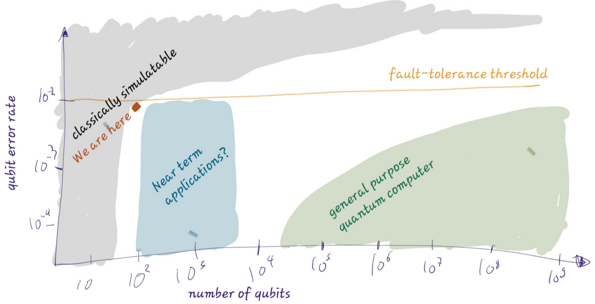
Quantum computing

QC2I project

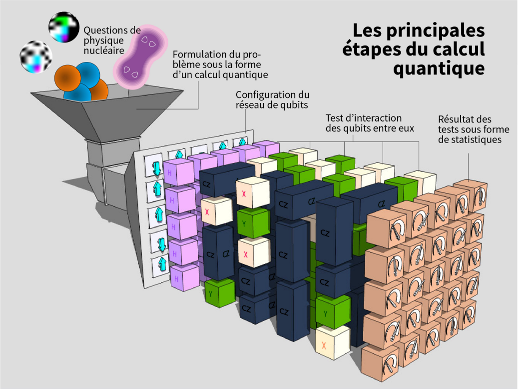
Denis Lacroix (IJCLab)

Depuis 80 ans, nos connaissances bâtissent de nouveaux mondes

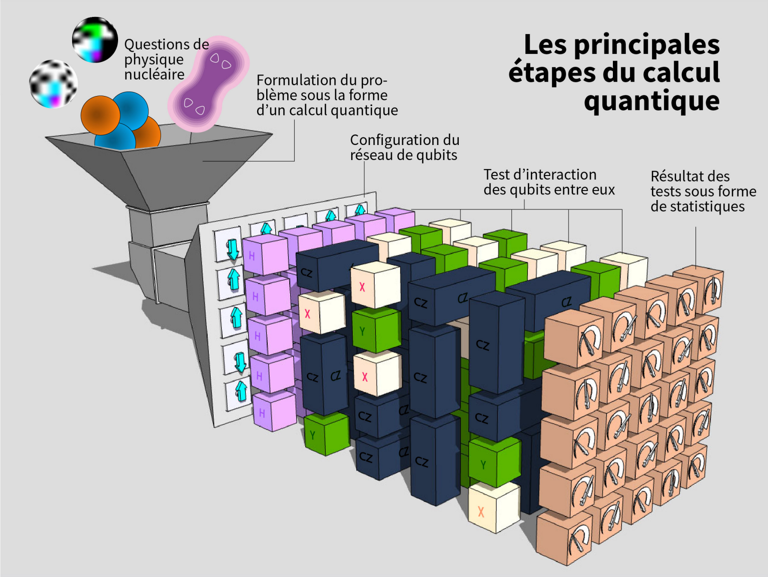
Current status and opportunities



Discussion on ongoing projects in complex many-body systems



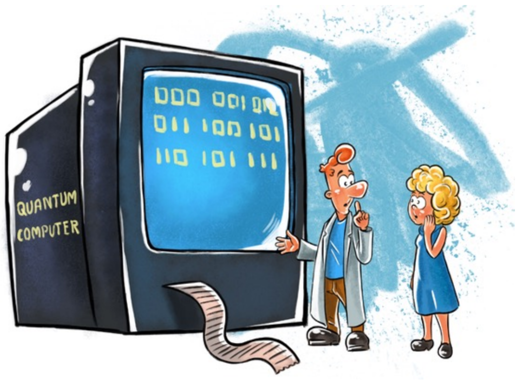
(I) WHY QUANTUM COMPUTING? (and WHY NOW?)



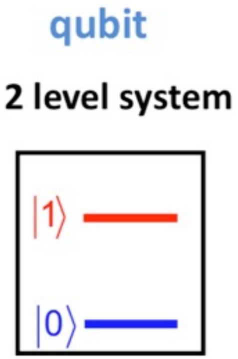
Short introduction to bit versus Qubits

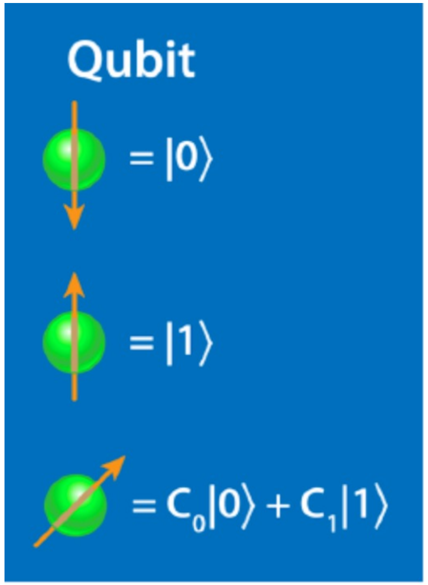
Classical computers
Works with bits

Quantum computers with
Quantum bits



Qubits can be seen
As two-level systems





Bits are only 0 or 1

A single Qubit can be any superposition of 0 and 1

Obvious advantage

Imagine you want to simulate where 0 appears with a probability p_0 and 1 appears with a probability p_1. On a classical computer, you do many events and average over events. On a quantum computer 1 single simulation is necessary (but many measurements).

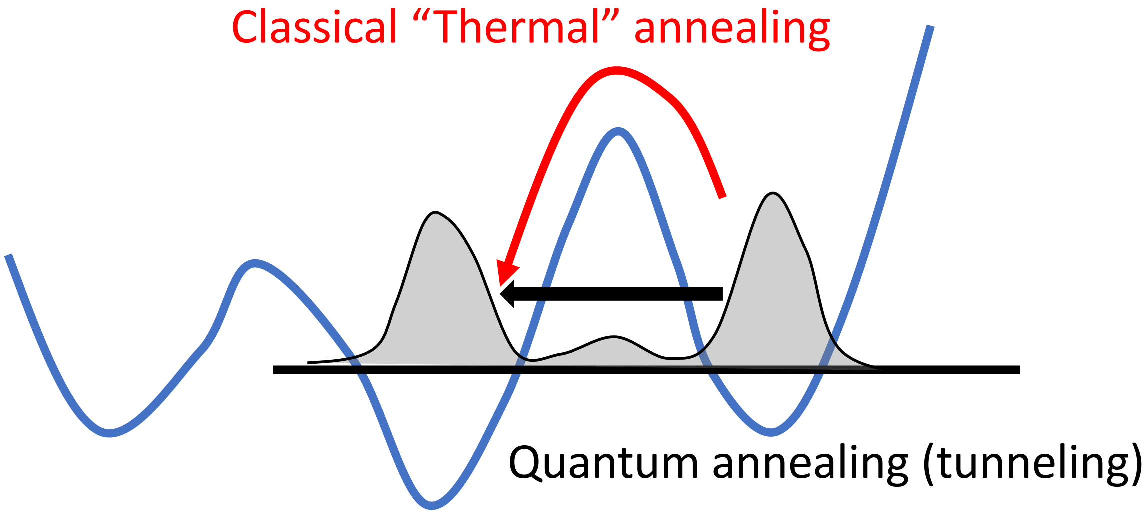
And with many
Qubits

New aspects can be used like quantum interference and entanglement

Short introduction to bit versus Qubits

Illustration of quantum advantages

Quantum Tunneling and quantum annealing



Quantum entanglement

Assume two persons (Alice and Bob)

The humor of A&B are encoded in the wave-function

$$|\Phi\rangle = \alpha|\overset{\overset{A}{\Downarrow}}{😀}\overset{\overset{B}{\Downarrow}}{😀}\rangle + \beta|\overset{\overset{A}{\Downarrow}}{😫}\overset{\overset{B}{\Downarrow}}{😫}\rangle$$

Suppose I measure Bob 😀 ➡ 😀

😫 ➡ 😫

I can measure partial info and get the full info

The info is destroyed after measurement

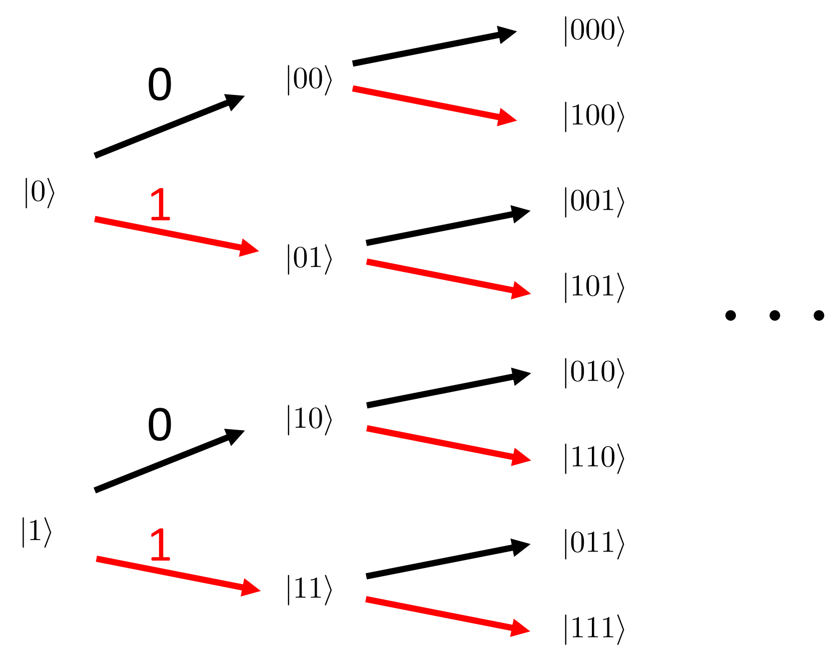
Hilbert Space dimention with qubits

Illustration of quantum advantages

Systems described on qubits

$$|\Psi\rangle = \sum_{s_i=0,1} \Psi_{s_1,\cdots,s_N}|s_1,\cdots,s_n\rangle$$

1 qubit **2 qubit** **3 qubit** . . .

