13e Journées Informatiques IN2P3/IRFU, 15-17 nov. 2021

L'informatique quantique :
préparer l'avenir à l'IN2P3 ?

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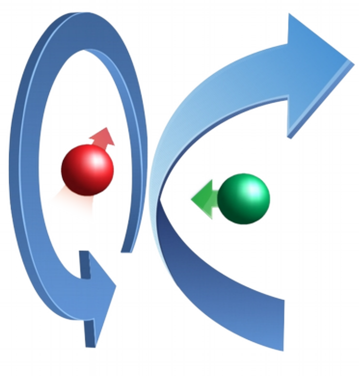
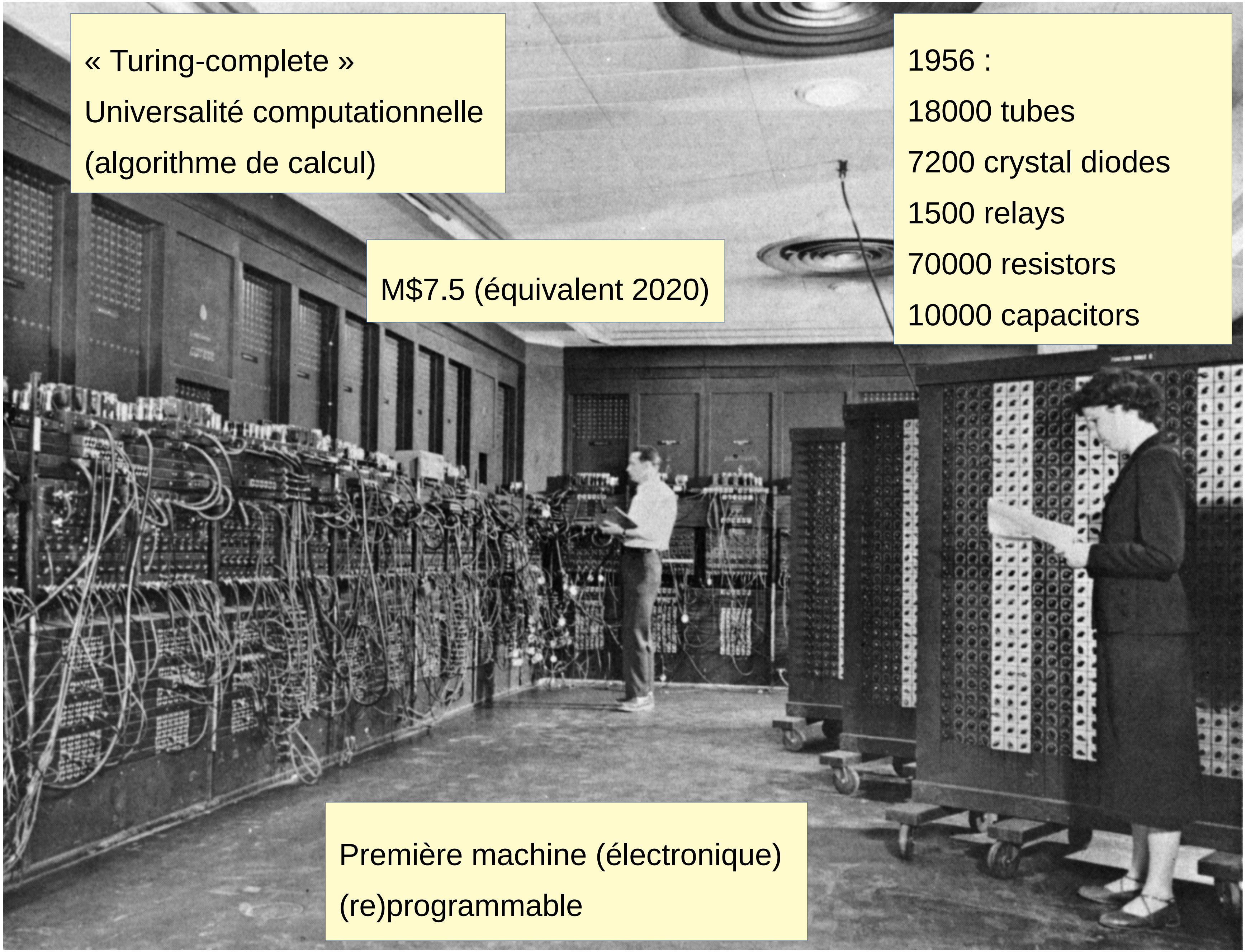
Laboratoire de Physique de Clermont



