Quantum Training :

Quantum algorithms for quantum computation and simulation

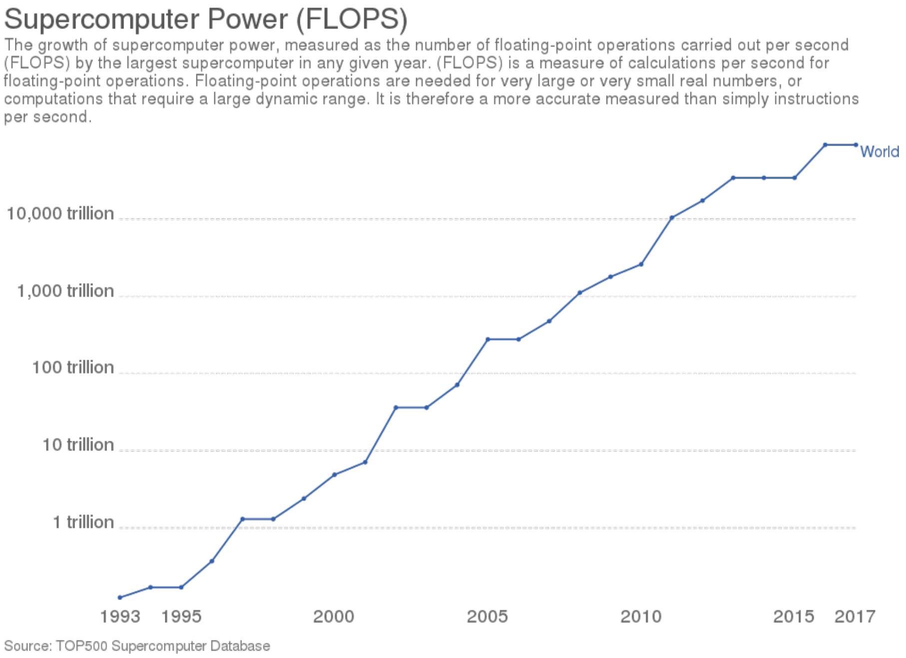
Benoit.vermersch@lpmmc.cnrs.fr
bvermersch.github.io

TPs with Nicolas Roch
Nicolas.roch@neel.cnrs.fr

Modern supercomputers

Exponential rise of supercomputer power

→ we may reach soon technological/financial/environmental barriers

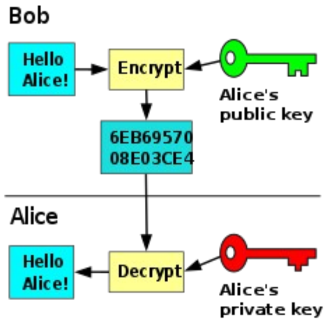


Rank	Rmax Rpeak (PFLOPS)	Name	Model
1 ▲	415.530 513.855	Fugaku	Supercomputer Fugaku
2 ▼	148.600 200.795	Summit	IBM Power System AC922
3 ▼	94.640 125.712	Sierra	IBM Power System S922LC
4 ▼	93.015 125.436	Sunway TaihuLight	Sunway MPP

Fugaku: 1 billion USD...

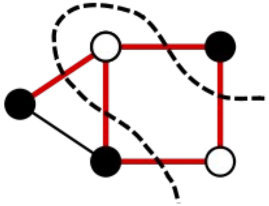
Some tough problems for computers

Integer factorization

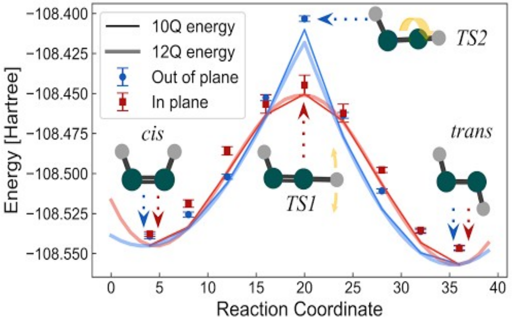


Database search

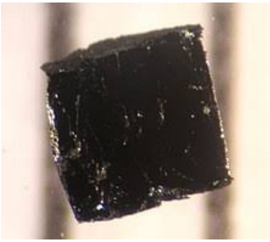
Optimization problems



Quantum chemistry



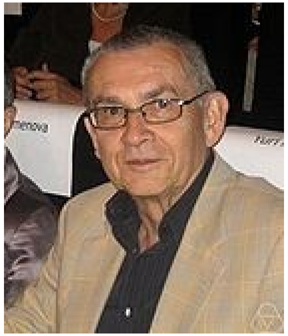
Strongly correlated quantum materials



What is a quantum computer ?

Paul Benioff

Richard Feynman



Yuri Manin

David Deutsch

A quantum machine that could imitate any quantum system, including the physical world

Why can a quantum computer be powerful?

1 classical bit

$$|\psi\rangle = |0\rangle$$
$$|\psi\rangle = |1\rangle$$

1 quantum bit (qubit)

$$|\psi\rangle = c_0 |0\rangle + c_1 |1\rangle$$

N classical bits

$$|\psi\rangle = |00000000\rangle$$

$$\updownarrow$$

$$|\psi\rangle = |11111111\rangle$$

2^N configurations

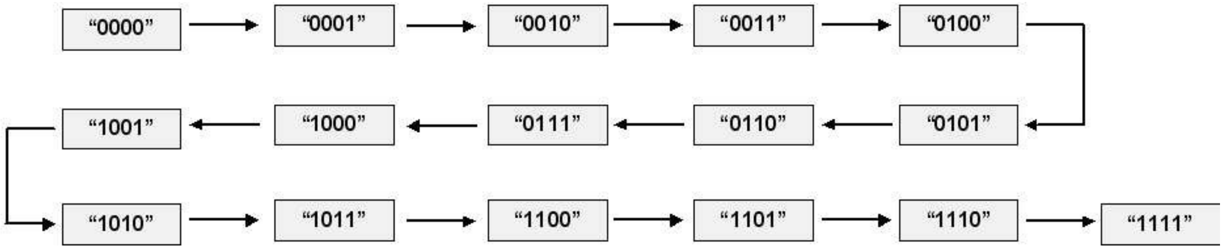
N qubits

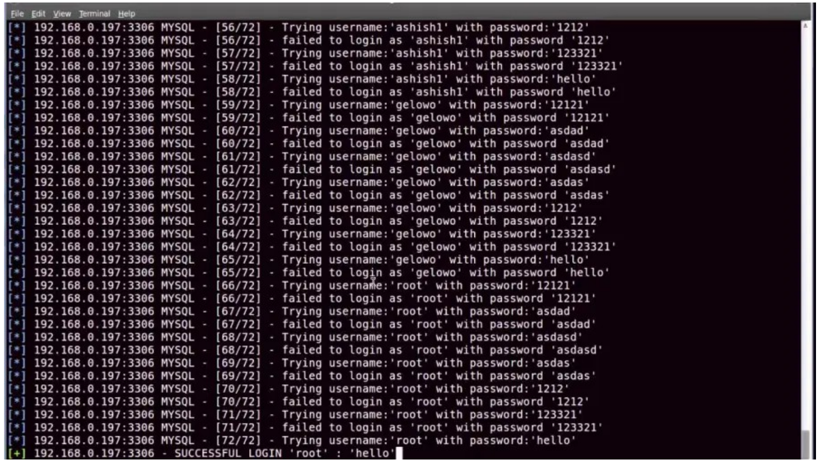
$$|\psi\rangle = c_0 |00000000\rangle + \cdots + c_{2^N-1} |11111111\rangle$$