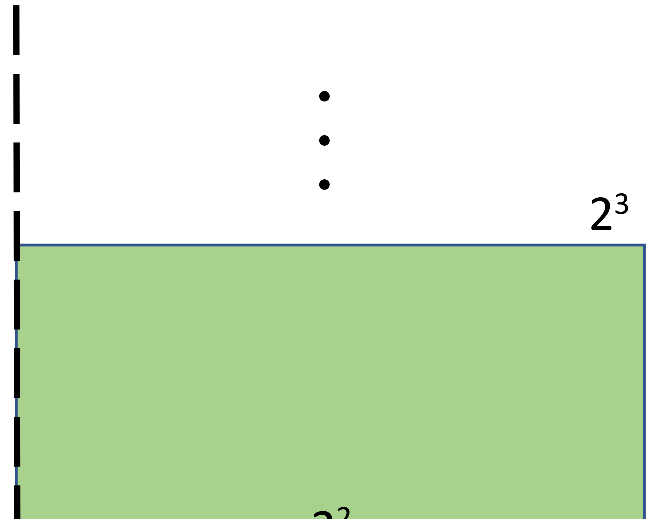

$|0\rangle$ 0 $|00\rangle$ $|000\rangle$ $|100\rangle$

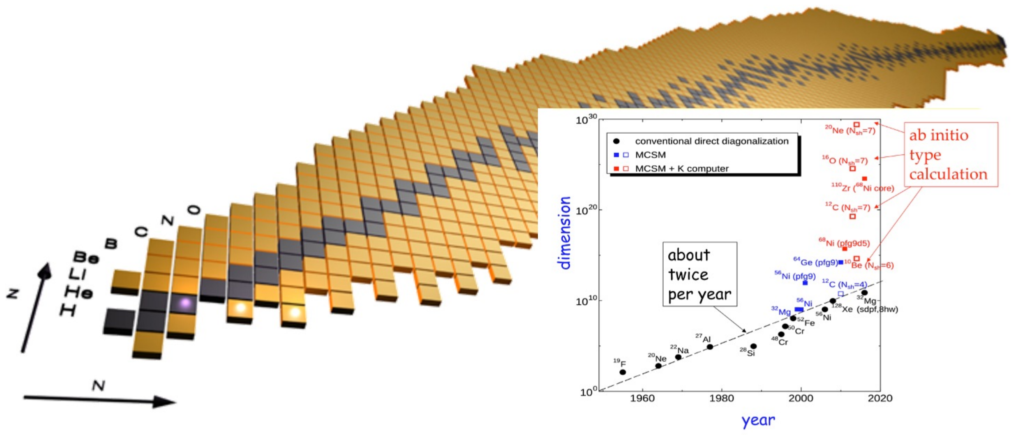
1 $|01\rangle$ $|001\rangle$ $|101\rangle$

$|1\rangle$ 0 $|10\rangle$ $|010\rangle$ $|110\rangle$

1 $|11\rangle$ $|011\rangle$ $|111\rangle$

. . .



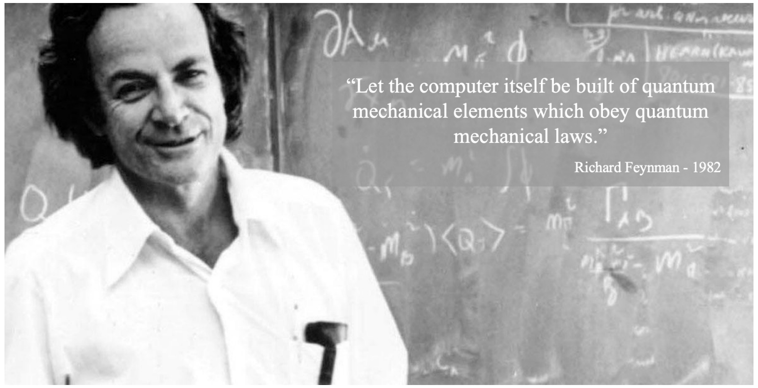


Quantum supremacy ~2^{50}

With 2^{300} (i.e. 300 qubits) the size is more than the number of particles In the universe. J. Preskill

What are the anticipated applications ?

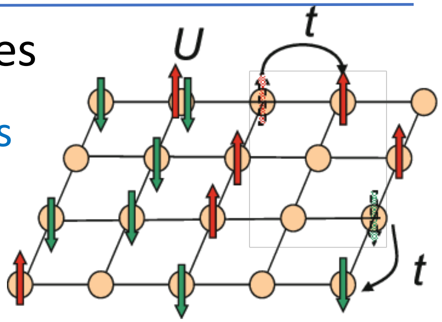
Simulation of Quantum complex systems



"Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws."

Richard Feynman - 1982

Ex: systems on lattices

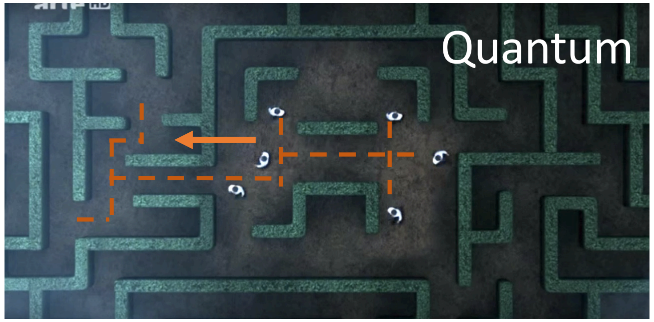


On classical computers
Can be solved exactly
For max 20 particles.

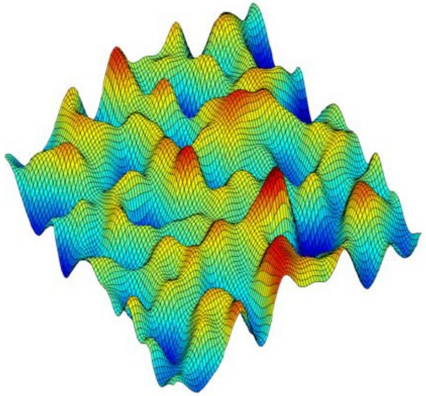
On quantum computers:
N sites means only N qubits

Quantum versus classical search

vs

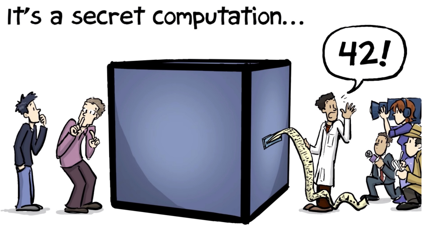


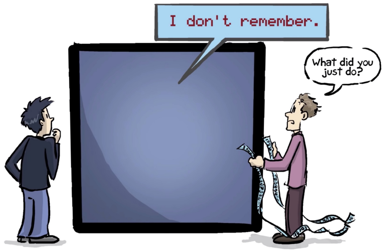
Credit: The Fabric of The Cosmos: Quantum Leap

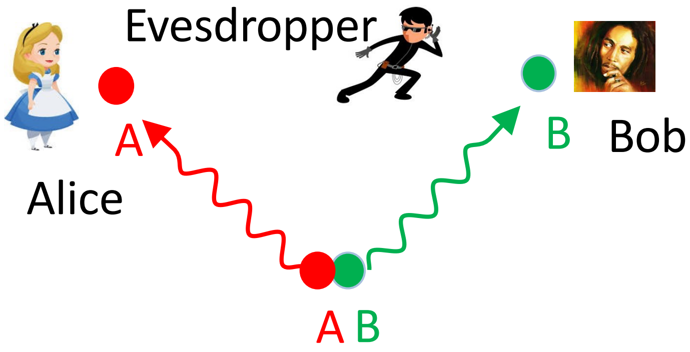


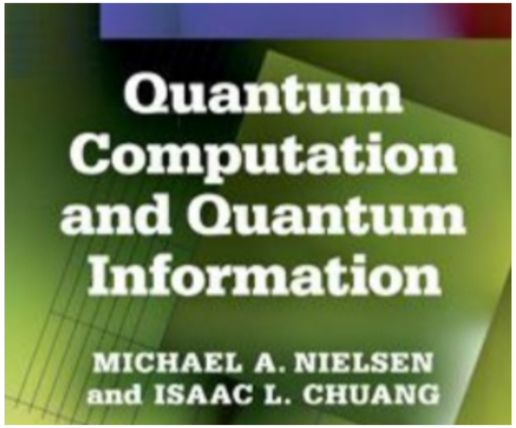
Exploring complex landscape:
molecules,
customers preferences (amazon), …

Quantum secrets (cryptography, quantum key, …)







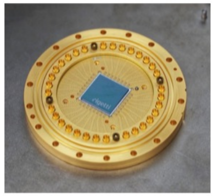


Quantum Computation and Quantum Information

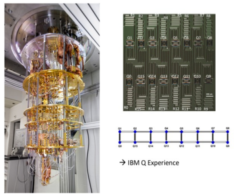
MICHAEL A. NIELSEN
and ISAAC L. CHUANG

Quantum computational advantage using photons, Science 370 (2020)