ENIAC ~1950



« Turing-complete »

Universalité computationnelle

(algorithme de calcul)

M$7.5 (équivalent 2020)

1956 :

18000 tubes

7200 crystal diodes

1500 relays

70000 resistors

10000 capacitors

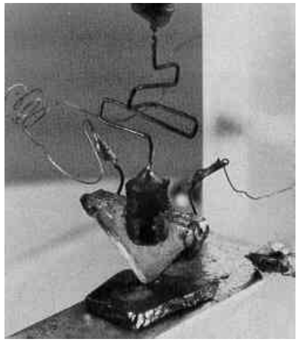
Première machine (électronique)

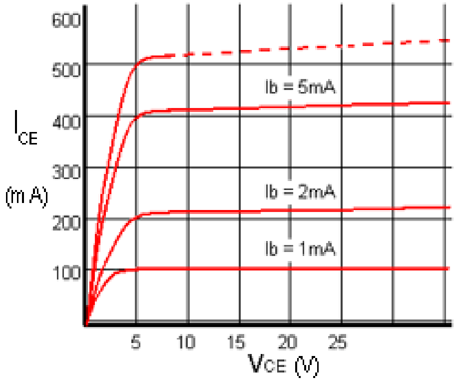
(re)programmable

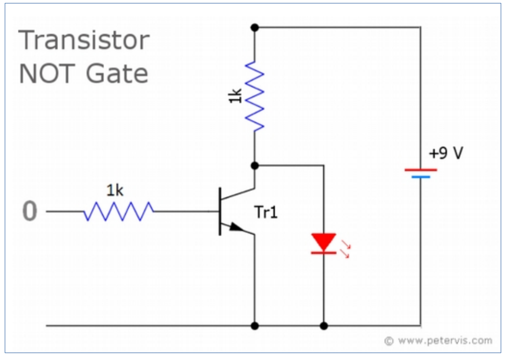
Source : Wikipedia

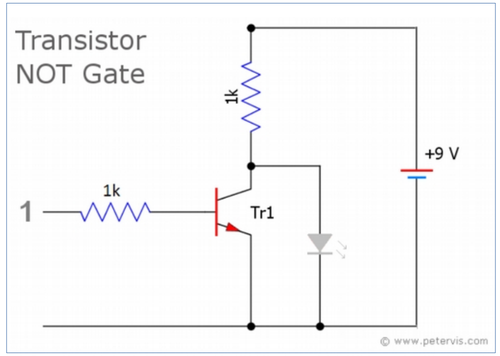
L'ordinateur classique = opérations Booleenes

Bell Labs, 1948









NOT

AND

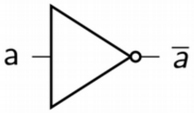
OR

XOR

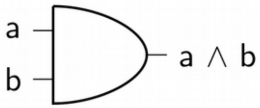
NAND

NOR

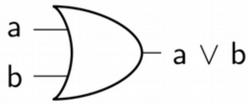
FANOUT



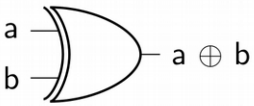
a	$\bar{a}$
0	1
1	0



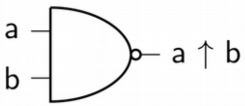
a	b	$a \wedge b$
0	0	0
0	1	0
1	0	0
1	1	1



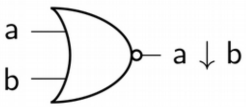
a	b	$a \vee b$
0	0	0
0	1	1
1	0	1
1	1	1



a	b	$a \oplus b$
0	0	0
0	1	1
1	0	1
1	1	0



a	b	$a \uparrow b$
0	0	1
0	1	1
1	0	1
1	1	0



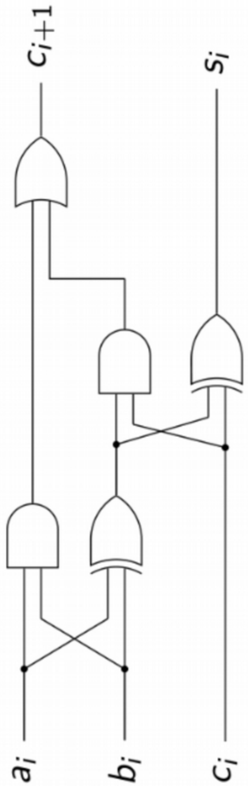
a	b	$a \downarrow b$
0	0	1
0	1	0
1	0	0
1	1	0