2^N configurations
‘simultaneously’

The power of quantum parallelism

Example : brute force attack on 4 bit keys





Complexity : $O(2^N)$

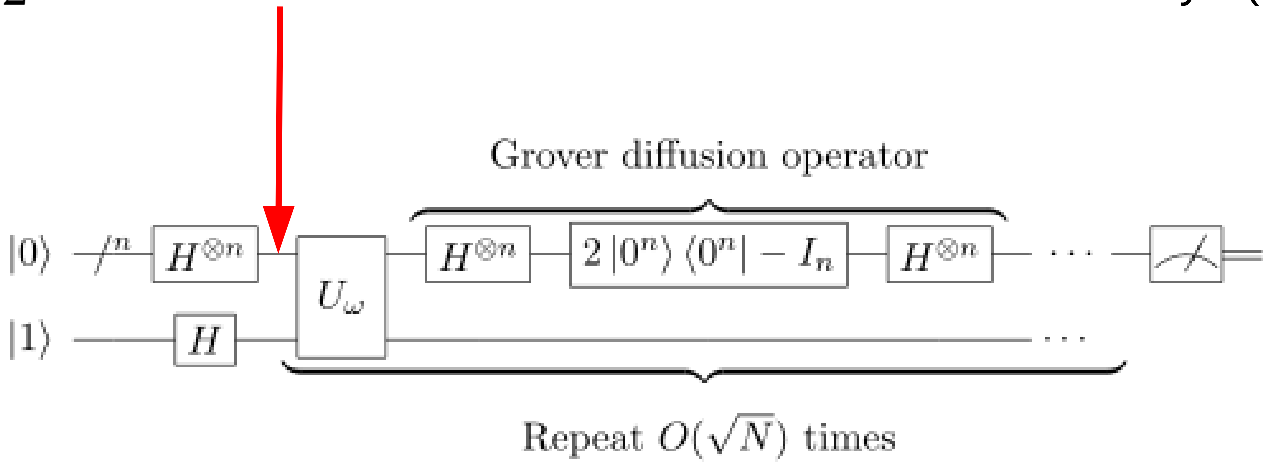
Credit : EE-Times

The power of quantum parallelism

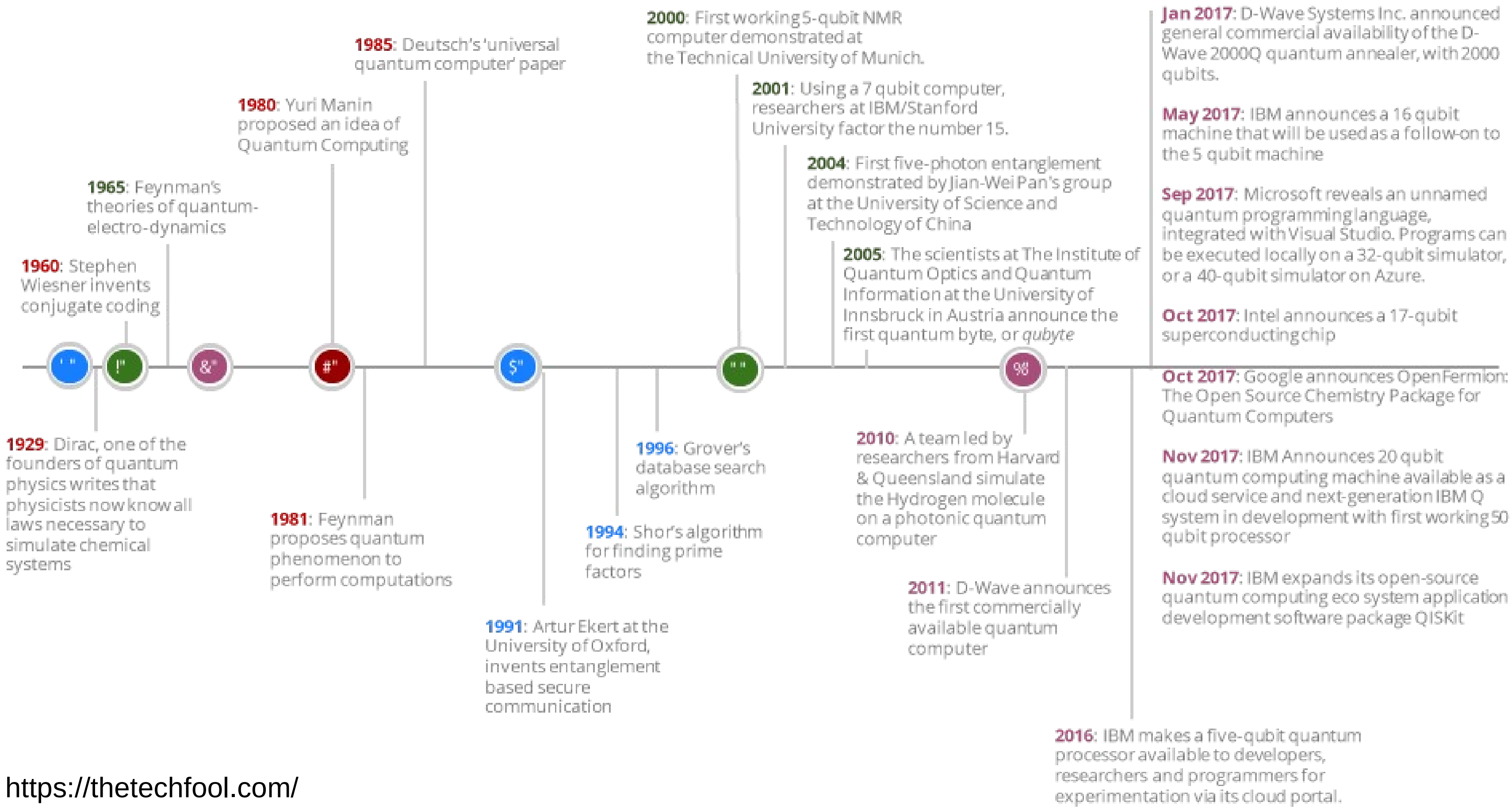
The quantum way

$$|s\rangle = \sqrt{\frac{1}{2^N}}\left(|0000\rangle + \cdots + |1111\rangle\right)$$

Grover's algorithm : We test all states simultaneously ! (see lecture 2)