RIGETTI superconducting 19 Qubit



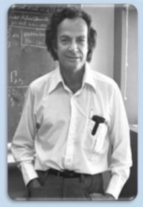
IBM QX5 (16 qubits)

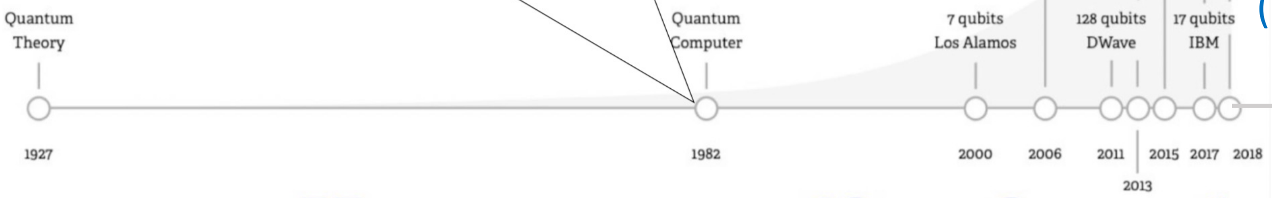


Simulating physics with computers-1982

Richard P. Feynman (Nobel Prize in Physics 1965)

> "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 Theory

1927

Quantum Computer

1982

7 qubits
Los Alamos

2000

12 qubits
MIT

2006

128 qubits
DWave

2011

512 qubits
DWave

2013

1152 qubits
DWave

2015

2048 qubits
DWave

50 qubits
IBM

17 qubits
IBM

2017

72 qubits
Google

128 qubits
Rigetti

2018

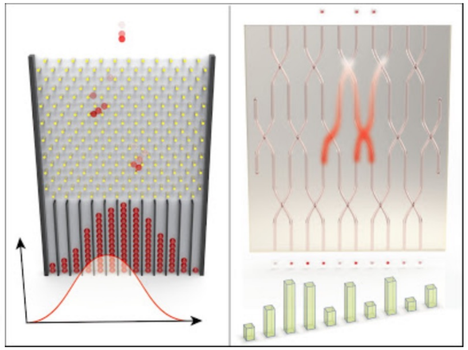
55
YEARS

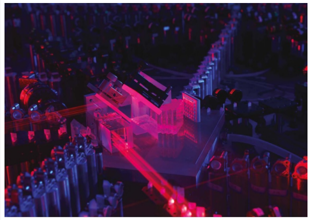
18
YEARS

6
YEARS

1
YEAR

IBM
Cloud

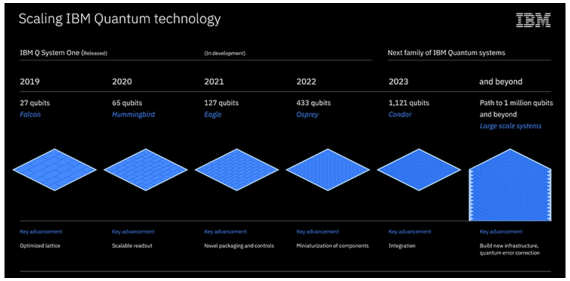




This photonic computer did a task that would take a classical computer 2.5 billion years.

(2020)

(2021)



Scaling IBM Quantum technology

IBM Q System One (Released)

(In development)

Next family of IBM Quantum systems

2019	2020	2021	2022	2023	and beyond
27 qubits *Falcon*	65 qubits *Hummingbird*	127 qubits *Eagle*	433 qubits *Osprey*	1,121 qubits *Condor*	Path to 1 million qubits and beyond *Large scale systems*
Key advancement Optimized lattice	Key advancement Scalable readout	Key advancement Novel packaging and controls	Key advancement Miniaturization of components	Key advancement Integration	Key advancement Build new infrastructure, quantum error correction

?

IonQ Gemini desk computer

Quantum supremacy using a programmable superconducting processor

Nature | Vol 574 | 24 OCTOBER 2019 | **505**

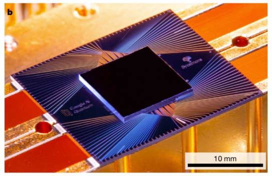
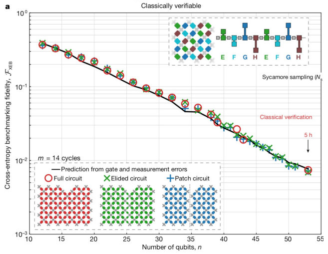
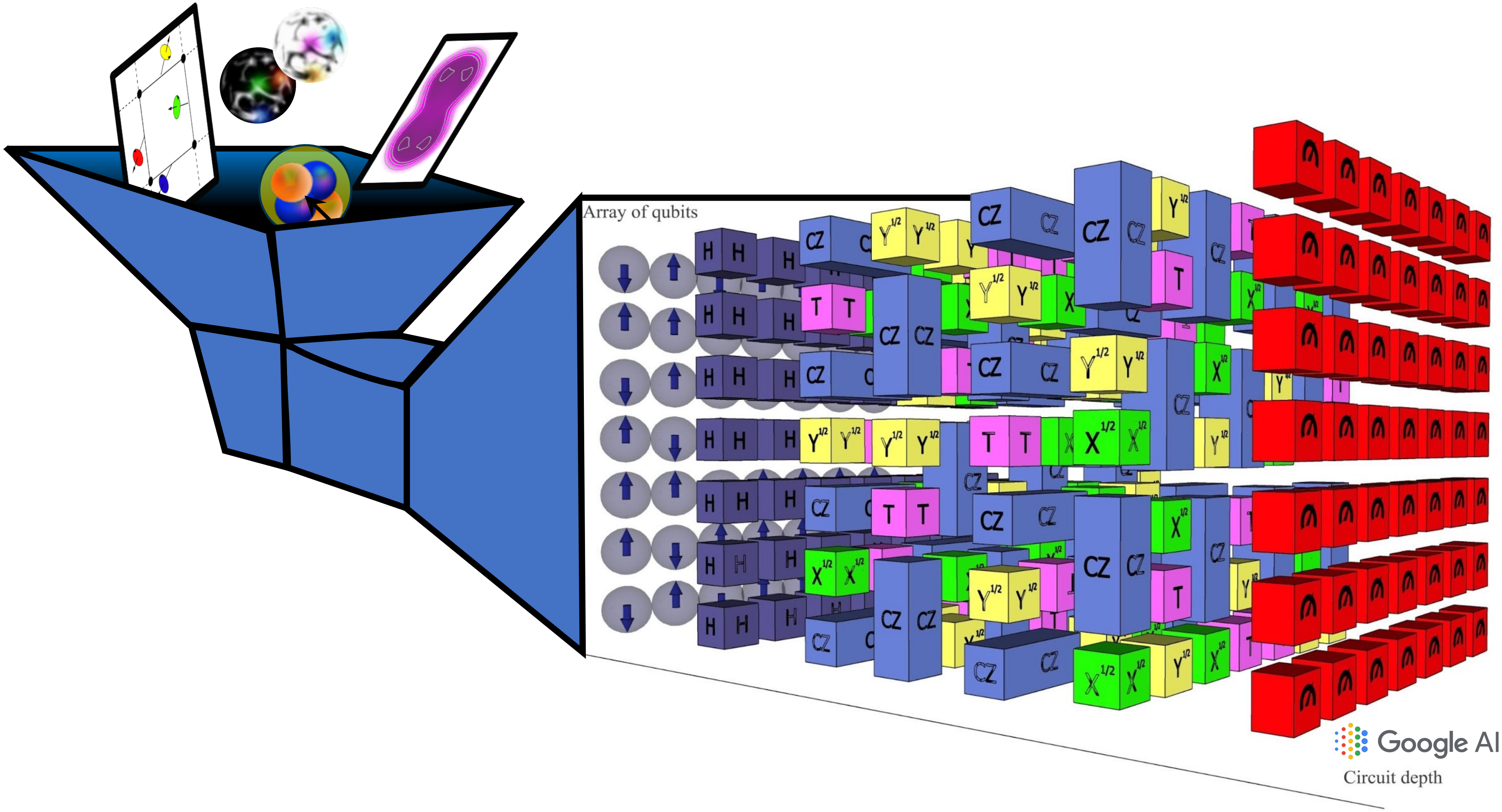


Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. **b**, Photograph of the Sycamore chip.