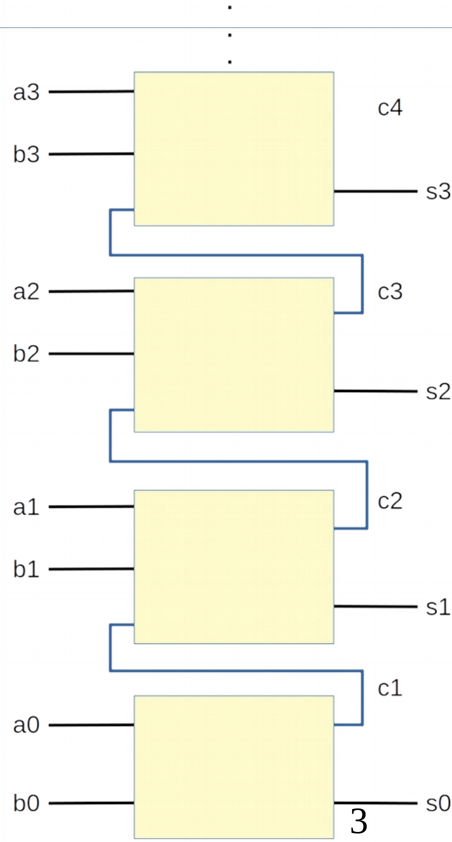
Addition ⇒

somme

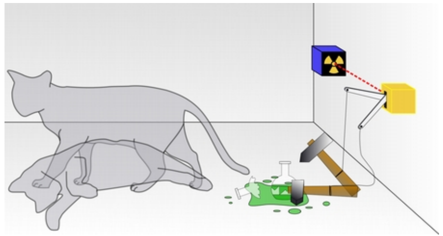
avec bit

de transport



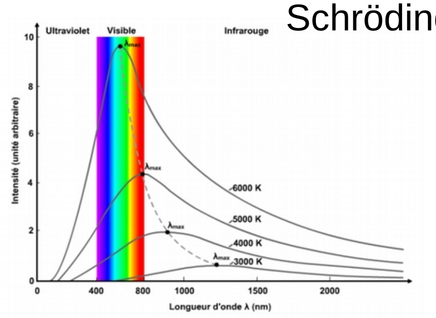


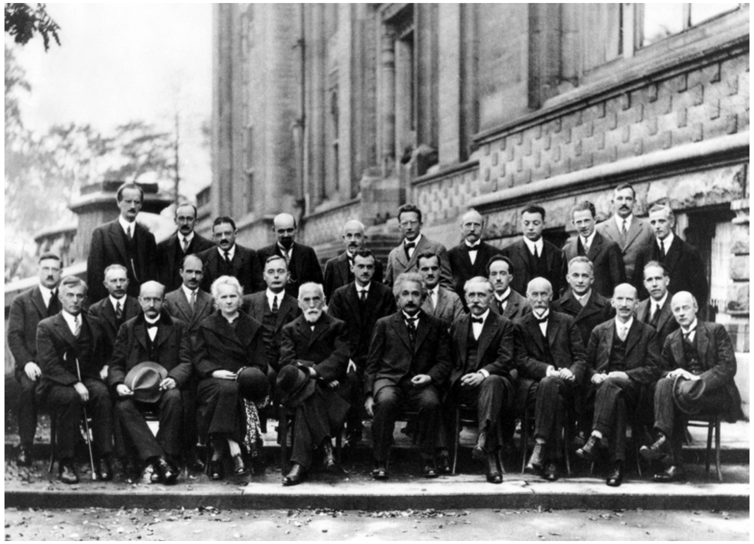
Phénomène quantique = paradoxe classique ?



