Quantum Information & Quantum Thermodynamics

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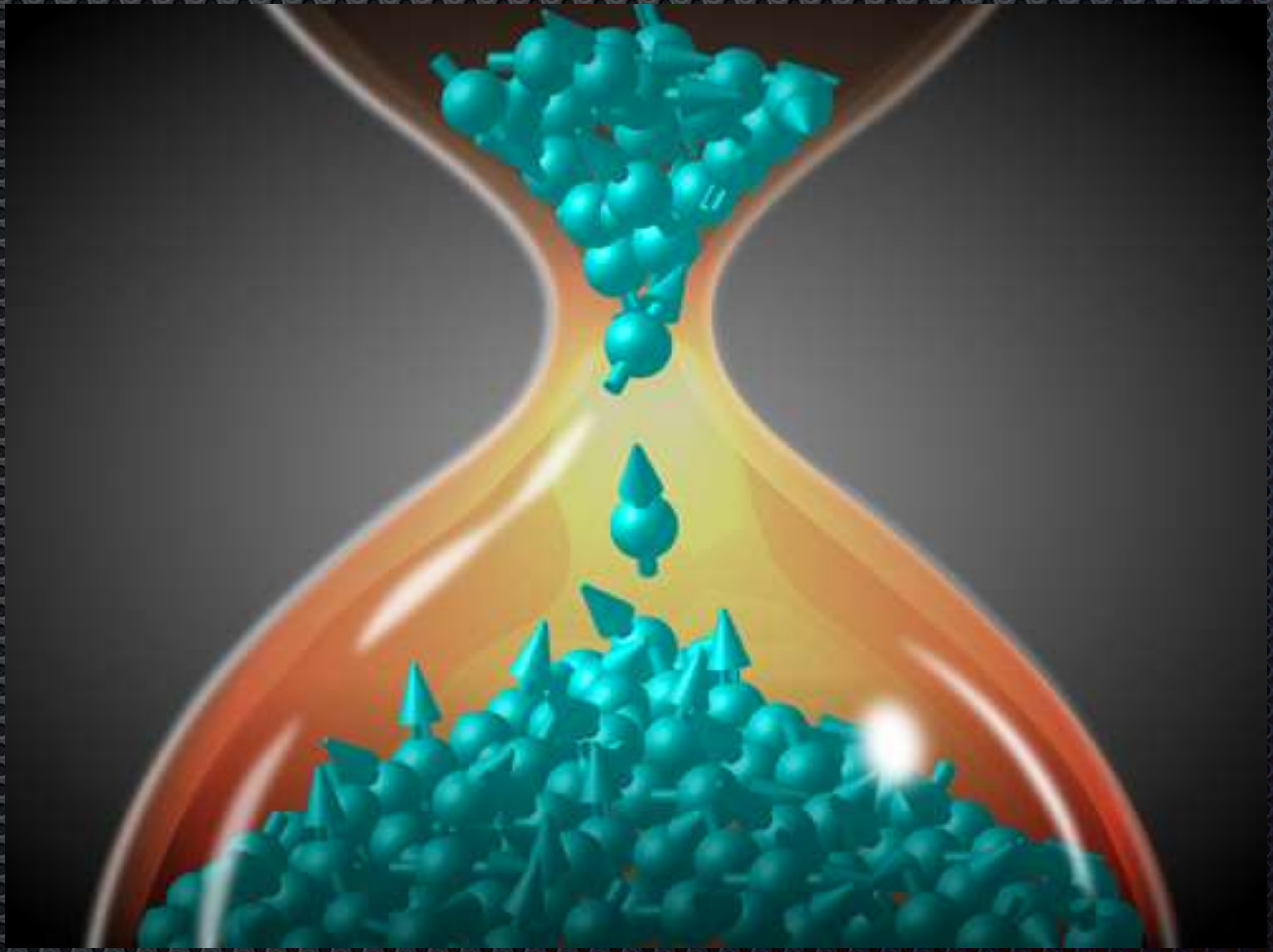

Brazilian National Institute for Science and Technology of Quantum Information

QIS @ UFABC

Web: quantum.ufabc.edu.br

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PEOPLE
Roberto M. Serra (Faculty)
Fernando L. Semião (Faculty)
Luciano Cruz (Faculty)
Rafael Paiva (Faculty)
Breno Marques (Faculty)
Jonas Floriano (Postdoc)
Saulo Moreira (Postdoc)
Carlos Ivan Henao Osorio (PhD Student)
Ivan Medina (PhD Student)
Patrice Camati (PhD student)
Wallace Santos Teixeira (PhD student)
Jeferson Guimarães (MSc Student)
Andrius (MSc student)

RESEARCH INTERESTS
Theoretical and experimental

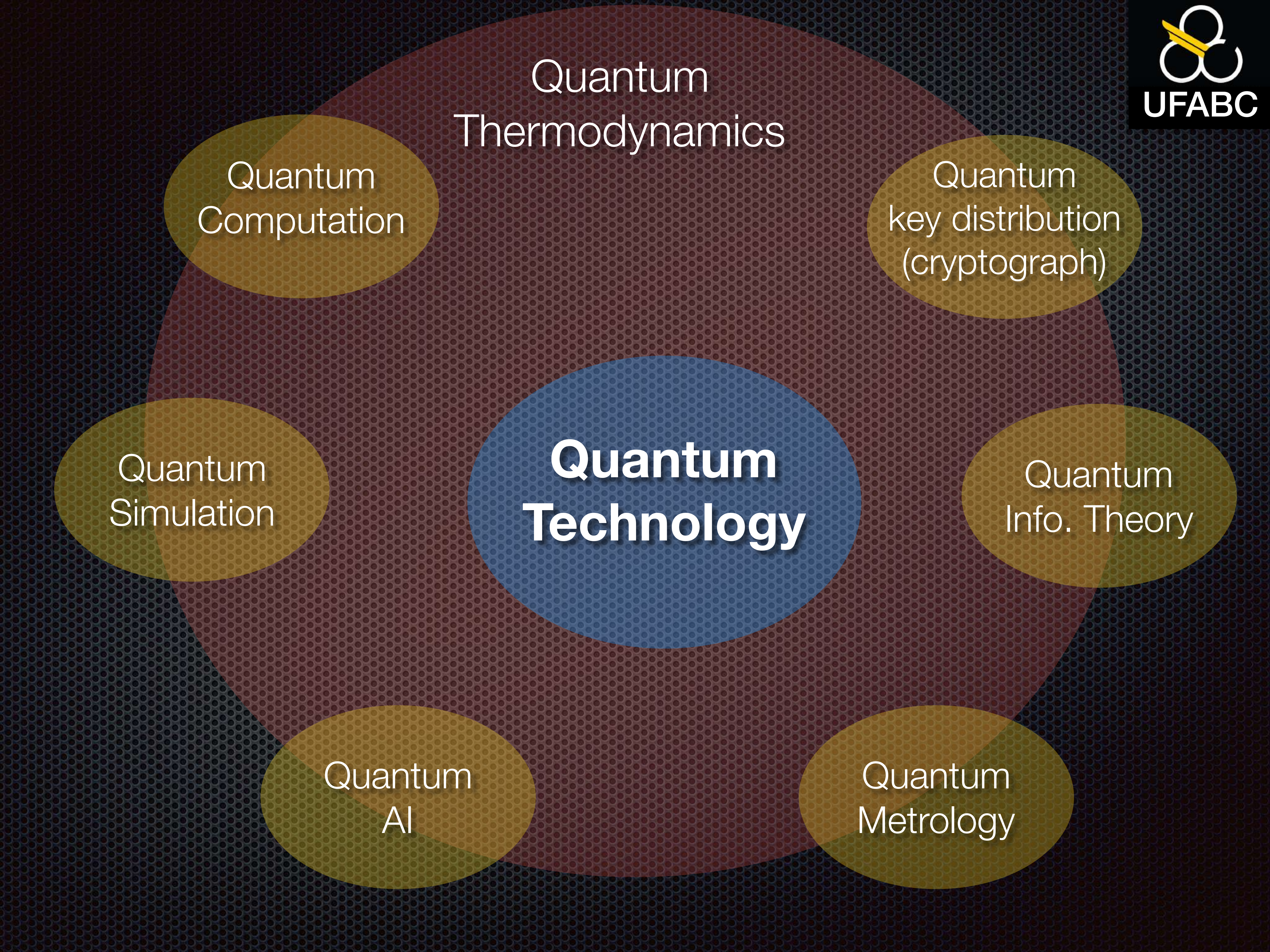
- Quantum information Science
- Quantum thermodynamics
- Experimental tests-of-principles in QIS
- Entanglement and non-locality
- Open quantum systems and decoherence
- Quantum computation
- Quantum coherence aspects in biology
- Quantum metrology