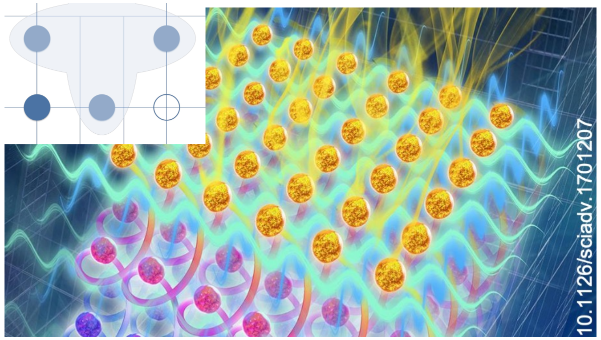


Personal motivations



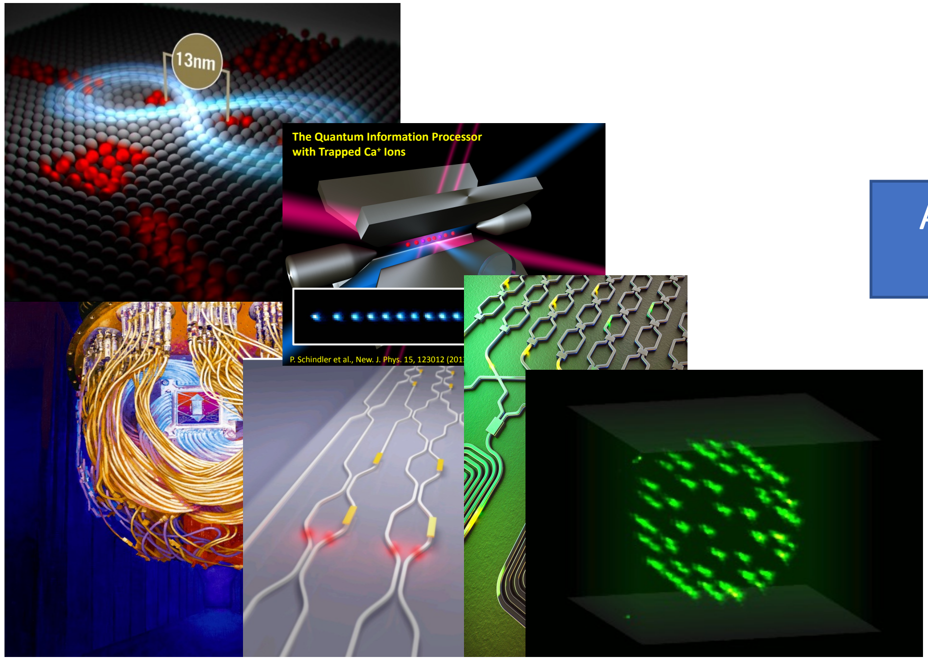
Few initiated applications in the world in IJCLab fields

Lattice gauge theories



Zohar, Kolck, Savage, …

E. Zohar, J. I. Cirac, B. Reznik, Phys. Rev. Lett. **110**, 125304 (2013)
E. Zohar, J. I. Cirac, B. Reznik, Phys. Rev. A **88** 023617 (2013)
E. Zohar, J. I. Cirac, B. Reznik, Rep. Prog. Phys. **79**, 014401 (2016)
D. González Cuadra, **E. Zohar**, J. I. Cirac, New J. Phys. **19** 063038 (2017)

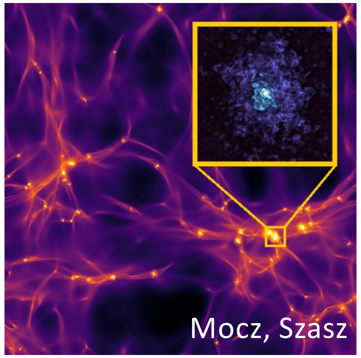


N-body problem

N-body nuclear systems

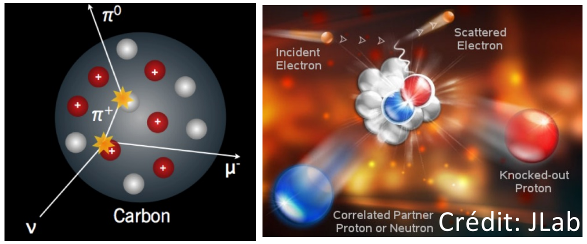
Dumitrescu, Hagen, Carlson, Papenbrock…

Dark matter



Mocz, Szasz

Dynamics: e, ν scattering

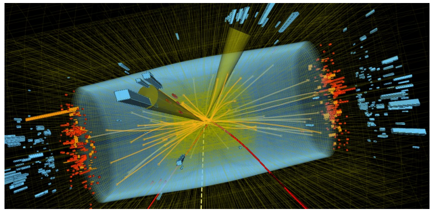


Crédit: JLab

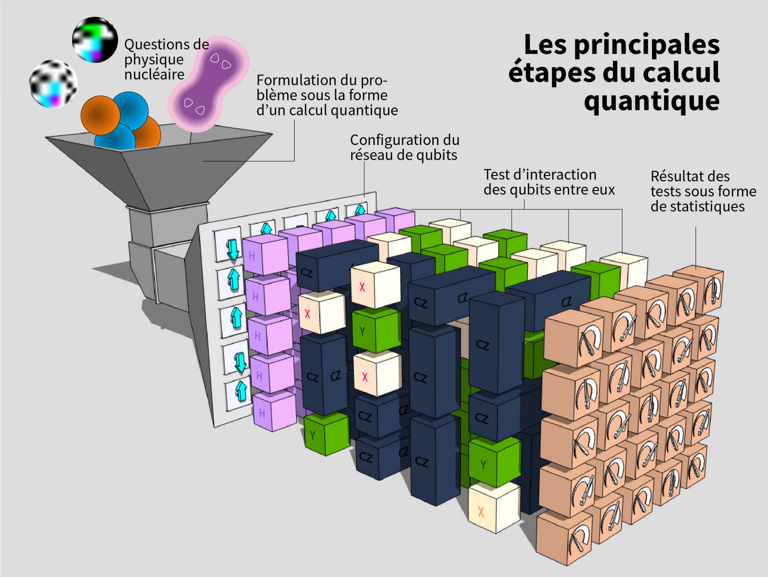
Roggero, Carlson, …

Applications to data mining (event classification)

CMS-detector (with LLR)



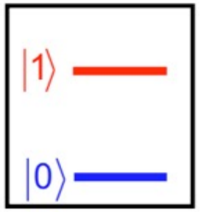
(II) PLAYING WITH QUBITS
(from texbooks)



Minimal - Practical aspects of quantum computers

qubit

2 level system



Manipulate the Qubits (Make rotations)

$|0\rangle$ Initial state

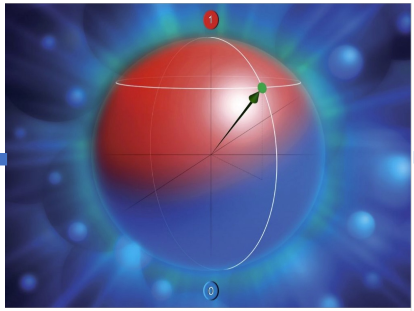


Illustration d'un qubit
CRÉDIT : MARK GARLICK / SCIENCE PHOTO LIBRA / MGA / SCIENCE PHOTO LIBRARY VIA AFP

Final state $c_0|0\rangle + c_1|1\rangle$

Measure the state

$|c_0|^2, \ |c_1|^2$

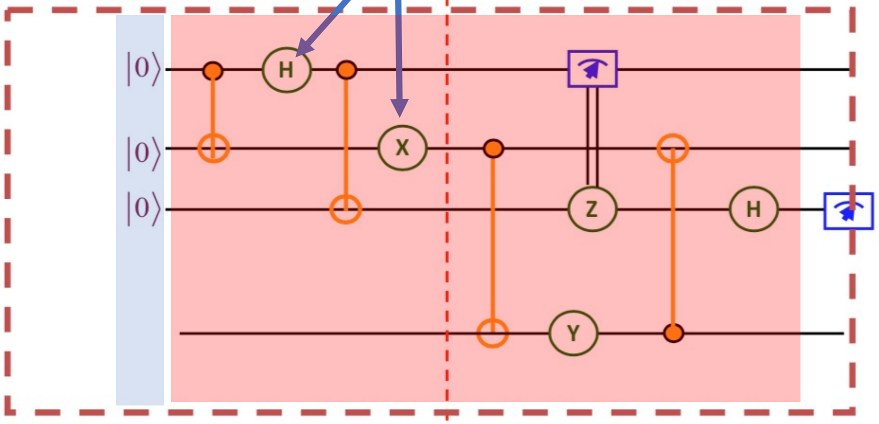
("destroy" the state)

With many Qubits

Initial state

Elementary operations

Quantum circuits



N = 2ⁿ computational basis states

$$\overbrace{|010001...1\rangle}^{n} = |p\rangle$$

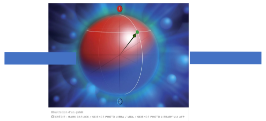
$$\sum_{i_k=0,1} a_{i_1 i_2 i_3 i_{4....} i_{2^N}} \left|i_1, i_2, i_3 ... i_{2^N}\right\rangle$$

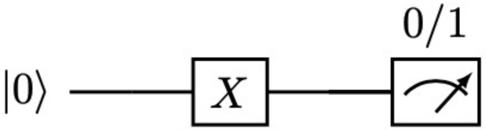
Gives the |a|²

Minimal - Practical aspects of quantum computers

The quantum computing toolkit

Unary operations





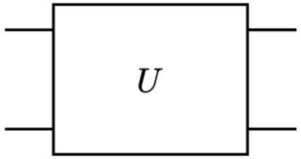
Rotations

$$-\boxed{R_X(\varphi) = e^{-i\varphi X/2}}-$$

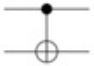
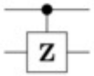
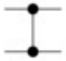
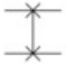
Standard examples

Pauli-X (X)	$\boxed{\mathbf{X}}$	$\oplus$	$\begin{array}{ccc} \|0\rangle & \|1\rangle & \\ 0 & 1 & \|0\rangle \\ 1 & 0 & \|1\rangle \end{array}$
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)	$\boxed{\mathbf{H}}$		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