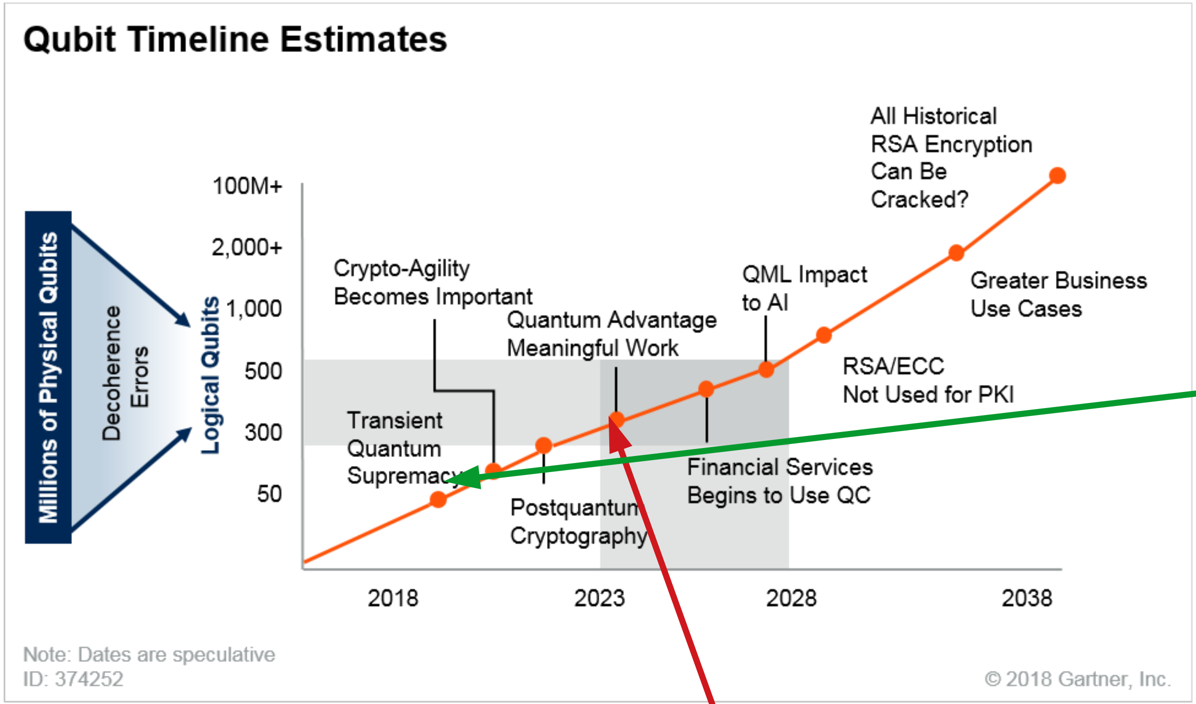
The first era of quantum computing

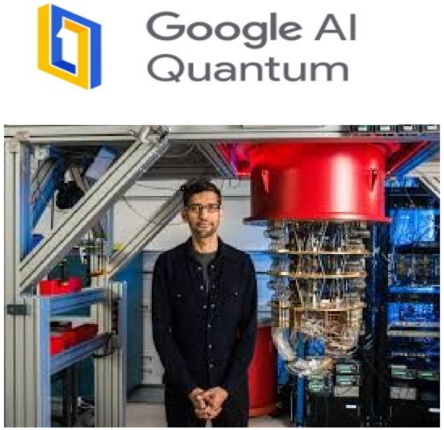


Credit: https://thetechfool.com/

The NISQ Era and beyond (2018-)

NISQ : noisy intermediate scale quantum

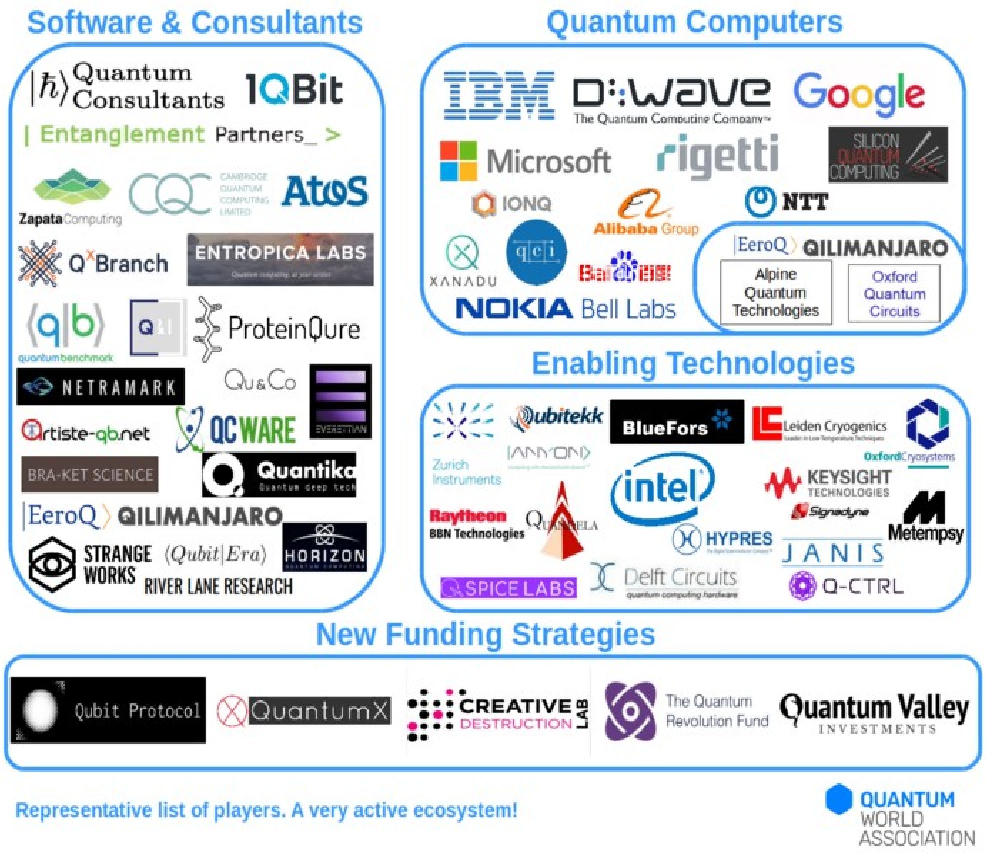


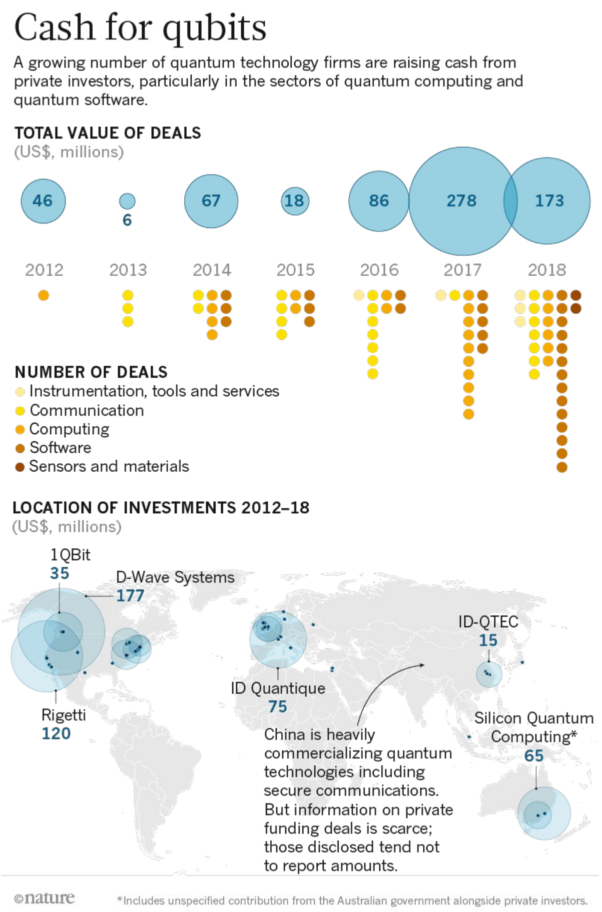


See lecture 4

The new challenge...