Our quantum playground

NMR spin qubits

Quantum Optics
twin-photons & squeezed light

Trapped ions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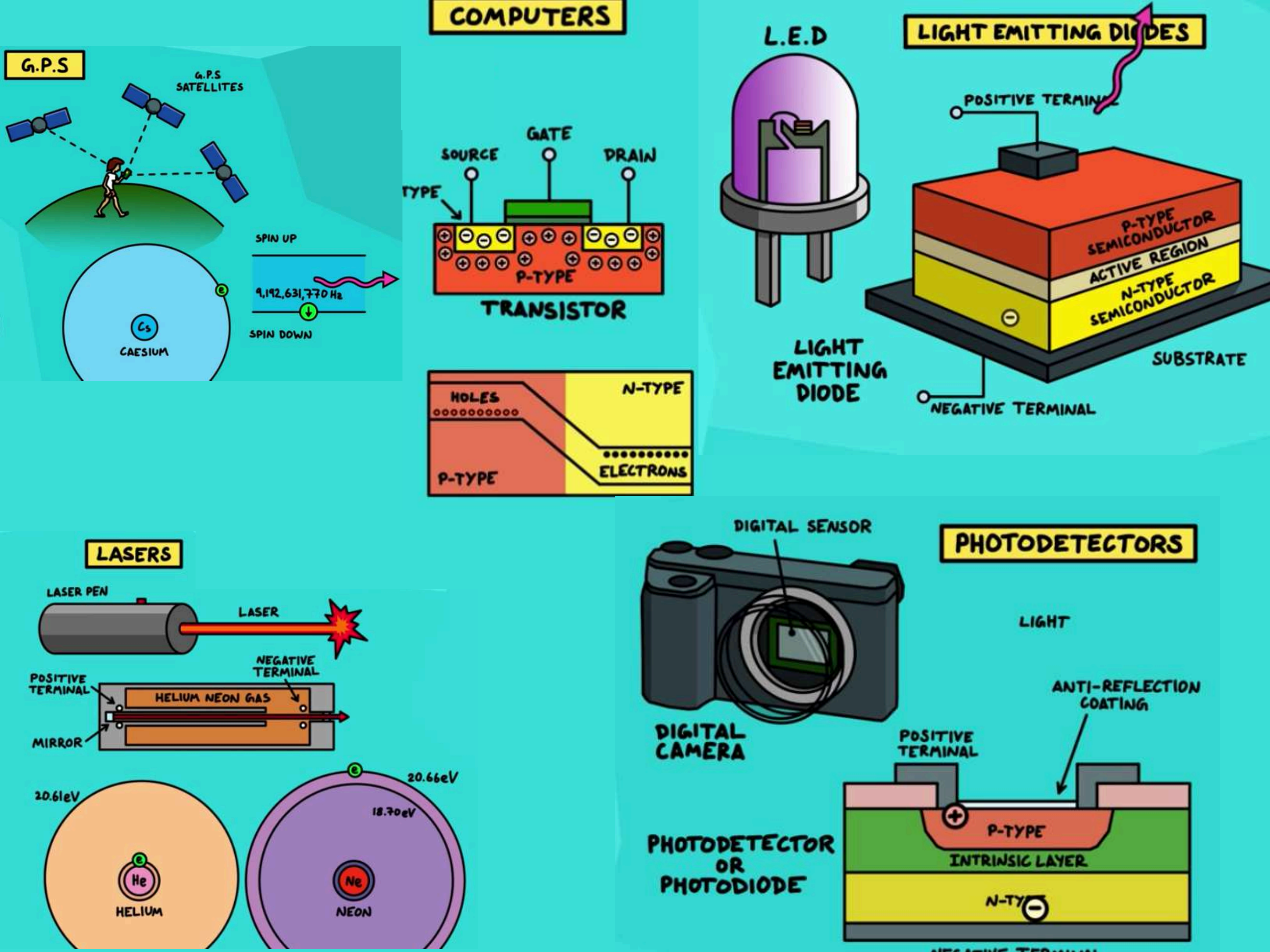
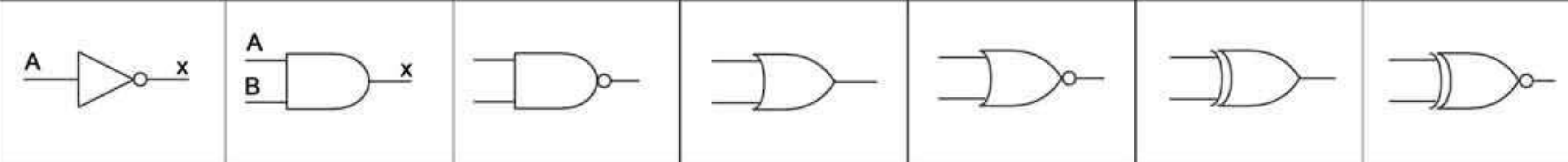
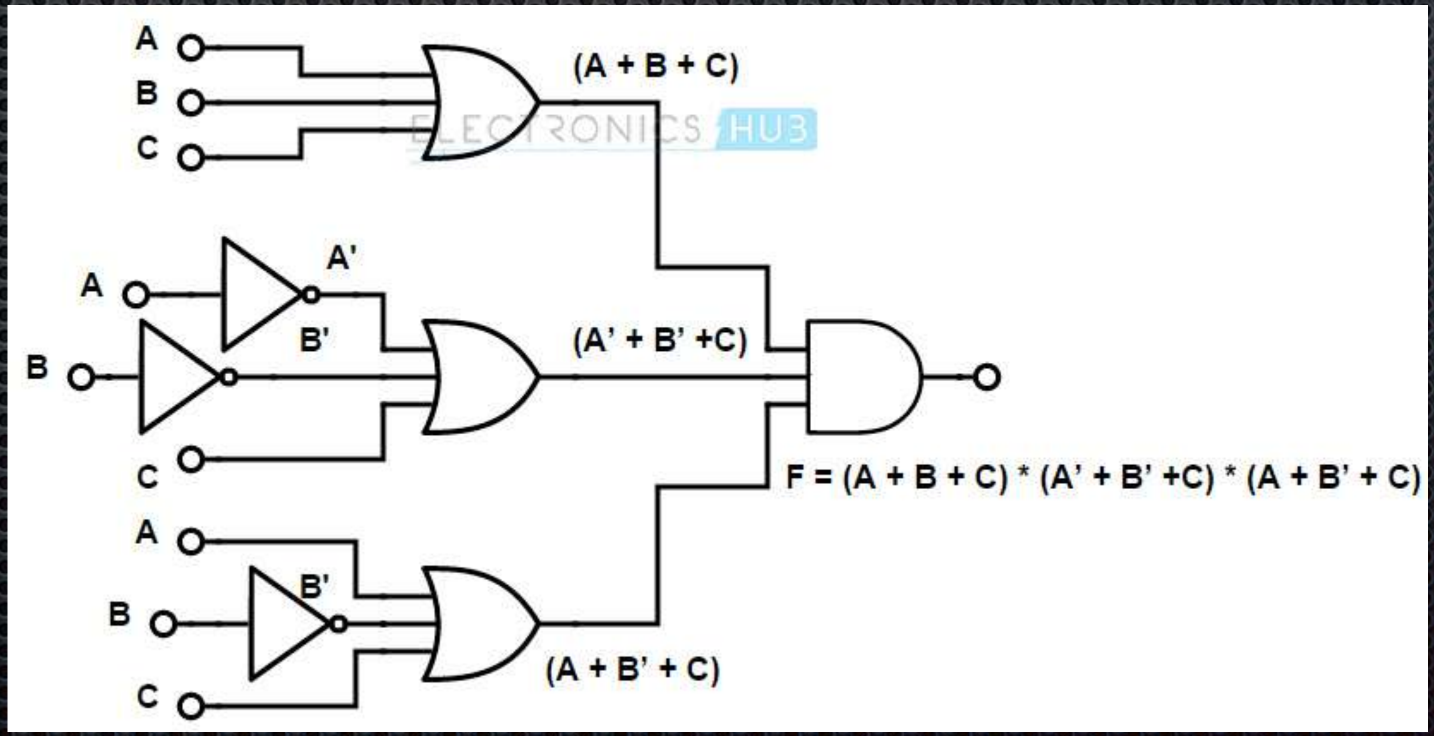
Quantum Thermodynamics
Quantum Computation
Quantum key distribution (cryptograph)
Quantum Simulation
Quantum Technology
Quantum Info. Theory
Quantum AI
Quantum Metrology