Schrödinger, 1935

Planck, 1900





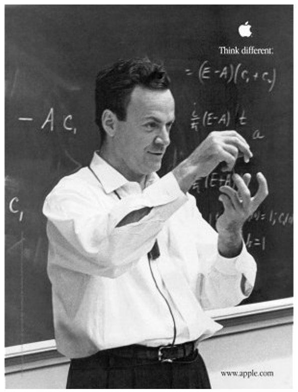
Solvay, 1927

Oui, le monde quantique existe et se gouverne selon ses propres lois.

La **mécanique quantique** est la théorie pour décrire ces phénomènes.

$$i\hbar \frac{d}{dt} |\psi(t)\rangle = H |\psi(t)\rangle$$

Les calculs de mécanique quantique = algèbre linéaire dans des espaces à hautes dimensions (inversion de matrices, vecteurs propres, valeurs propres, …, O(exp(N)).



Quantum Mechanical Computers

By Richard P. Feynman

Introduction

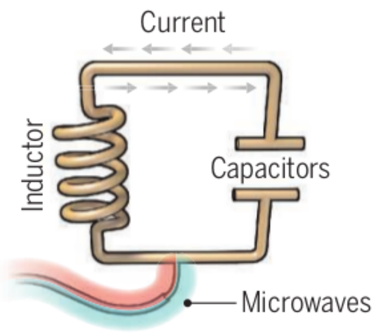
This work is a part of an effort to analyze the physical limitations of computers due to the laws of physics. For example, Bennett[1] has made a careful study of the free energy such. We see we really have two more logical primitives, FAN OUT when two wires are connected to one, and EXCHANGE, when wires are crossed. In the usual computer the NOT and NAND primitives are implemented by transistors, possibly as in Fig. 2. could be stored in an inductance, or other reactive element.

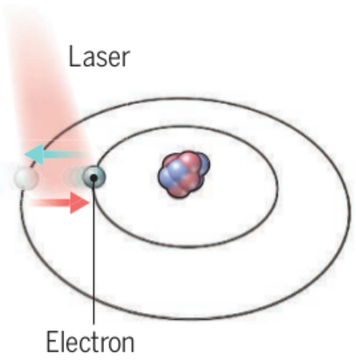
However, it is apparently very difficult to make inductive elements on silicon wafers with present techniques. Even Nature, in her DNA copying machine, dissipates about 100 kT per bit

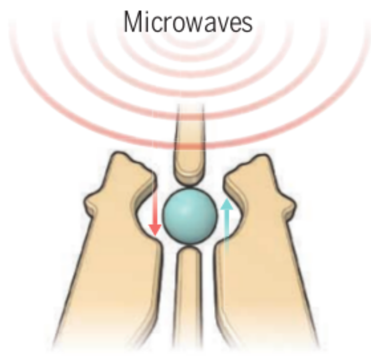
1985

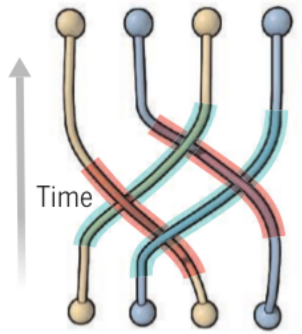
« What we have done is only to try to imitate as closely as possible the digital machine of conventional sequential architecture. »

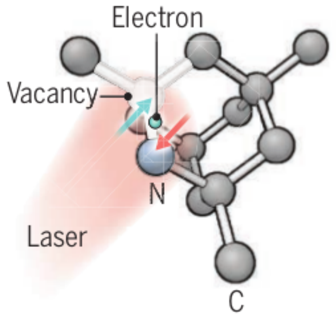
Comment utiliser un système quantique pour implémenter des <u>primitives de calcul réversibles</u> (qubit = 0 et 1 quantique).