The NISQ Era and beyond (2018-)

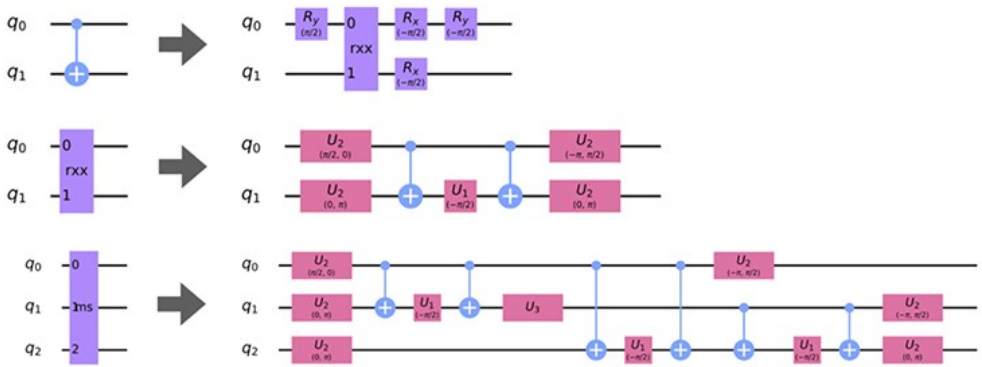




Quantum softwares

Qiskit
Elements for building a quantum future

Cirq



→ **TPs with Nicolas Roch**

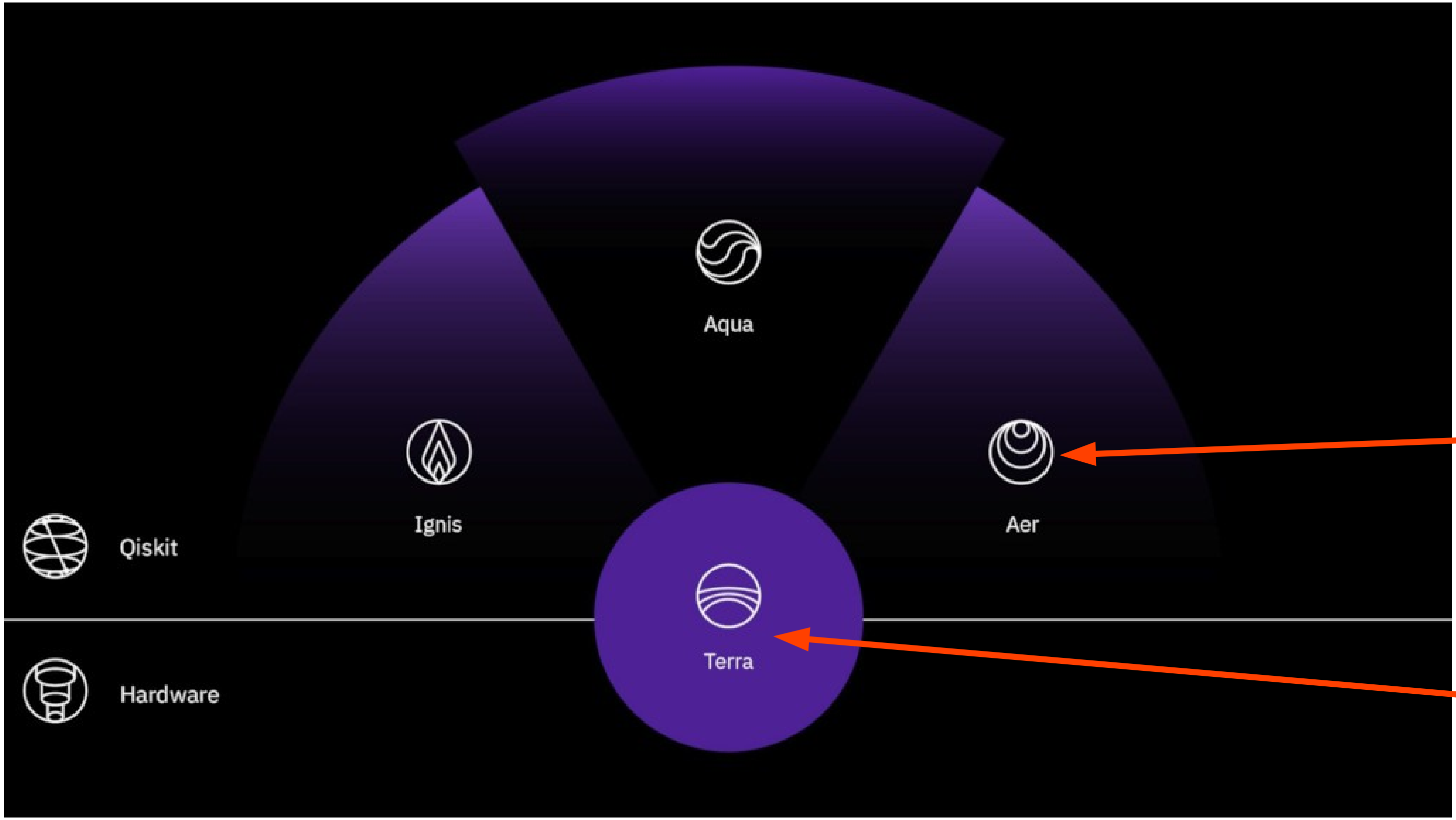
```
[23] circuit = cirq.Circuit()
     circuit.append(basic_circuit())
     print(circuit)

(0, 0): ───X^0.5───@───X^0.5───M('alpha')───
                   │
(0, 1): ───X^0.5───@───X^0.5───M('beta')────

[24] from cirq import Simulator
     simulator = Simulator()
     result = simulator.run(circuit)
     print(result)

alpha=0
beta=1
```

Qiskit architecture



« Simulator »

Includes
quantum hardware
(TPs with N. Roch)