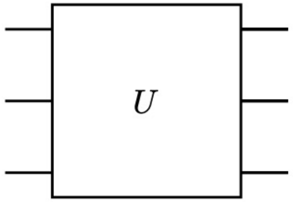
Binary operations



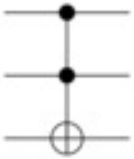
Standard examples

Controlled Not (CNOT, CX)			$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$	$\|11\rangle \leftrightarrow \|10\rangle$
Controlled Z (CZ)			$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$	$\|11\rangle \leftrightarrow -\|11\rangle$
SWAP			$\left[\begin{array}{cccc} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{array}\right]\begin{array}{c} \|00\rangle \\ \|01\rangle \\ \|10\rangle \\ \|11\rangle \end{array}$	$\|01\rangle \leftrightarrow \|10\rangle$

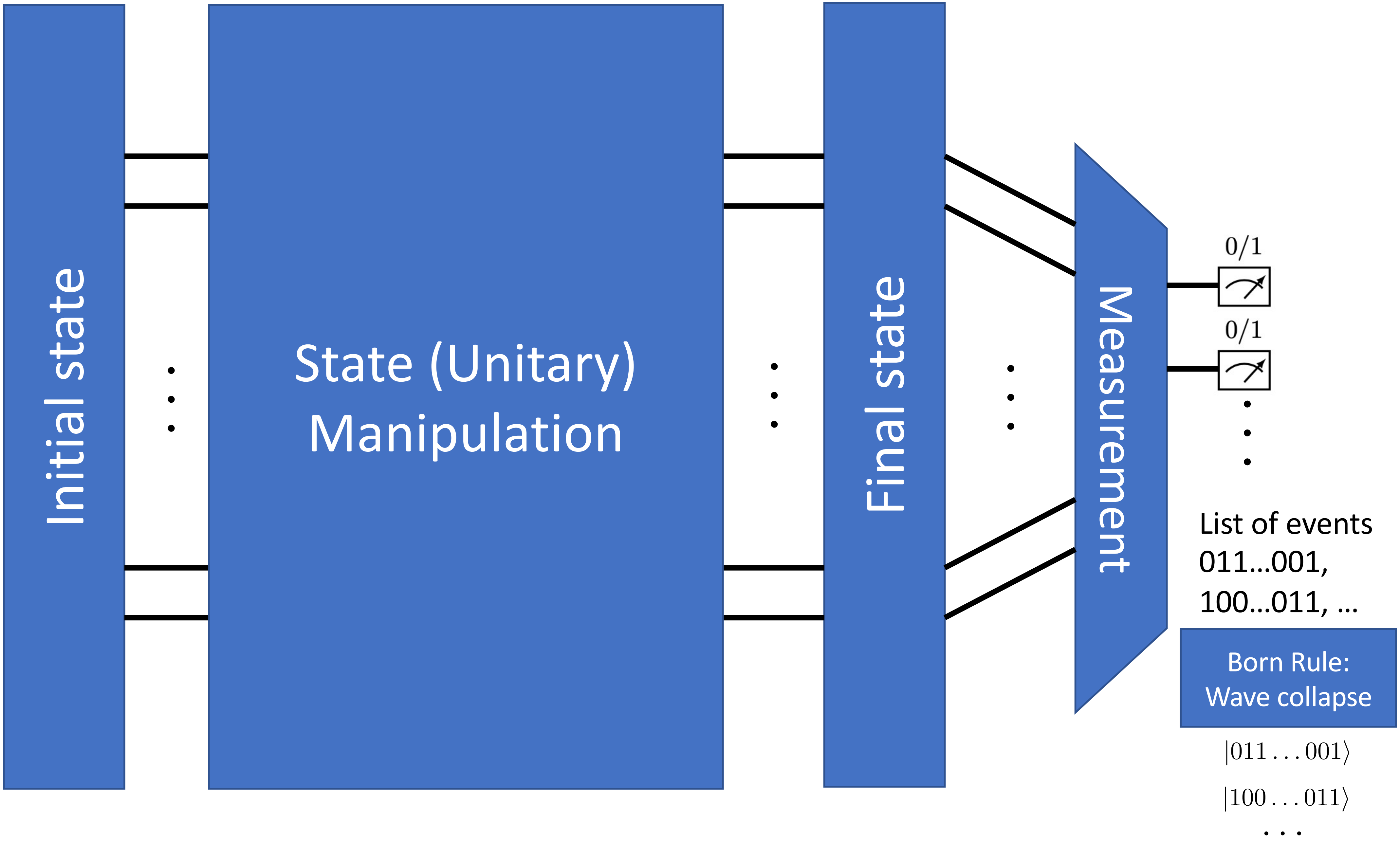
Ternary operations



Standard example

Toffoli (CCNOT, CCX, TOFF)		$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$	$\|110\rangle \leftrightarrow \|111\rangle$

Schematic view of the quantum computing programming



Initial state

State (Unitary) Manipulation

Final state

Measurement

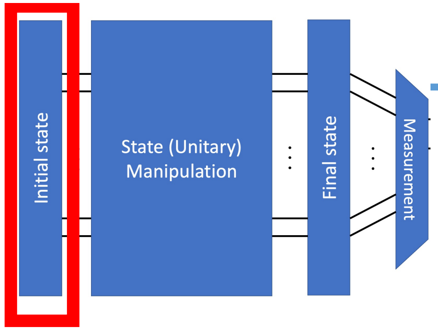
List of events
011…001,
100…011, …

Born Rule:
Wave collapse

$|011\ldots001\rangle$

$|100\ldots011\rangle$

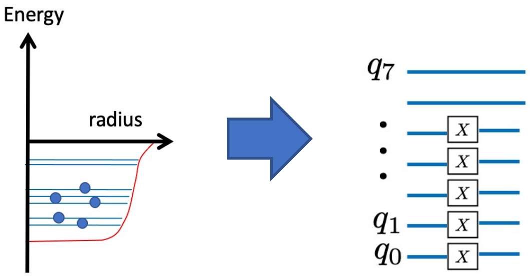
$\ldots$

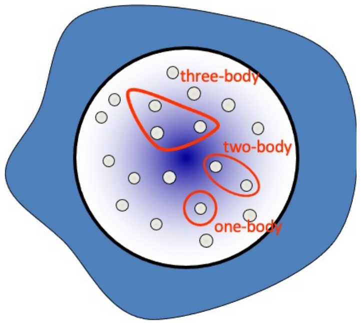


Some flash of what is happening now: many-body systems

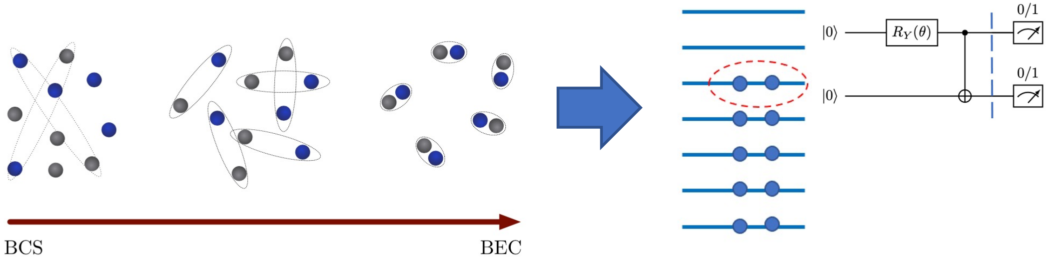
The many ways to prepare a system

Independent particles

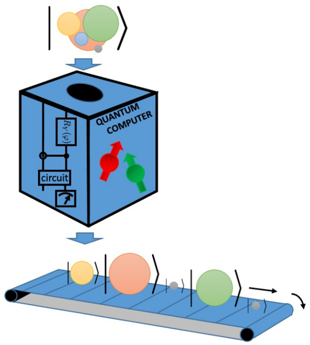




Superfluid systems



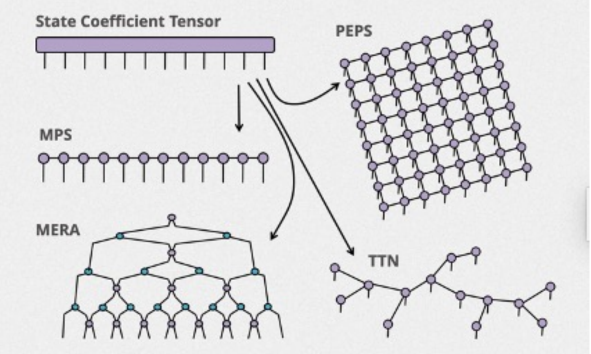
Requires symmetry breaking and restauration tools



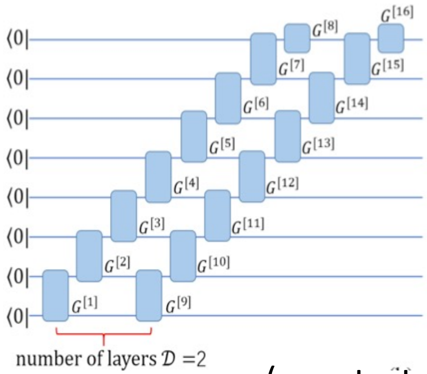
D. Lacroix, PRL 125, 230502 (2020).