	Superconducting loops	**Trapped ions**	**Silicon quantum dots**	**Topological qubits**	**Diamond vacancies**
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
⊕ **Pros**	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
⊖ **Cons**	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

Gabriel Popkin, Quest for Qubits, in Science Magazine, December 2016

L’ordinateur quantique :

entre universalité computationnelle et suprématie de calcul

- calcul classique universel ⇨ $f_i : \{0,1\}^n \rightarrow \{0,1\}, \qquad (i = 1, 2, ..., m)$
- utiliser le **continuum** des états des qubits (Feynman)

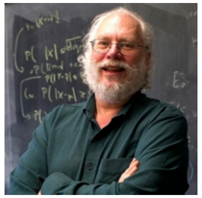
$$|\psi\rangle = \alpha\ |0\rangle + \beta\ |1\rangle$$

a	a_2	a_1	a_0	$f(a)$
$a^{(1)} = 1$	0	0	1	1
$a^{(2)} = 3$	0	1	1	1
$a^{(3)} = 6$	1	1	0	1
$a^{(4)} = 0$	0	0	0	0
$a^{(5)} = 2$	0	1	0	0
$a^{(6)} = 4$	1	0	0	0
$a^{(7)} = 5$	1	0	1	0
$a^{(8)} = 7$	1	1	1	0

$$f^{(1)} = \bar{a}_2 \wedge \bar{a}_1 \wedge a_0$$
$$f^{(2)} = \bar{a}_2 \wedge a_1 \wedge a_0$$
$$f^{(3)} = a_2 \wedge a_1 \wedge \bar{a}_0$$

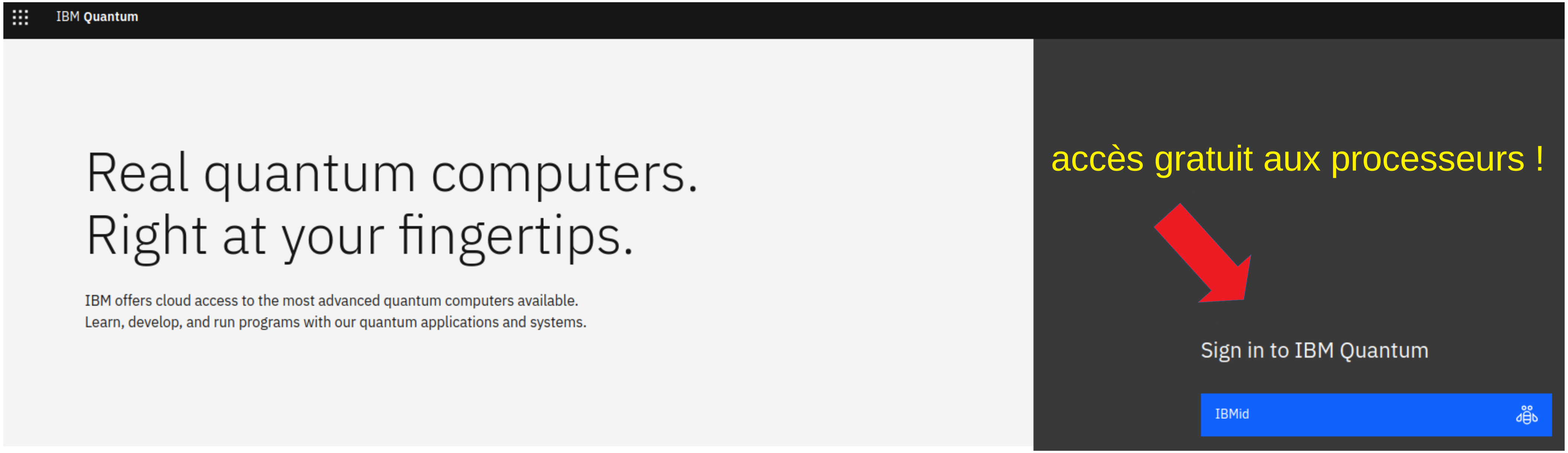
$$f(a) = f^{(1)}(a) \vee f^{(2)}(a) \vee f^{(3)}(a)$$

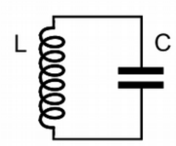
- **superposition**
- **interférence**
- **intrication**
- algorithmes quantiques :
  - Deutsch-Josza, 1992 (quantum-facile et classique-difficile, exponentiel)
  - Grover 1996 (quantum search, O(√N) versus O(N))
  - Shor, 1994 (factorisation d’un nombre entier, ~ exponentiel, RSA !)
  - cryptographie quantique