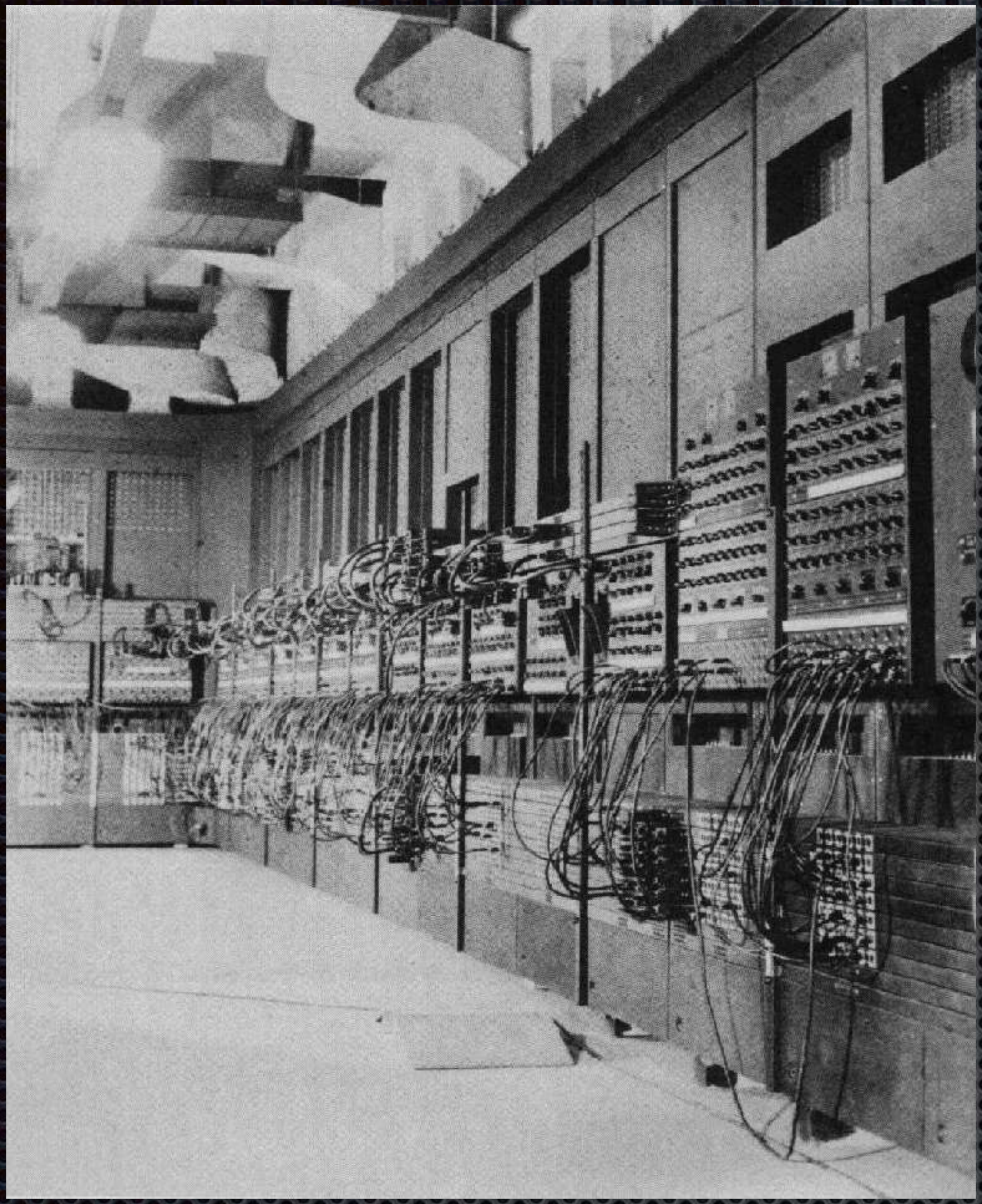

G.P.S
G.P.S SATELLITES
SPIN UP
9,192,631,770 Hz
SPIN DOWN
Cs
CAESIUM
COMPUTERS
SOURCE
GATE
DRAIN
TYPE
P-TYPE
TRANSISTOR
HOLES
N-TYPE
ELECTRONS
P-TYPE
L.E.D
LIGHT EMITTING DIODES
POSITIVE TERMINAL
P-TYPE SEMICONDUCTOR
ACTIVE REGION
N-TYPE SEMICONDUCTOR
SUBSTRATE
LIGHT EMITTING DIODE
NEGATIVE TERMINAL
LASERS
LASER PEN
LASER
POSITIVE TERMINAL
NEGATIVE TERMINAL
HELIUM NEON GAS
MIRROR
20.61eV
He
HELIUM
20.66eV
18.70eV
Ne
NEON
DIGITAL SENSOR
PHOTODETECTORS
LIGHT
DIGITAL CAMERA
POSITIVE TERMINAL
ANTI-REFLECTION COATING
P-TYPE
INTRINSIC LAYER
N-TYPE
PHOTODETECTOR OR PHOTODIODE

Logic Gates

Name	NOT	AND	NAND	OR	NOR	XOR	XNOR
Alg. Expr.	$\overline{A}$	AB	$\overline{AB}$	$A+B$	$\overline{A+B}$	$A\oplus B$	$\overline{A\oplus B}$
Symbol							
Truth Table	A X 0 1 1 0	B A X 0 0 0 0 1 0 1 0 0 1 1 1	B A X 0 0 1 0 1 1 1 0 1 1 1 0	B A X 0 0 0 0 1 1 1 0 1 1 1 1	B A X 0 0 1 0 1 0 1 0 0 1 1 0	B A X 0 0 0 0 1 1 1 0 1 1 1 0	B A X 0 0 1 0 1 0 1 0 0 1 1 1



ENIAC (1946)