Outline

Wednesday 23/09 2pm-3.30pm, room Amphi Mag MdM	Lecture 1 (all students) Benoit Vermersch, Quantum bits, quantum gates
Wednesday 30/09 2pm-3.30pm, room Amphi Mag MdM	Lecture 2 (all students) Benoit Vermersch, Quantum algorithms
Wednesday 07/10 2pm-4pm, room Amphi Mag MdM	**Group 1:** Nicolas Roch, Implementation on simulators and quantum computers: 1
Wednesday 07/10 2pm-4pm, room Mag1 MdM	**Group 2:** Benoit Vermersh, Implementation on simulators and quantum computers: 1
Wednesday 07/10 4pm-6pm, room Amphi Mag MdM	**Group 3:** Nicolas Roch, Implementation on simulators and quantum computers: 1
Wednesday 21/10 2pm-4pm, room Amphi Mag MdM	**Group 1:** Nicolas Roch, Implementation on simulators and quantum computers: 2
Wednesday 21/10 2pm-4pm, room Mag1 MdM	**Group 2:** Benoit Vermersh, Implementation on simulators and quantum computers: 2
Wednesday 21/10 4pm-6pm, room Amphi Mag MdM	**Group 3:** Nicolas Roch, Implementation on simulators and quantum computers: 2
Wednesday 04/11 2pm-3.30pm, room Amphi Mag MdM	Lecture 3 (all students) Benoit Vermersch, Quantum error correction codes
Wednesday 18/11 2pm-4pm, room Amphi Mag MdM	**Group 1:** Nicolas Roch, Implementation on simulators and quantum computers: 3
Wednesday 18/11 2pm-4pm, room Mag1 MdM	**Group 2:** Benoit Vermersh, Implementation on simulators and quantum computers: 3
Wednesday 18/11 4pm-6pm, room Amphi Mag MdM	**Group 3:** Nicolas Roch, Implementation on simulators and quantum computers: 3
Wednesday 25/11 2pm-3.30pm, room Amphi Mag MdM	Lecture 4 (all students) Benoit Vermersch, Quantum Optimization/Simulation - Quantum advantage
Wednesday 02/12 2pm-4pm, room Amphi Mag MdM	**Group 1:** Nicolas Roch, Implementation on simulators and quantum computers: 4
Wednesday 02/12 2pm-4pm, room Mag1 MdM	**Group 2:** Benoit Vermersh, Implementation on simulators and quantum computers: 4
Wednesday 02/12 4pm-6pm, room Amphi Mag MdM	**Group 3:** Nicolas Roch, Implementation on simulators and quantum computers : 4
Wednesday 09/12 2pm-6pm, room Amphi Mag, MdM	Exam (all students): Oral presentations by the students

Useful references

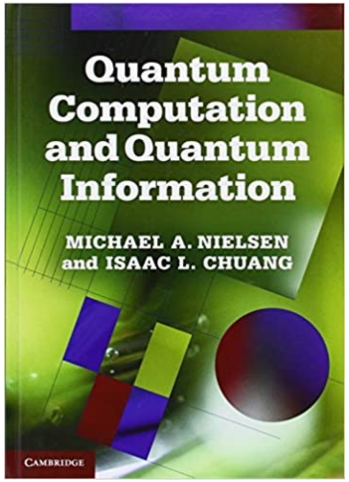
- **Quantum computation and quantum information**

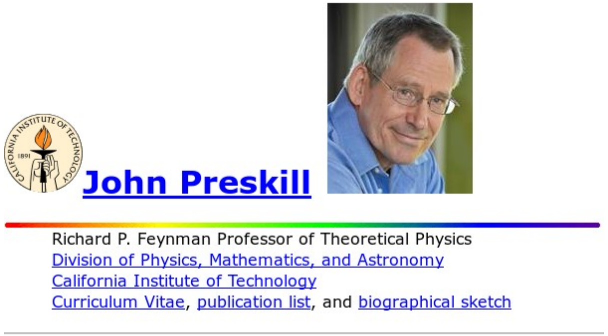
  (Nielsen and Chuang)

- **John Preskill’s quantum information course:** http://theory.caltech.edu/~preskill/ph219/index.html

- **Quantum world II** (Zoller and Gardiner)

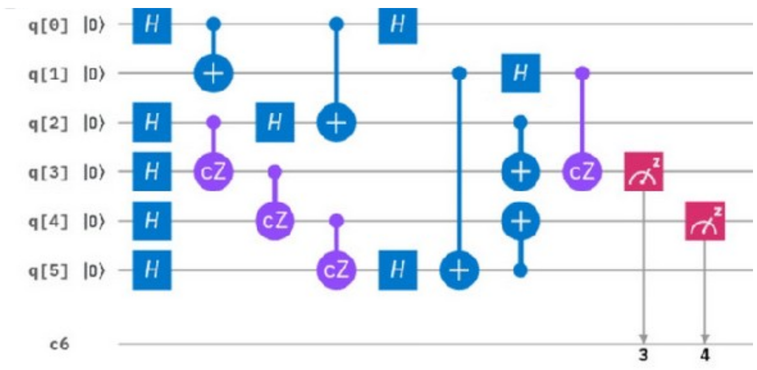
- **Surface code** : https://arxiv.org/abs/1208.0928





Lecture 1 : Quantum Circuits

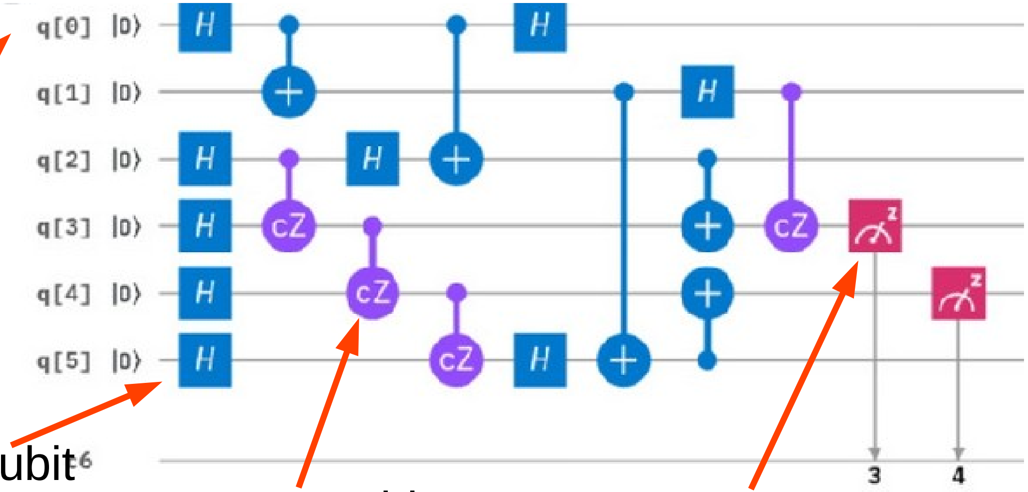
- Presentations of a quantum circuit
- Single qubit : structure and operation (gates)
- Multi-qubit case : Universal set of gates
- The Measurement
- Physical realizations



What is a quantum circuit ?