Processeurs quantiques chez IBM Quantum

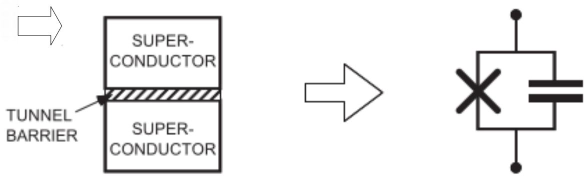
https://quantum-computing.ibm.com/



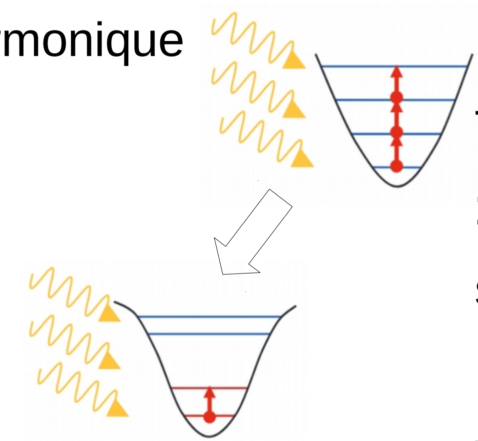


$$H = \frac{\Phi^2}{2L} + \frac{Q^2}{2C}$$

oscillateur harmonique



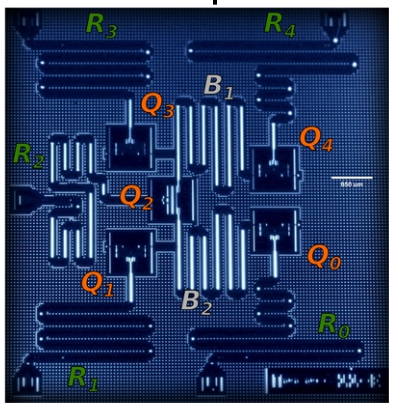
La jonction Josephson introduit une non-linéarité dans les niveaux d'énergie (par l'effet tunnel).



qubit

Température : **15mK**, en régime supra-conducteur. Domaine des fréquences : ~**GHz** (micro-ondes).

ibmqx2



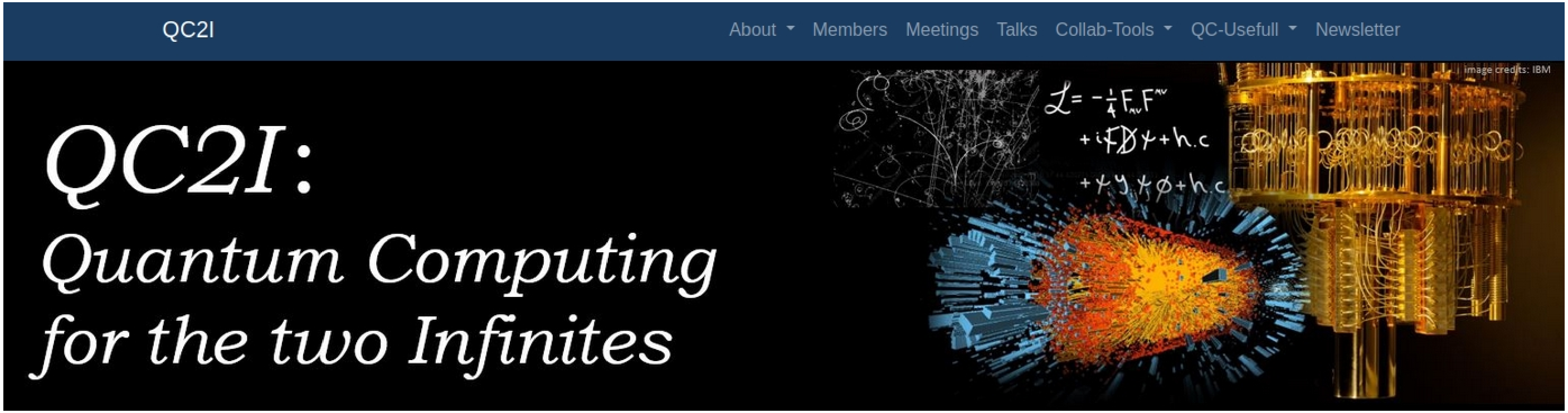
Les technologies quantiques en France (CNRS, autres)