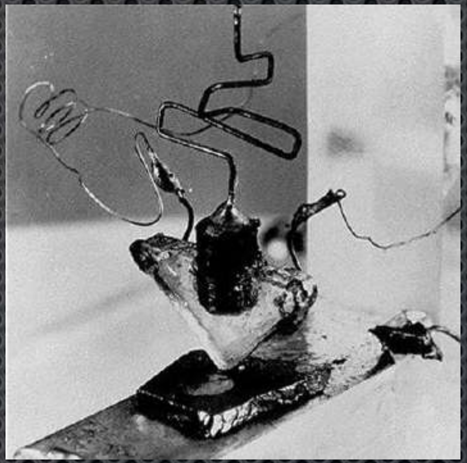


Frist quantum revolution

microelectronics

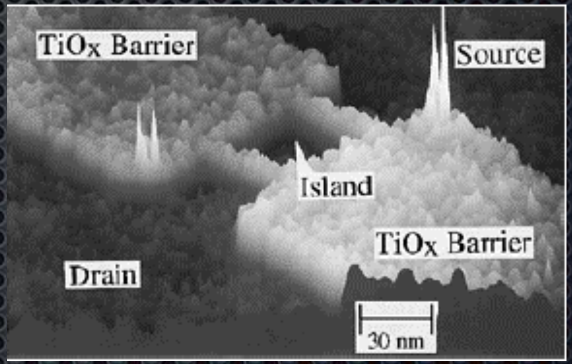
vacuum

valves



Frist transistor

1947



Single electron

transistor

1987

Thermodynamics and information processing

M. P. Frank, *The Physical Limits of Computing,* Comput. Sci. Eng. **4** (3), 16 (2002)

According Landauer
the limit for the irreversible
computational model is

$$-k_B T \ln 2$$

$$\approx 0.69\ k_B T$$

per erased bit

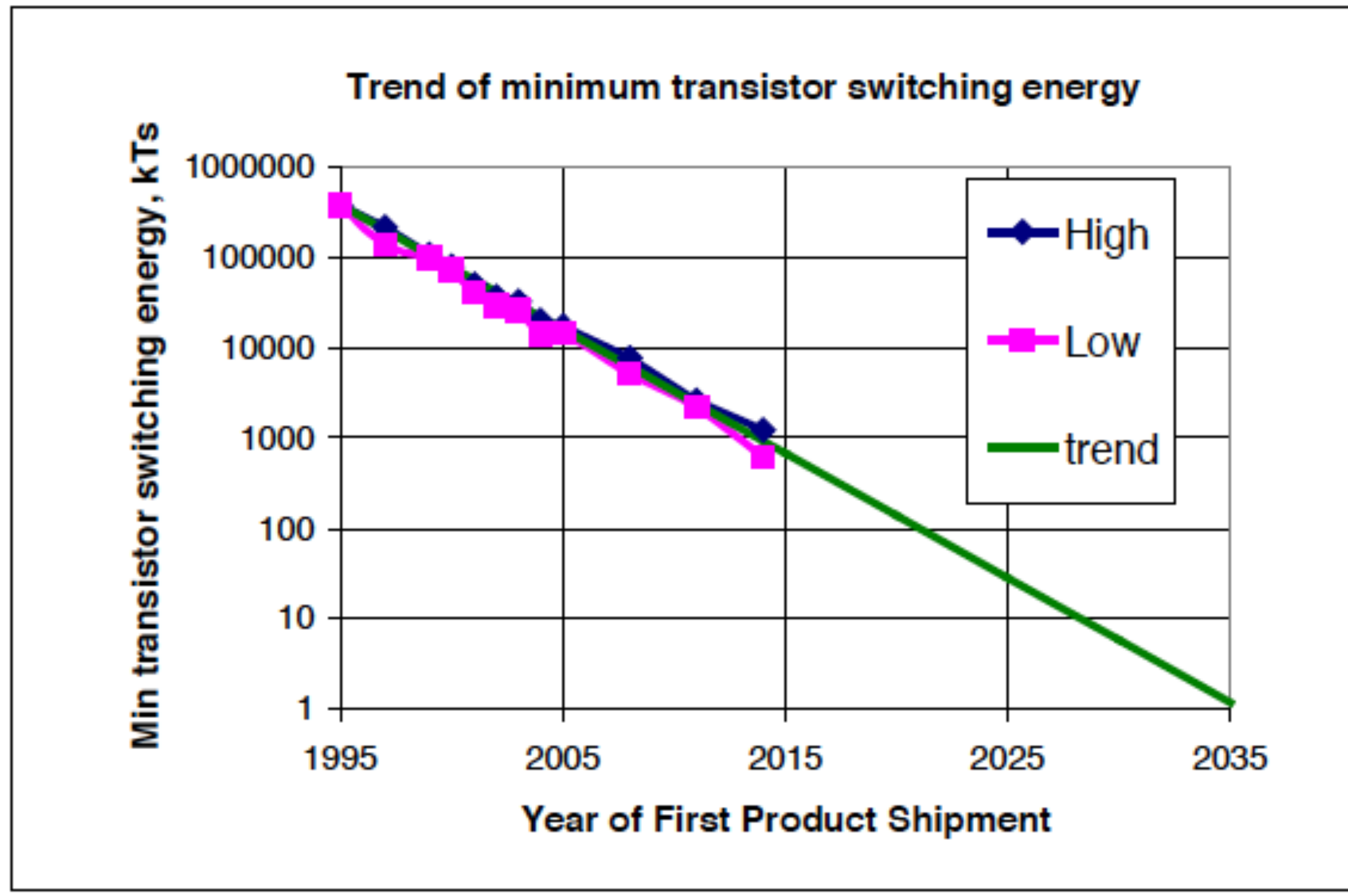
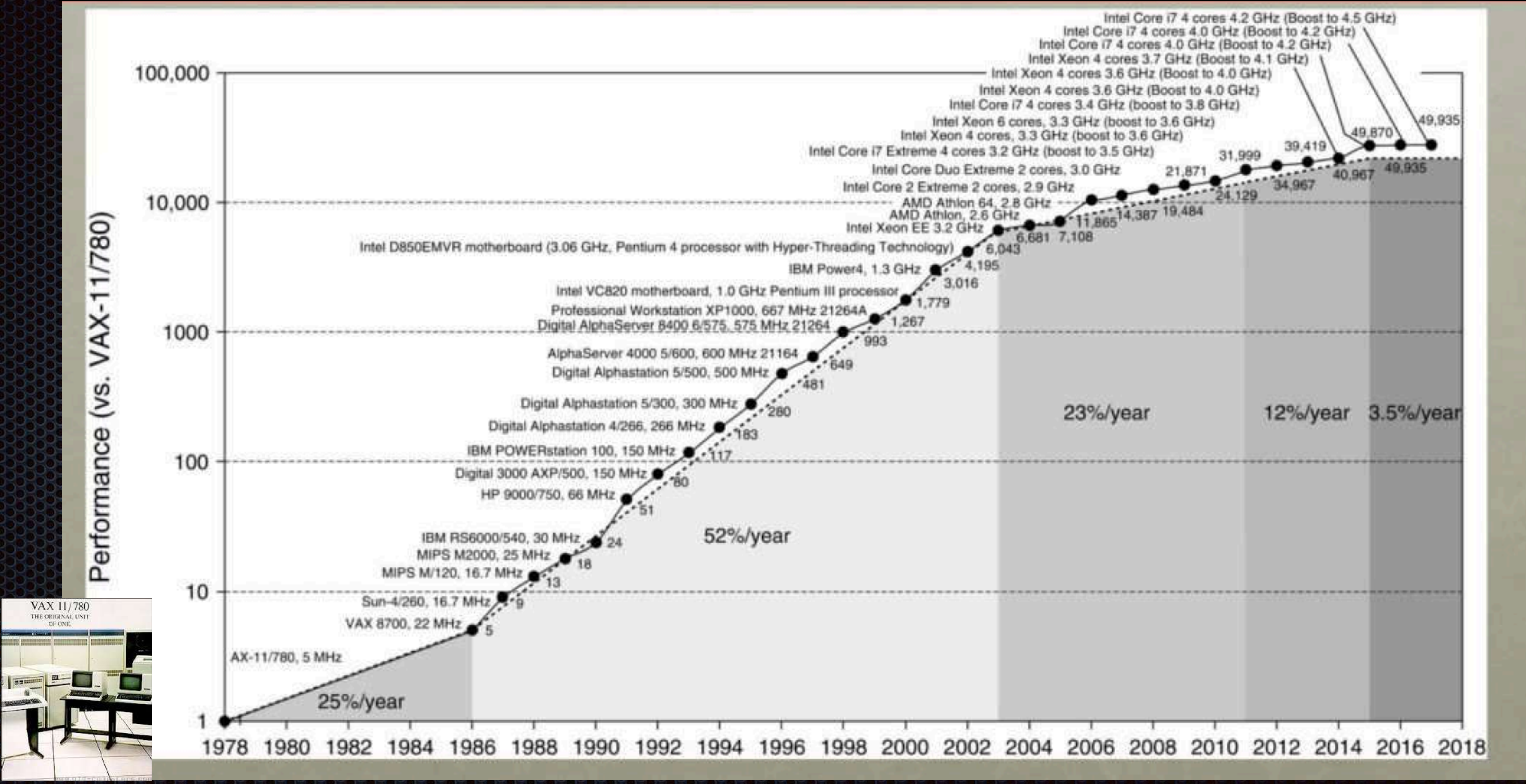


Figure 7: Trendline of minimum ½CV^2 transistor switching energy. Values were calculated using the goals for high-performance and low-power processors in the 1999 International Technology Roadmap for Semiconductors [3]. Energy is expressed as a multiple of room-temperature *kT*, which also is the number of nats of information associated with that energy. If the trend is followed, thermal noise will begin to become significant in the 2030s, when transistor