A quantum circuit executes the most common type of **quantum algorithms**

Qubits



Single qubit gate

Two-qubit gate

Measurement

time

There exists other types! e.g., quantum annealing/analog quantum simulation (see Lecture 4)

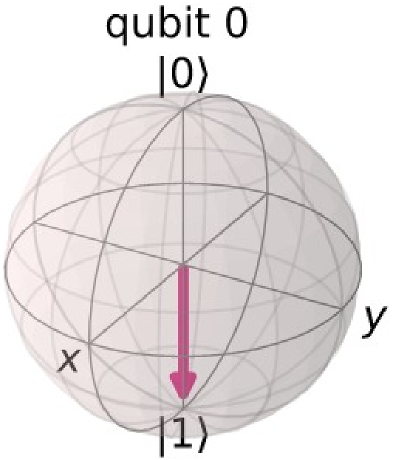
Single qubit : structure and operation (gates)

A qubit is a two-level quantum system (e.g., a two-level atom)

$$|\psi\rangle = c_0\,|0\rangle + c_1\,|1\rangle = \begin{bmatrix} c_0 \\ c_1 \end{bmatrix}$$

The state of a pure single qubit state can be represented by a Bloch vector **on the Bloch sphere**

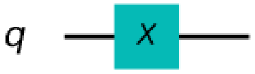
$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + \sin\left(\frac{\theta}{2}\right)e^{i\phi}\,|1\rangle$$



Classical bits are limiting cases of a qubit

Single qubit gates

A single qubit gate converts a single qubit state to another single qubit state

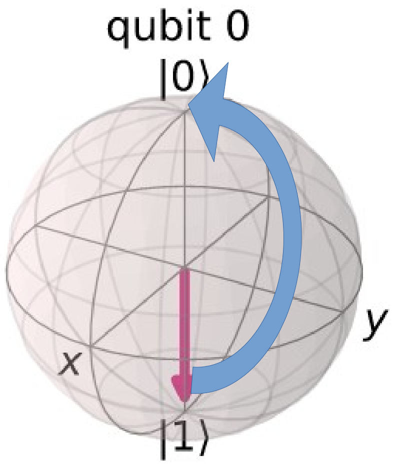


$$|\psi'\rangle = X\,|\psi\rangle$$

It is described by a unitary 2x2 matrix

$$UU^{\dagger} = 1$$

Or, equivalently, by a rotation on the Bloch sphere



Important Single qubit gates

Pauli-X (X)	$-\boxed{\mathbf{X}}-$	$-\oplus-$	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)	$-\boxed{\mathbf{Y}}-$		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)	$-\boxed{\mathbf{Z}}-$		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)	$-\boxed{\mathbf{H}}-$		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)	$-\boxed{\mathbf{S}}-$		$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)	$-\boxed{\mathbf{T}}-$		$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$

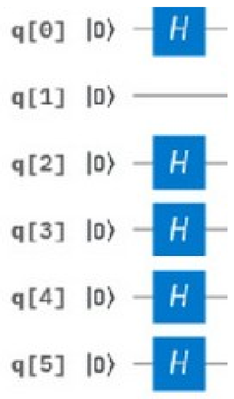
Question: How can I create an equal-weight superposition state from the logical state |0> ?

Concatenation: from left to right

Multi-qubit case

Single qubit gates can act on parallel in a tensor product space

$$|0\rangle\,|0\rangle\,|0\rangle\,|0\rangle\,|0\rangle\,|0\rangle \rightarrow H\,|0\rangle\,|0\rangle\,H\,|0\rangle\,H\,|0\rangle\,H\,|0\rangle\,H\,|0\rangle$$



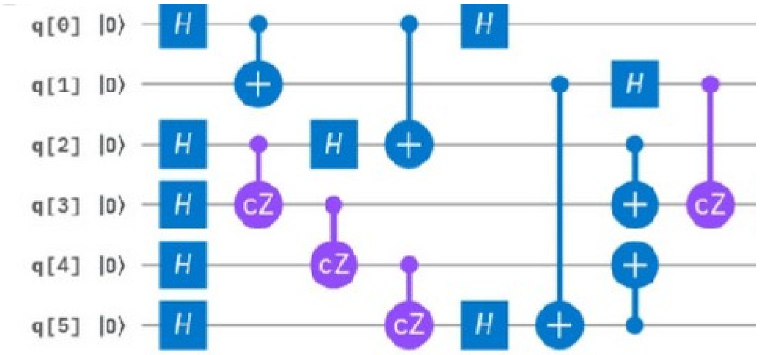
However, for a **universal quantum computer**, every global unitary operation of the 2^Nx2^N Hilbert space must be available

→ **Entangling operations required**

Multi-qubit case

Deutsch (1989):

A universal quantum computer can be realized with a set of single qubit and two qubit gates

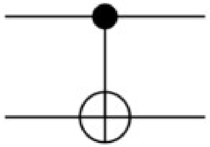


The number of gates required to realize a certain operation is not necessarily small

Efficient algorithms are the one that a require polynomial number of gates

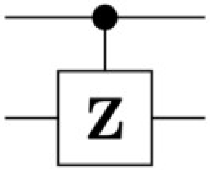
Important two-qubit gates

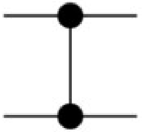
Controlled Not (CNOT, CX)



$$\begin{array}{cccc} |00\rangle & |01\rangle & |10\rangle & |11\rangle \\ \end{array}$$
$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Controlled Z (CZ)





$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

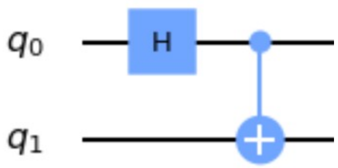
CNOT: Flip the target qubit iff the control qubit is 1

CZ: minus sign if both qubits are 1

Two qubit gates generate entanglement

Creation of a Bell state

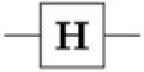
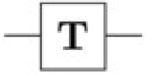
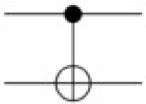
Two ingredients: Hadamard and CNOT



$$|0\rangle\,|0\rangle \rightarrow \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)\,|0\rangle \rightarrow \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

We have created a maximally entangled state!

Universal set of gates

Hadamard (H)		$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$
Phase (S, P)		$\begin{bmatrix}1 & 0\\ 0 & i\end{bmatrix}$
$\pi/8$ (T)		$\begin{bmatrix}1 & 0\\ 0 & e^{i\pi/4}\end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix}$

This set is not unique

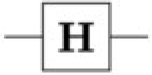
With one set, I can reach any state up to arbitrary accuracy

Note: phase gate is optional here (but convenient)

Universal set of gates (example)

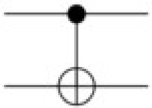
Build a CZ gate from a CNOT gate and two Hadamard gates

Hadamard (H)



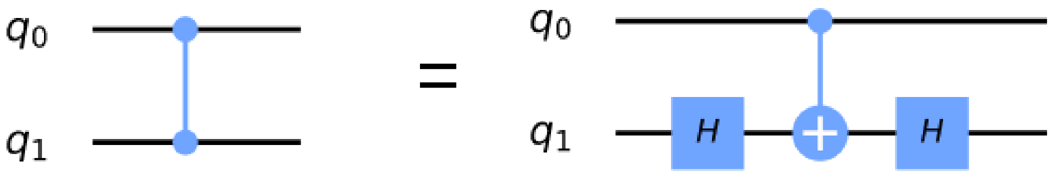
$$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$$