- Centre de Nanosciences et Nanotechnologies (C2N, Paris-Saclay)
- Laboratoire Photonique, Numérique & Nanosciences (LP2N, Bordeaux)
- Laboratoire Matériaux et Phénomènes Quantiques (MPQ, Paris)
- CEA (Paris-Saclay, Grenoble)
- Laboratoire Charles Fabry (Paris-Saclay)
- Institut de Physique de Nice
- Institut de Physique du College de France (Paris)
- Institut de Recherche en Informatique Fondamentale (IRIF, Paris)
- Institut Néel (Grenoble)
- Laboratoire Kastler Brossel (Paris)

GDR IQFA (Ingénierie Quantique, de Fondements aux Applications), depuis 2010

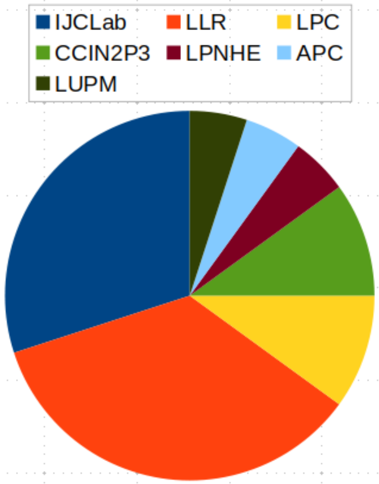
Quantum Computing et l'IN2P3

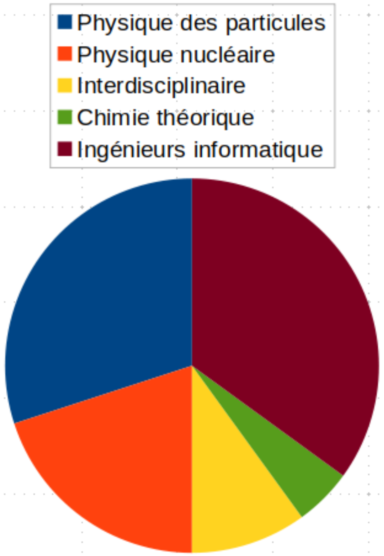
https://qc.pages.in2p3.fr/web/



(depuis janvier 2021)

QC2I = ~20 membres

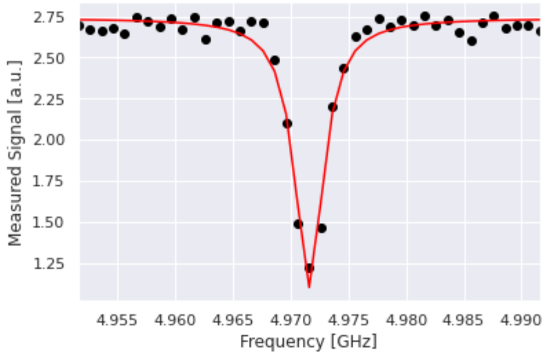




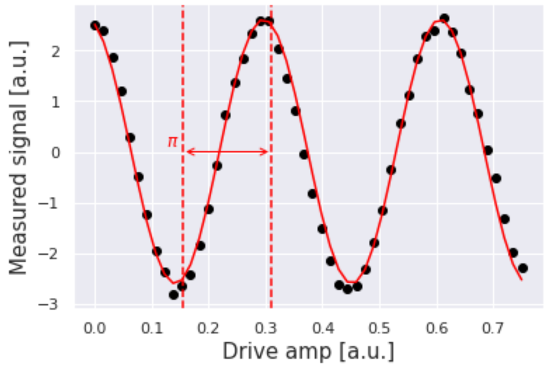
- physique nucléaire : solutions quantiques pour les problèmes à N-corps (exp(N))
- quantum machine learning
- préparer la révolution quantique
- les technologies ?

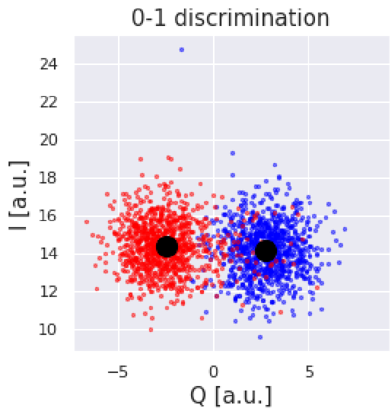
Atelier « hands-on » sur le processeur à 1-qubit de IBM

