processor