Parametrizing general states: Tensor network

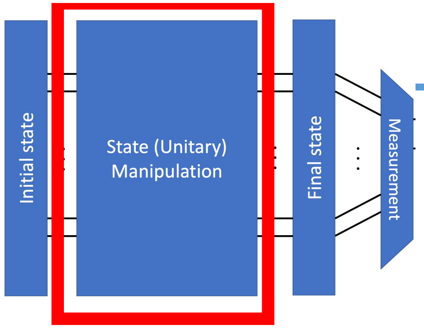
$$\Psi^{s_1,s_2,\cdots s_{n-1},s_n} = \sum_{\{\alpha_i\}} G^{s_1}_{\alpha_1} G^{s_2}_{\alpha_1\alpha_2} \cdots G^{s_{n-1}}_{\alpha_{n-2}\alpha_{n-1}} G^{s_n}_{\alpha_{n-1}}$$



Examples:



(now tested with A. Ruiz Guzman [PhD])

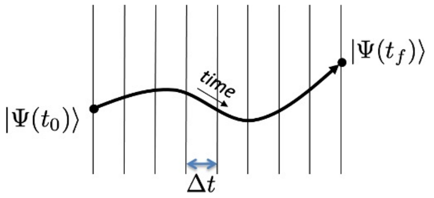


Some flash of what is happening now: many-body systems

State manipulation/evolution

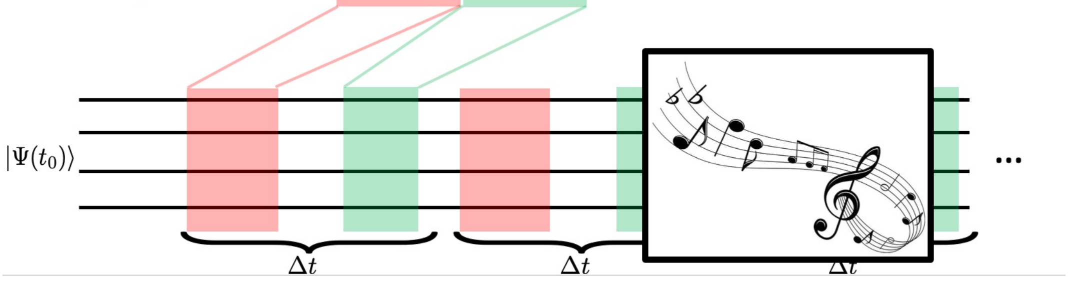
Exact evolution

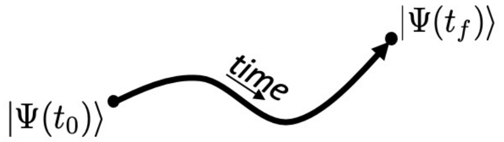
Example Trotter-Suzuki



$$e^{-ix(A+B)} = \left(e^{-iAx/N}e^{-iBx/N}\right)^N + \mathcal{O}(t^2/N)$$

Example : $e^{i\Delta t H_1/\hbar} = e^{-i\Delta t H_1/\hbar} e^{-i\Delta t H_2/\hbar}$



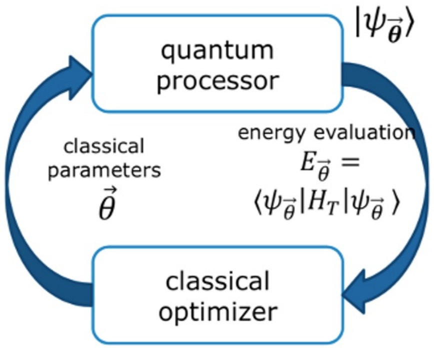


$$= e^{\frac{1}{i\hbar}(t-t_0)H}|\Psi(t_0)\rangle$$

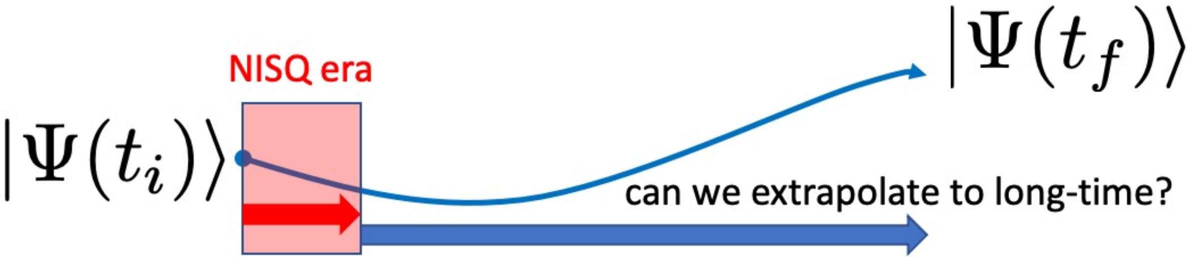
H is usually a big matrix

Approximate evolutions

Variational methods



Long time evolution from short time simulation



A. ruiz-Guzman and DL, arXiv:2104.08181

(III) FROM DREAM TO REALITY

Quantum programming is "easy" but working really with quantum computers is difficult

-adapt to the technology.
-search of efficient algorithms on this technology.
-try to correct for nasty noise as much as possible.

This looks more like an experimental program than informatic or quantum theory.

QC is not unique

Digital QC

Qubit, Qutrit, qudits

Analog computing

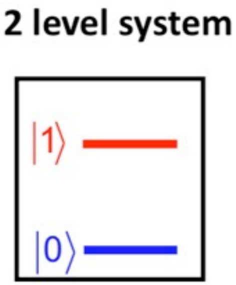
Quantum computing today is firstly an experimental challenge

REALITY

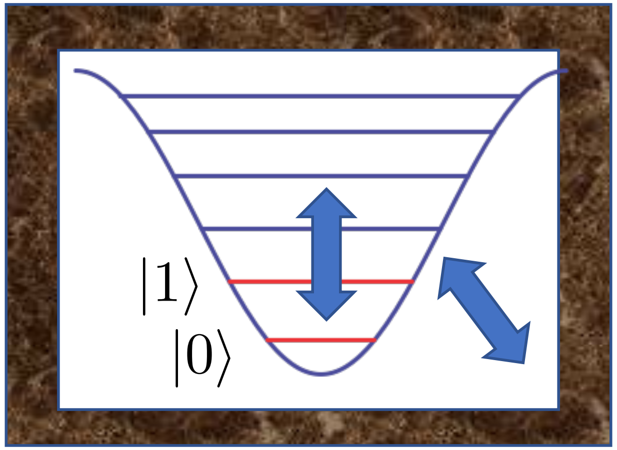
Everything around want to destroy the ideal picture and the quantum coherence.

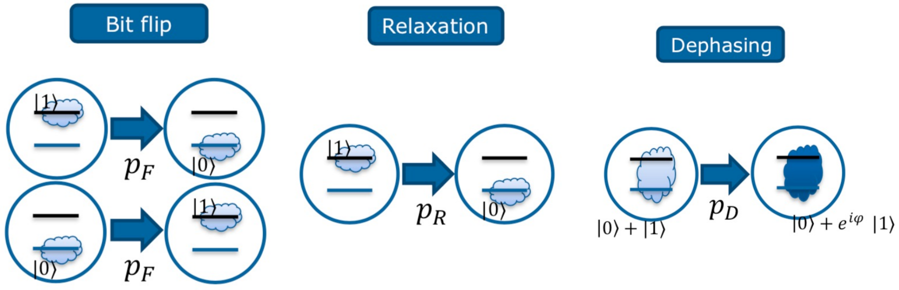
Leads to loss of information
And decoherence

Ideal Qubits



External Exp. Setup



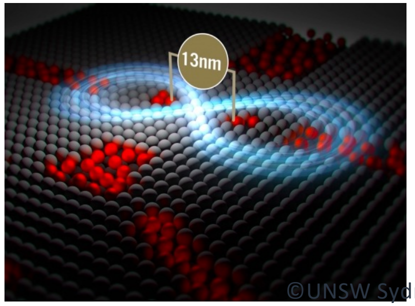


For multi-Qubits, also cross-talk
(making operations on one qubit
Impacts other qubits)

Noise correction is a business by itself

Working with quantum computers now means working in a noise environment short programs (before decoherence occurs)

Building quantum computers: companies



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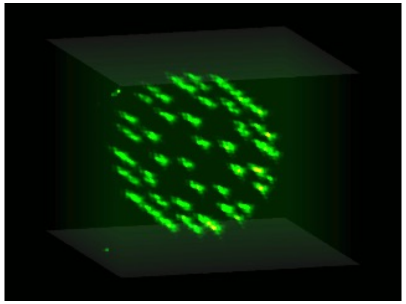
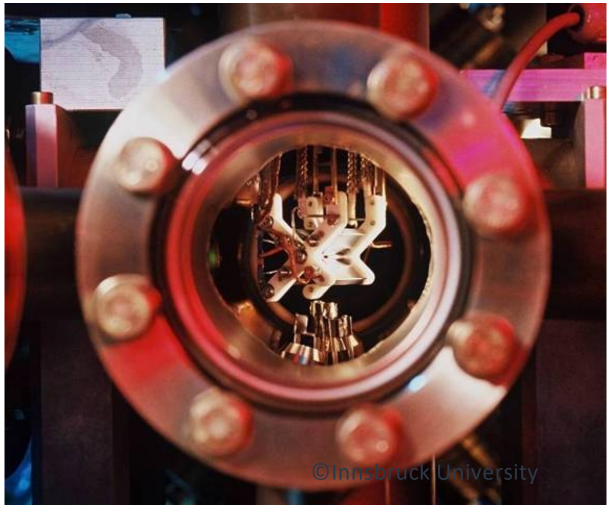
Silicon qubits