energies approach small multiples of *kT*. Shortly after 2035 (if not sooner) this trend will be *forced* to begin leveling off, since a bit of information *requires* at least 0.69 *kT* to carry it [37]. However, if reversible operations are used, the order-*kT* bit energies need not be *dissipated* [19,18], and so the dissipation per reversible bit manipulation might continue decreasing along this curve a while longer.

The ending of Moore Law

# of transistors in chip doubles about ever two years (not even more!)

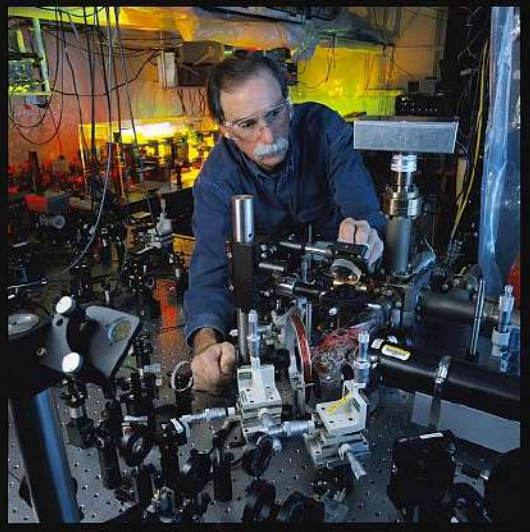
Single core performance

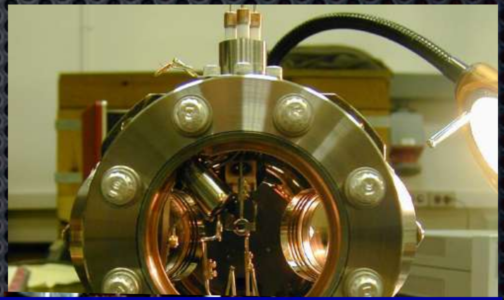


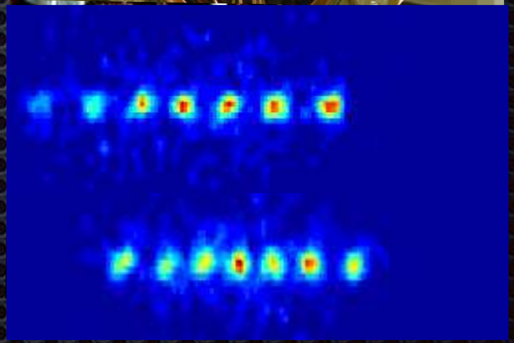
"....One never realizes experiments with a single electron or an atom or a small molecule. In thought experiments, one assumes that sometimes this is possible; invariably, this leads to ridiculous consequences....One may say that one does not realize experiments with single particles, more than one raises ichthyosaurs in the zoo."