Controlled Not (CNOT, CX)



$$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix}$$

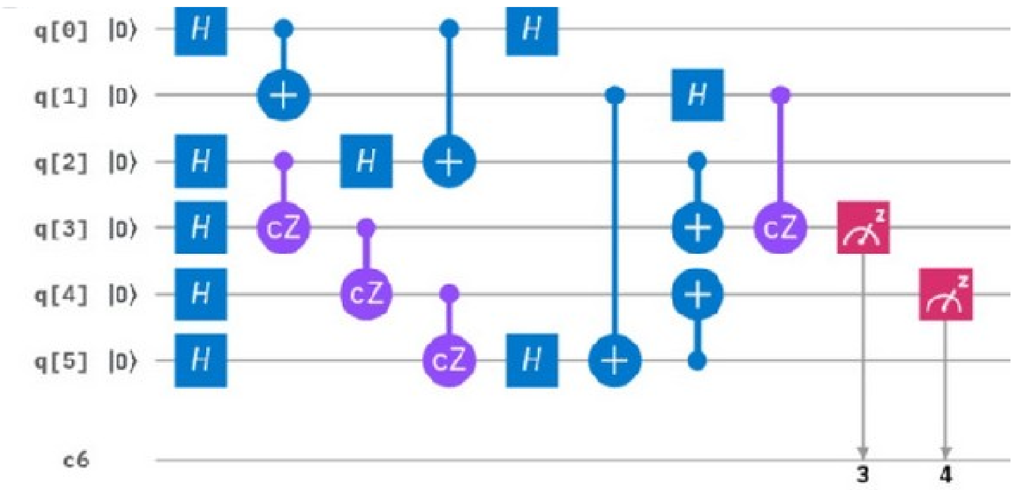
Idea : Change of basis from the Hadamard : $HXH = Z$



Exercice : Check the identity

Measurement

The measurement is often the last step of a quantum circuit



Mapping of quantum states to classical information (classical registers)

Very crucial step (readout errors)

Quantum operations based on measurement outcomes are possible (ex: error correction lecture 3)

Measurement

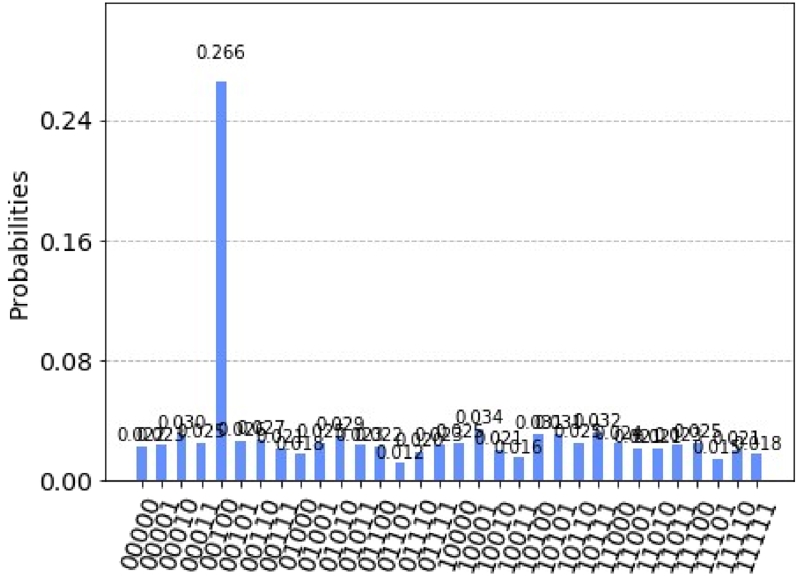
A measurement is described by a set of n measurement outcomes $(a_i)_{i=1,n}$

A quantum state is measured (and projected) in the state $|a_i\rangle$ with probability $|\langle a_i|\psi\rangle|^2$

In a quantum circuit, measurements in the `computational basis',

Histogram obtained after 1024 repetitions of the circuit

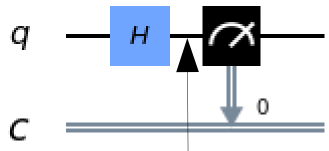
$$|\langle s|\psi\rangle|^2$$



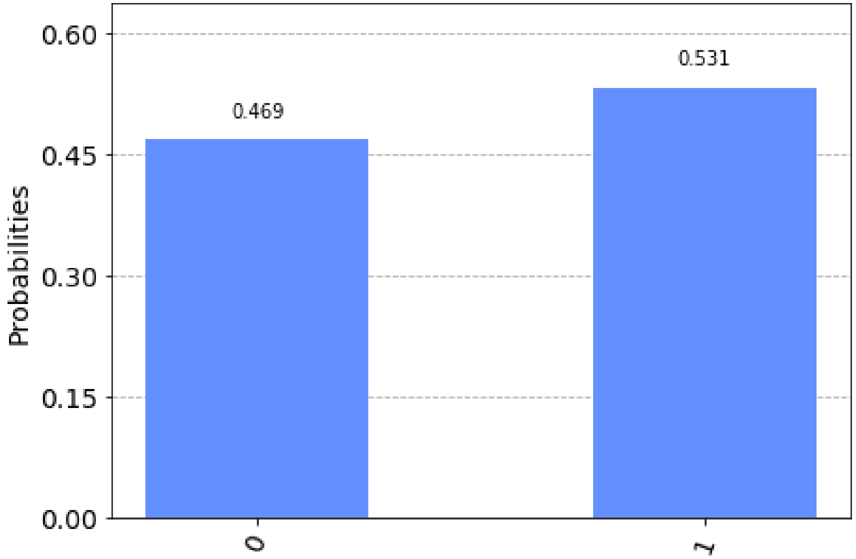
Bit string s

Measurement (examples)

Measurement of **a superposition state** (in the computational basis)



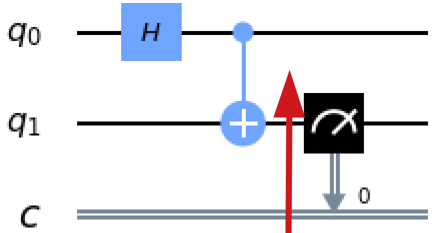
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$



A single shot is not generically sufficient to characterize a quantum state
A single measurement basis is also not always sufficient

Measurement (examples)

Non-destructive measurement (very important for the next lectures..)

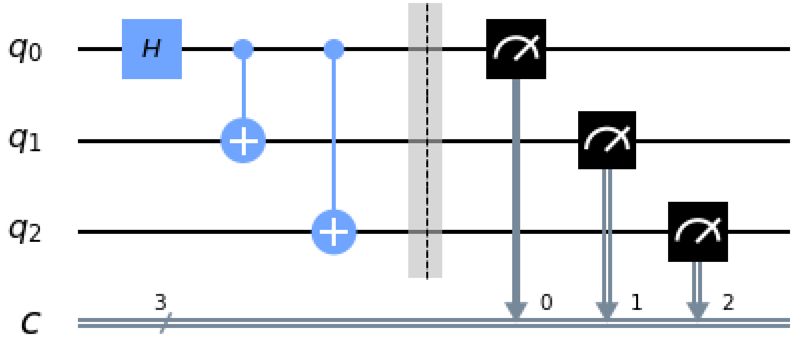


Question :
What is the final state of the first qubit q0 ???