Neutral atoms

NMR



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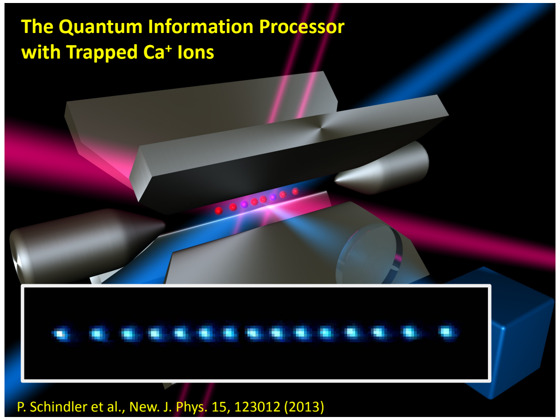
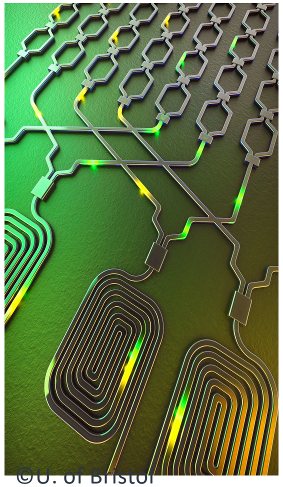
Trapped ions



P. Schindler et al., New. J. Phys. 15, 123012 (2013)



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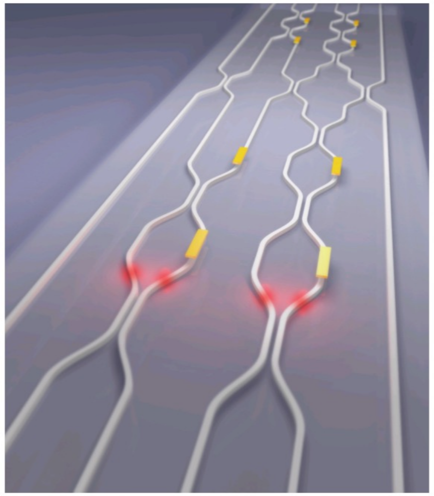
Photons



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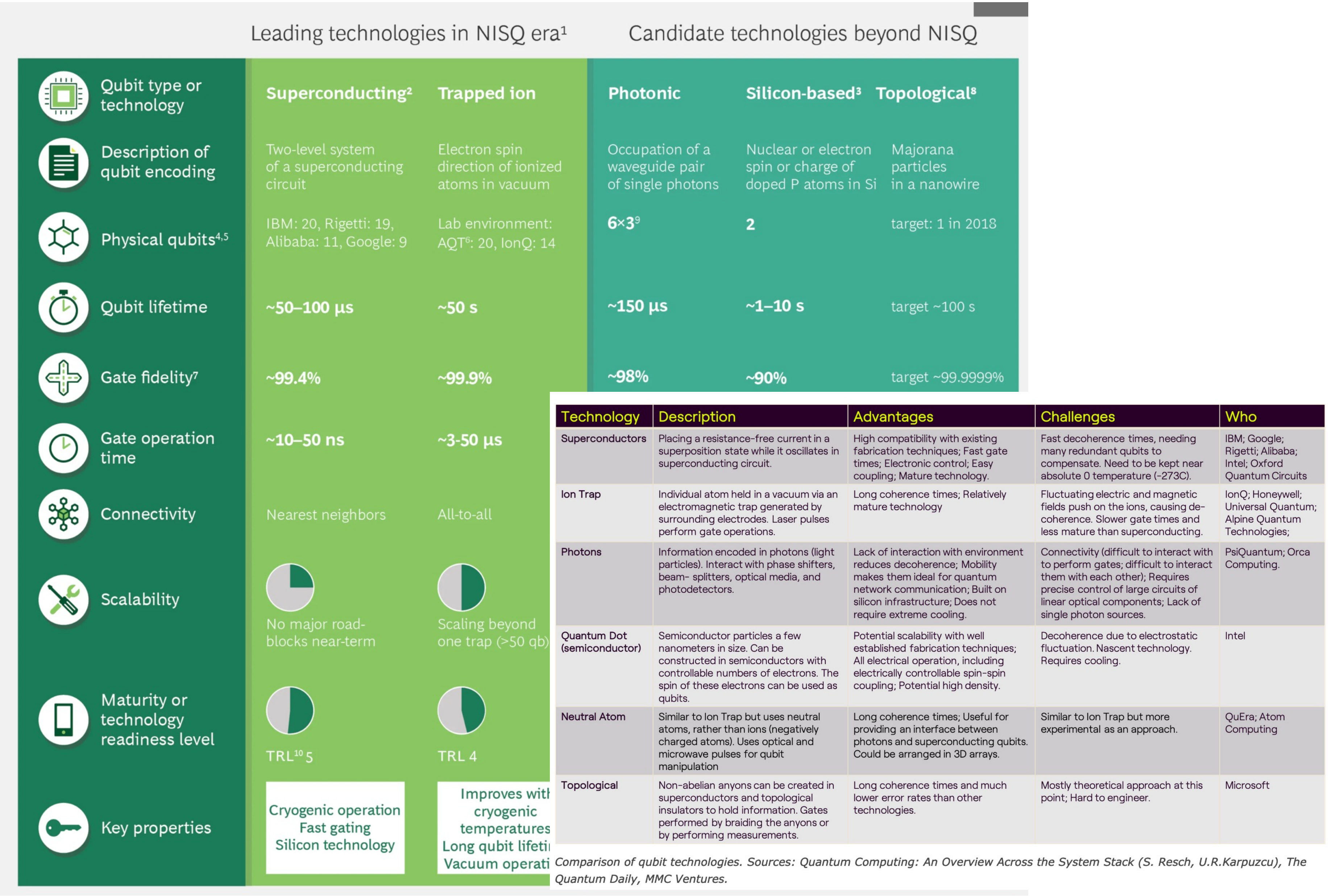
Superconducting qubits

Platforms comparison



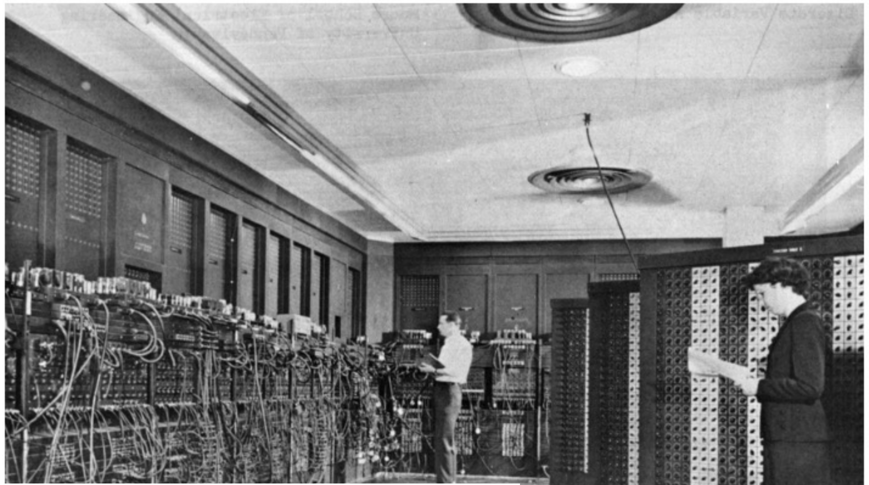
	Leading technologies in NISQ era[1]		Candidate technologies beyond NISQ		
Qubit type or technology	**Superconducting[2]**	**Trapped ion**	**Photonic**	**Silicon-based[3]**	**Topological[8]**
Description of qubit encoding	Two-level system of a superconducting circuit	Electron spin direction of ionized atoms in vacuum	Occupation of a waveguide pair of single photons	Nuclear or electron spin or charge of doped P atoms in Si	Majorana particles in a nanowire
Physical qubits[4,5]	IBM: 20, Rigetti: 19, Alibaba: 11, Google: 9	Lab environment: AQT[6]: 20, IonQ: 14	**6×3[9]**	**2**	target: 1 in 2018
Qubit lifetime	**~50–100 µs**	**~50 s**	**~150 µs**	**~1–10 s**	target ~100 s
Gate fidelity[7]	**~99.4%**	**~99.9%**	**~98%**	**~90%**	target ~99.9999%
Gate operation time	**~10–50 ns**	**~3-50 µs**			
Connectivity	Nearest neighbors	All-to-all			
Scalability	No major road-blocks near-term	Scaling beyond one trap (>50 qb)			
Maturity or technology readiness level	TRL[10] 5	TRL 4			
Key properties	Cryogenic operation Fast gating Silicon technology	Improves wit cryogenic temperatures Long qubit lifeti Vacuum operati			