E. Schrödinger (1952)

Br. J. Philosophy Sci. ***3*** *109 (1952)*

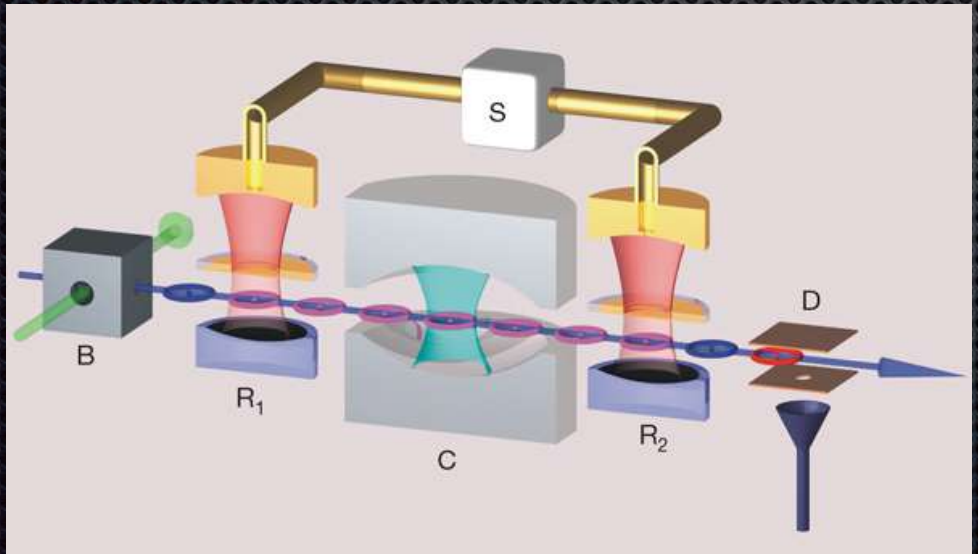






Trapped Ions, D. Wineland group (Nobel prize, 2012)

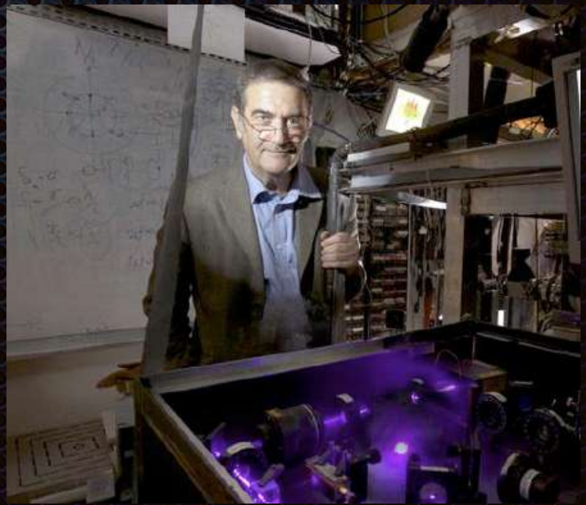
Bolder, USA



Single photons, single atoms,

S. Haroche group (Nobel prize, 2012)

Paris, France



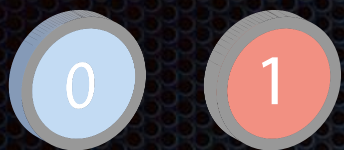
QUANTUM COMPUTING

Devices based on quantum systems (employing subatomic physics, photons, and/or nano-technology) could make calculation far faster than conventional machines if nothing spoils the quantum weirdness.

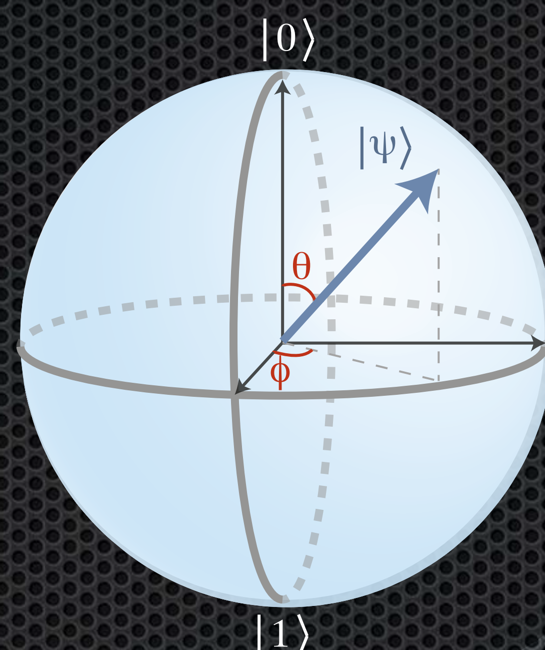
Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.

— Richard P. Feynman —

Quantum bits (qubits) - superposition logic



Bit
A classical computer encodes information in strings of bits which can take 0 or 1 value