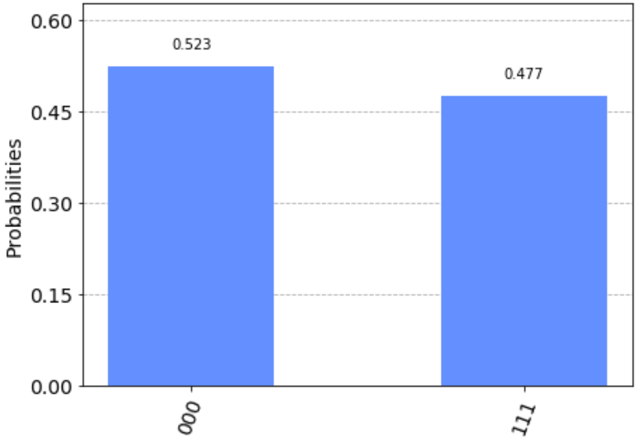
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$ Bell state

Measurement (examples)

Full measurement of a multi qubit state in the computational basis

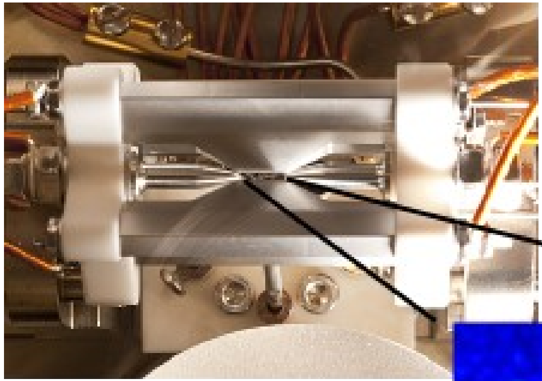


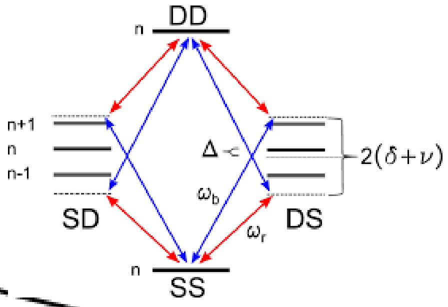
Can you make sense of this measurement statistics ?

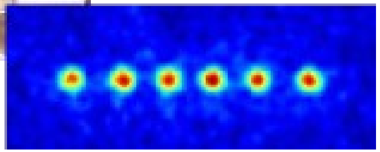


Entertainment : Real quantum computers

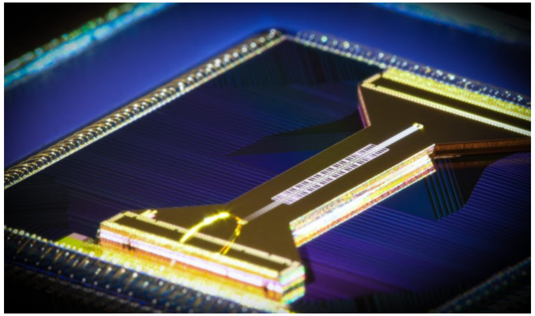
Ion traps







University of Innsbruck



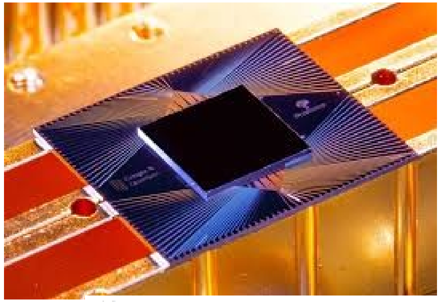
Honeywell

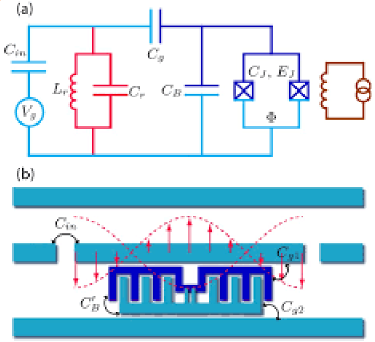
The physics of these devices can be understood from atomic physics and quantum optics

Entertainment : Real quantum computers

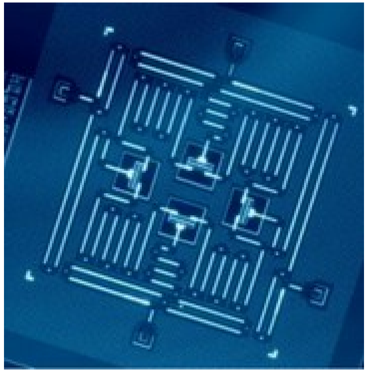
Superconducting quantum circuits

IBM Q





Google AI Quantum



The physics of these devices can be understood from solid-state physics and quantum optics

Many other platforms : NMR qubits, silicon qubits, Rydberg atoms

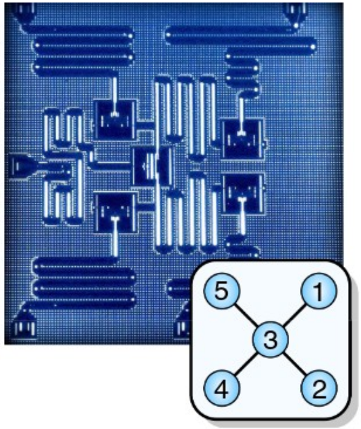
Grenoble is an important place: N. Roch, O. Buisson, T. Meunier, M. Vinet,.. https://quantum.univ-grenoble-alpes.fr/

Real quantum computers

Performances

Table 2. Summary of the achieved success probabilities for the implemented circuits, in percentages

Connectivity	Star shaped			Fully connected		
Hardware	Superconducting			Ion trap		
Success probability/%	Obs	Rand	Sys	Obs	Rand	Sys
Margolus	74.1(7)	82	75	90.1(2)	91	81
Toffoli	52.6(8)	78	59	85.0(2)	89	78
Bernstein–Vazirani	72.8(5)	80	74	85.1(1)	90	77
Hidden shift	35.1(6)	75	52	77.1(2)	86	57



Experimental Comparison of Two Quantum Computing Architectures," N. M. Linke, D. Maslov, M. Roetteler, S. Debnath, C. Figgatt, K. A. Landsman, K. Wright, C. Monroe, Proc. Natl. Acad. Sci. 114, 13 (2017).

Performance : Remarquable exprimental progressess, quantum computers do exist (since 2005)!

Speed : 1 Hz for trapped ions, ~10 kHz for superconducting circuits

Summary Lecture 1

- **Quantum circuits** are an architecture for developing quantum algorithms
- Basic ingredients : **qubits**, single qubit **gates** and two qubit gates (sufficient for universal quantum computation), and **measurement**
- **Different physical platforms** can now implement quantum circuits : trapped ion, superconducting quantum circuits, etc