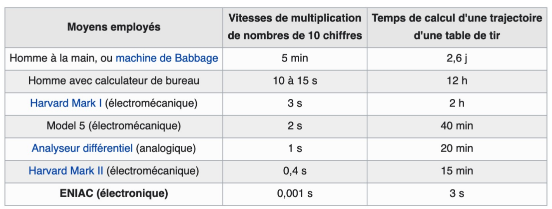
Technology	Description	Advantages	Challenges	Who
Superconductors	Placing a resistance-free current in a superposition state while it oscillates in superconducting circuit.	High compatibility with existing fabrication techniques; Fast gate times; Electronic control; Easy coupling; Mature technology.	Fast decoherence times, needing many redundant qubits to compensate. Need to be kept near absolute 0 temperature (-273C).	IBM; Google; Rigetti; Alibaba; Intel; Oxford Quantum Circuits
Ion Trap	Individual atom held in a vacuum via an electromagnetic trap generated by surrounding electrodes. Laser pulses perform gate operations.	Long coherence times; Relatively mature technology	Fluctuating electric and magnetic fields push on the ions, causing de-coherence. Slower gate times and less mature than superconducting.	IonQ; Honeywell; Universal Quantum; Alpine Quantum Technologies;
Photons	Information encoded in photons (light particles). Interact with phase shifters, beam- splitters, optical media, and photodetectors.	Lack of interaction with environment reduces decoherence; Mobility makes them ideal for quantum network communication; Built on silicon infrastructure; Does not require extreme cooling.	Connectivity (difficult to interact with to perform gates; difficult to interact them with each other); Requires precise control of large circuits of linear optical components; Lack of single photon sources.	PsiQuantum; Orca Computing.
Quantum Dot (semiconductor)	Semiconductor particles a few nanometers in size. Can be constructed in semiconductors with controllable numbers of electrons. The spin of these electrons can be used as qubits.	Potential scalability with well established fabrication techniques; All electrical operation, including electrically controllable spin-spin coupling; Potential high density.	Decoherence due to electrostatic fluctuation. Nascent technology. Requires cooling.	Intel
Neutral Atom	Similar to Ion Trap but uses neutral atoms, rather than ions (negatively charged atoms). Uses optical and microwave pulses for qubit manipulation	Long coherence times; Useful for providing an interface between photons and superconducting qubits. Could be arranged in 3D arrays.	Similar to Ion Trap but more experimental as an approach.	QuEra; Atom Computing
Topological	Non-abelian anyons can be created in superconductors and topological insulators to hold information. Gates performed by braiding the anyons or by performing measurements.	Long coherence times and much lower error rates than other technologies.	Mostly theoretical approach at this point; Hard to engineer.	Microsoft

Comparison of qubit technologies. Sources: Quantum Computing: An Overview Across the System Stack (S. Resch, U.R.Karpuzcu), The Quantum Daily, MMC Ventures.

Boston Consulting Group – Nov 2018

Eniac ~1950





Moyens employés	Vitesses de multiplication de nombres de 10 chiffres	Temps de calcul d'une trajectoire d'une table de tir
Homme à la main, ou machine de Babbage	5 min	2,6 j
Homme avec calculateur de bureau	10 à 15 s	12 h
Harvard Mark I (électromécanique)	3 s	2 h
Model 5 (électromécanique)	2 s	40 min
Analyseur différentiel (analogique)	1 s	20 min
Harvard Mark II (électromécanique)	0,4 s	15 min
ENIAC (électronique)	0,001 s	3 s

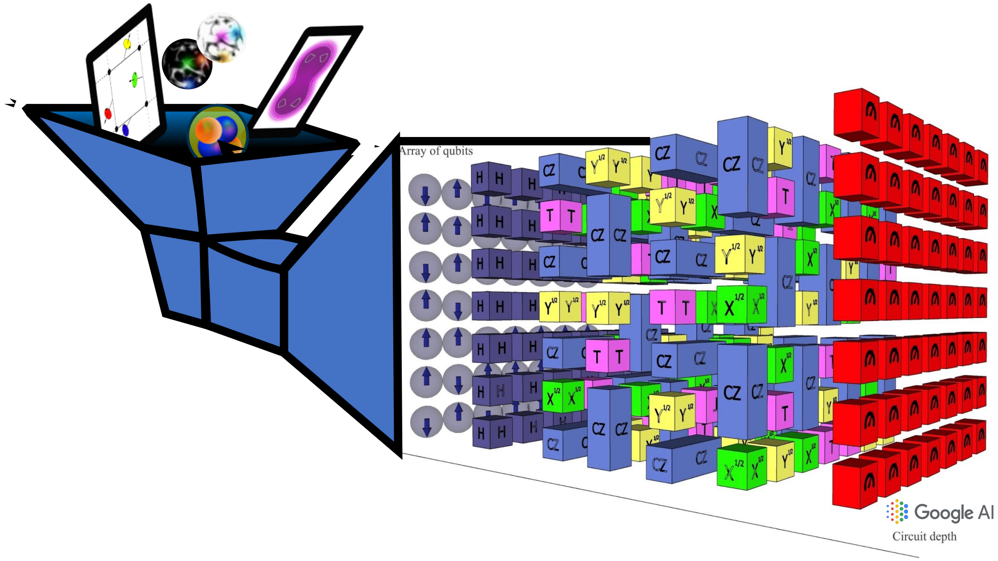
IBM ~2020

?

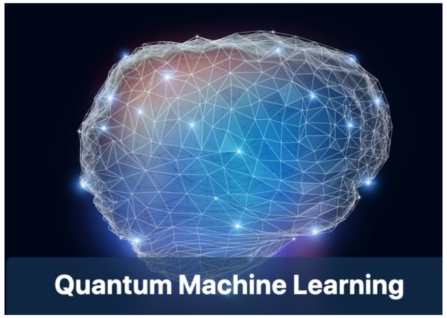
From B. Vulpescu

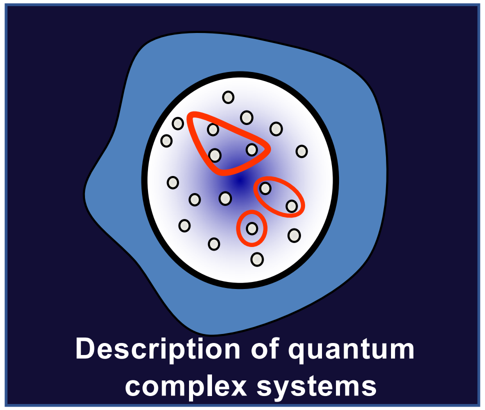
Projets sur l’informatique quantique à IJCLab

IJCLab
Irène Joliot-Curie
Laboratoire de Physique
des 2 Infinis




Prepare the Quantum Computing Revolution

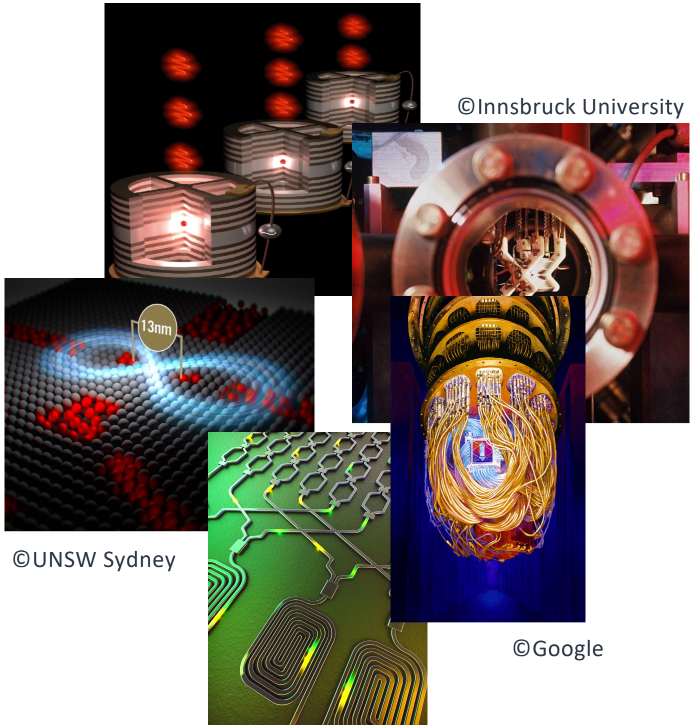

Quantum Machine Learning


Description of quantum complex systems


QC2I: Quantum Computing for the Physics of the Infinites

Denis Lacroix (IJCLab)

Summary



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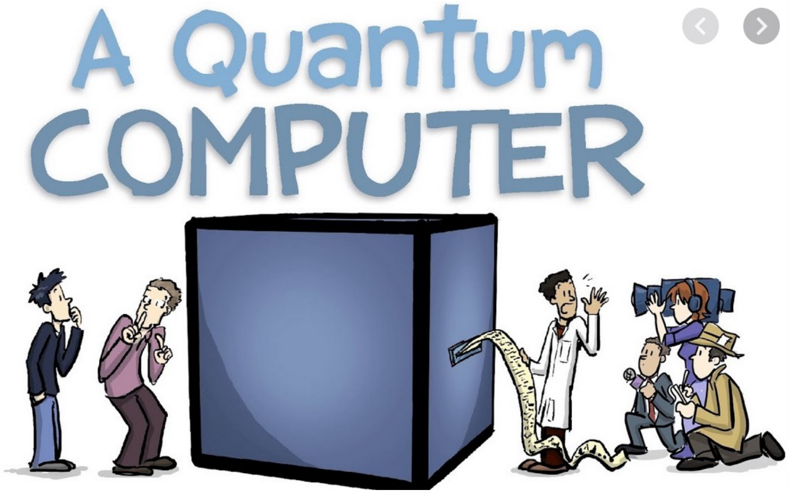
- Quantum computing is a high risk/high benefit interdisciplinary field
- It might lead to unprecedented boost in theory (or more generally in complex problems)
- It leads to natural link between public research and private companies (IBM, Google, …)
- Emerging QC programs in France



Thank you !