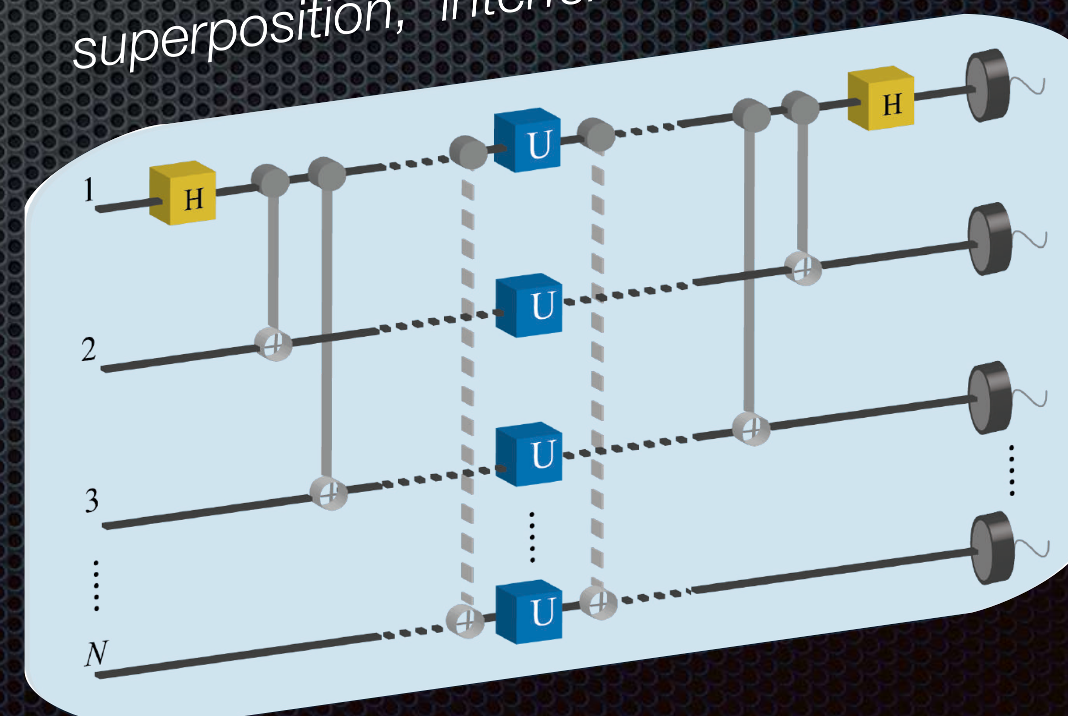


Qubit
Quantum Bits can be encoded in two-level systems (i.e. 1/2-spin, up and down state) and can exist in a superposition of 0 and 1 simultaneously. It can be represented as a vector in the Bloch sphere.

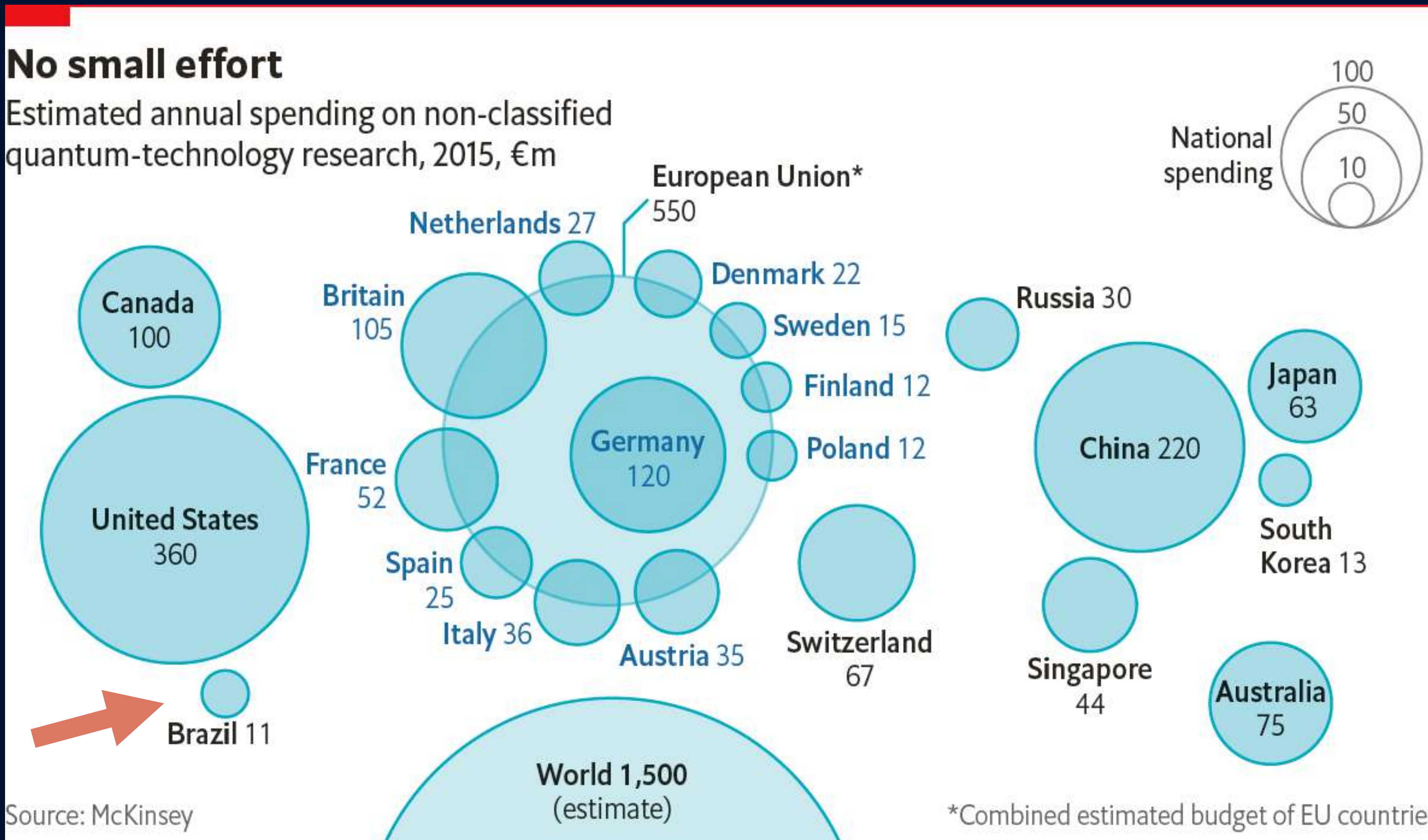
$$|\psi\rangle = \cos\frac{\theta}{2}\,|0\rangle + e^{i\phi}\sin\frac{\theta}{2}\,|1\rangle$$