Courbe de résonance



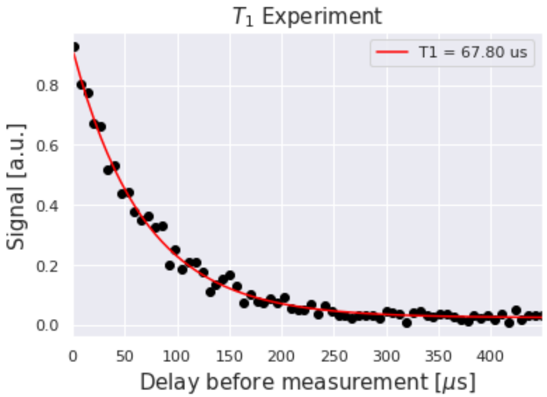
Expérience Rabi



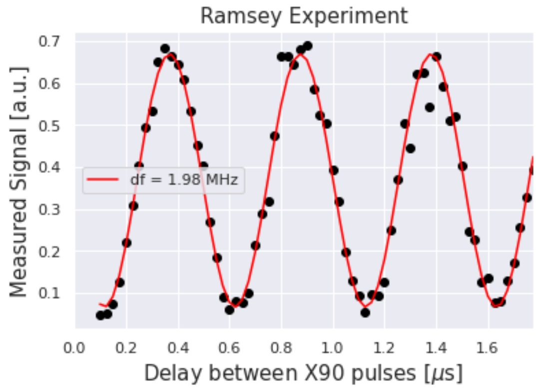


Sélection et discrimination des états 0 et 1

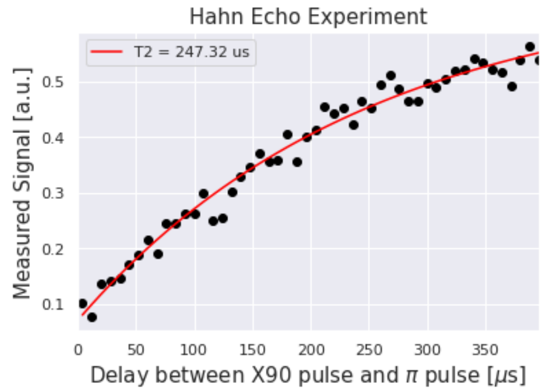
Relaxation longitudinale



Expérience Ramsey

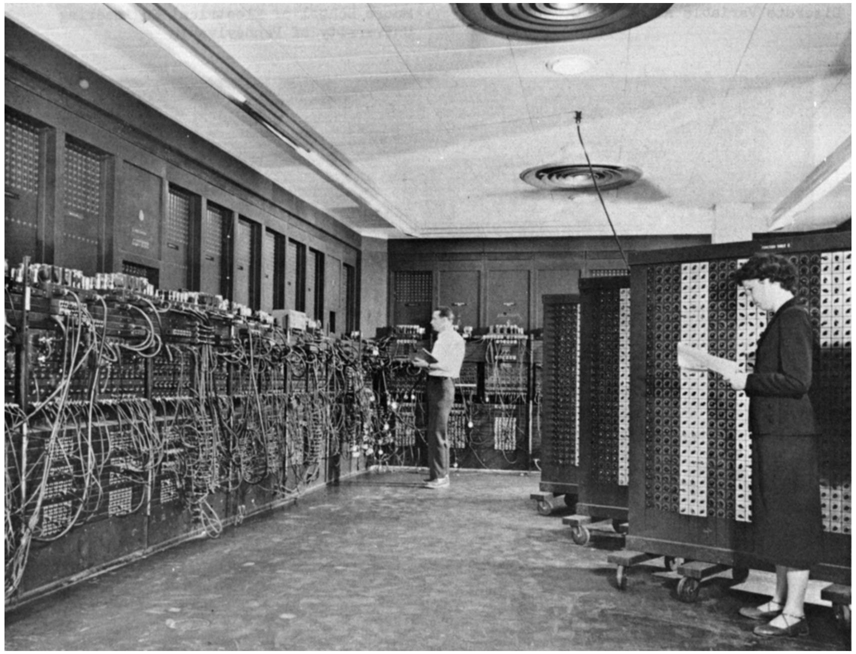


Relaxation transversale



(découvrir le hardware du qubit IBM, Qiskit, notebooks Jupyter)

ENIAC ~1950



IBM ~2020

?