Quantum advantage
massive parallel processing w/ quantum logic

Quantum algorithms
superposition, interference , entanglement



Huge investment on quantum technology - **second quantum revolution**



The Economist

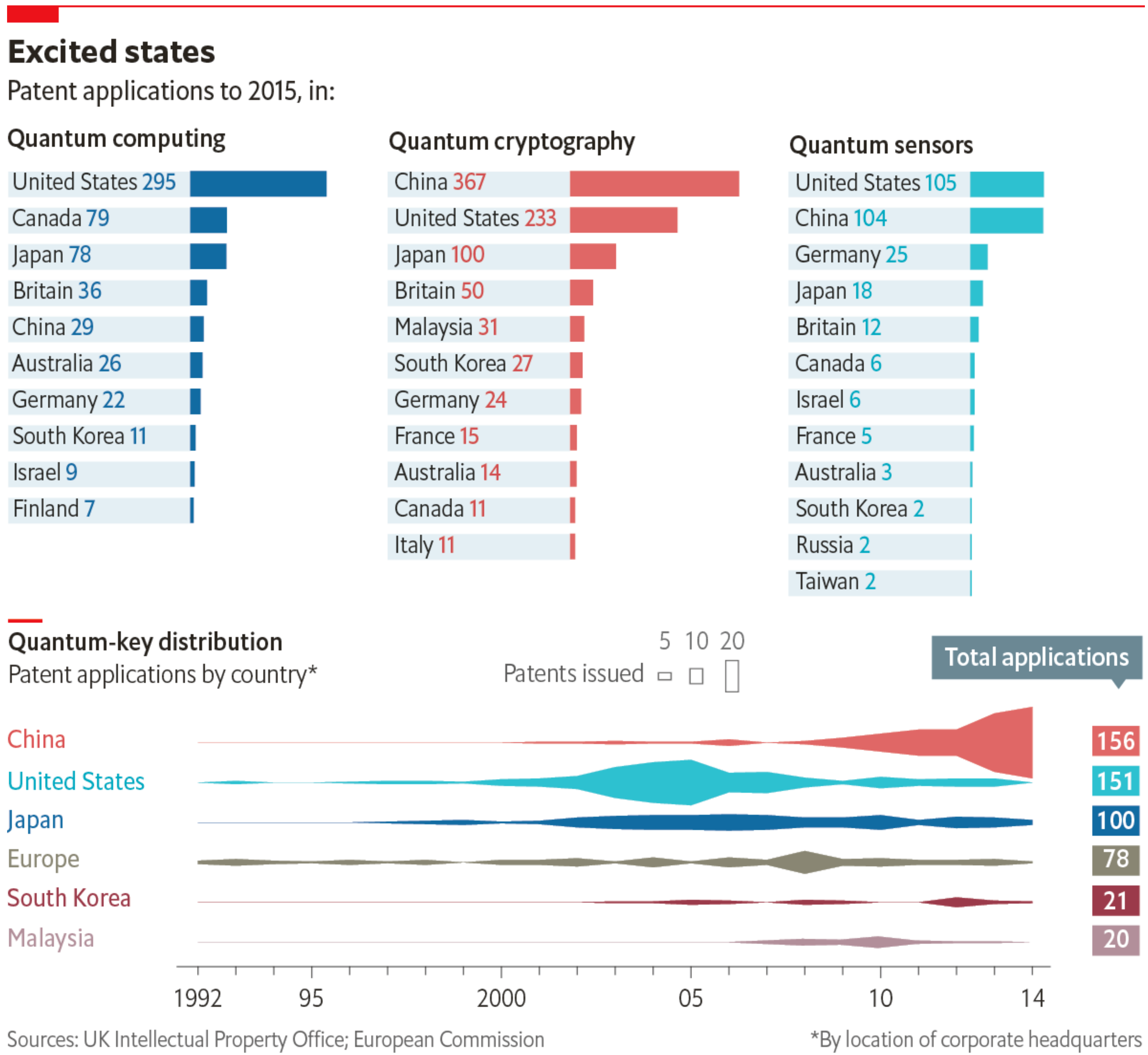
“Technology Quarterly Here, There and Everywhere," The Economist (2017)

INCT-IQ

Brazilian National Institute for Science and Technology of Quantum Information

120 Principal investigators
29 research institutions
13 states e 25 cities
Hundreds of PhD and MSc students
Dozens of Postdoctoral researchers

"Technology Quarterly Here, There and Everywhere," The Economist (2017)



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AIP | American Institute of Physics

FYI Bulletin

SCIENCE POLICY NEWS FROM AIP

National Quantum Initiative Signed into Law

SHARE THIS

Publication date: January 2019 Number: 2

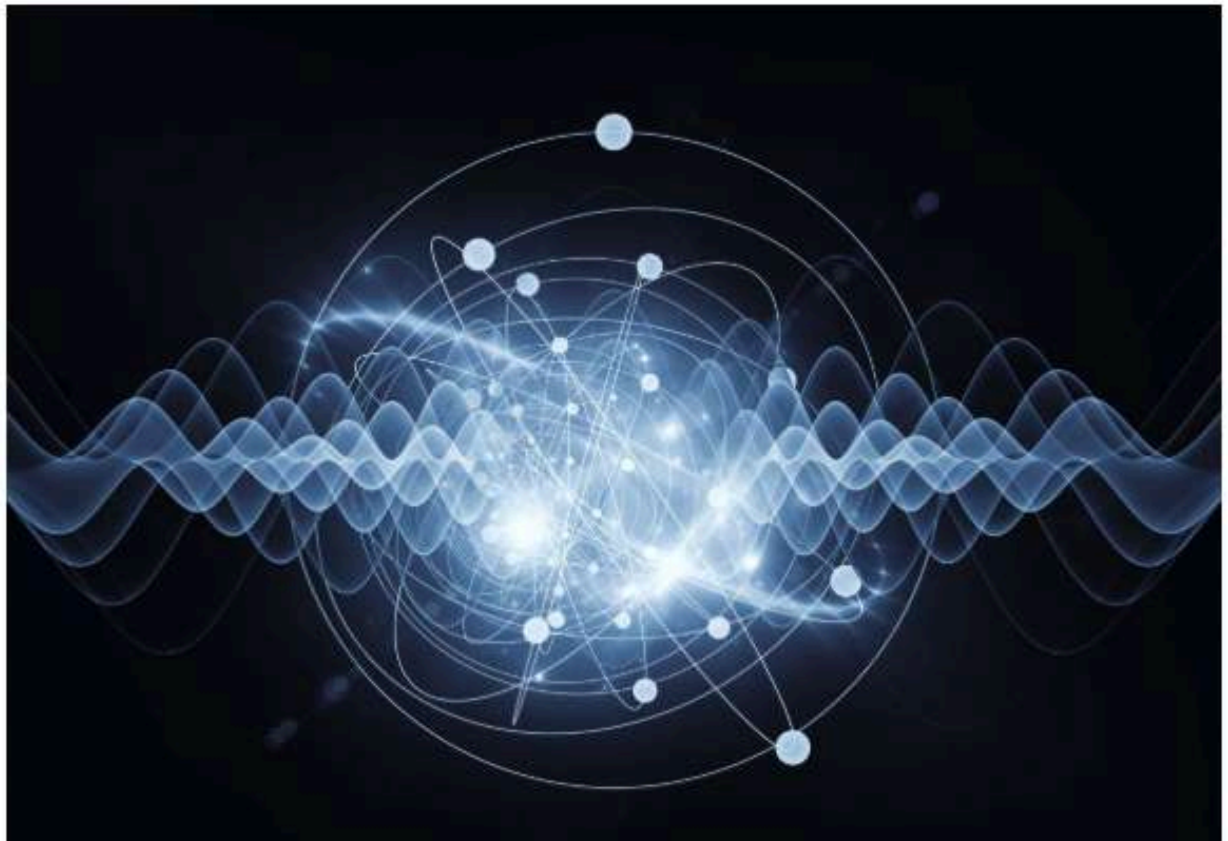
The enactment of the National Quantum Initiative Act on Dec. 21 creates a multiagency program spanning the National Institute of Standards and Technology, National Science Foundation, and Department of Energy. As part of the initiative, NSF and DOE will each establish between two and five competitively awarded research centers.

President Trump poses with the signed National Quantum Initiative Act. Behind him

European Commission

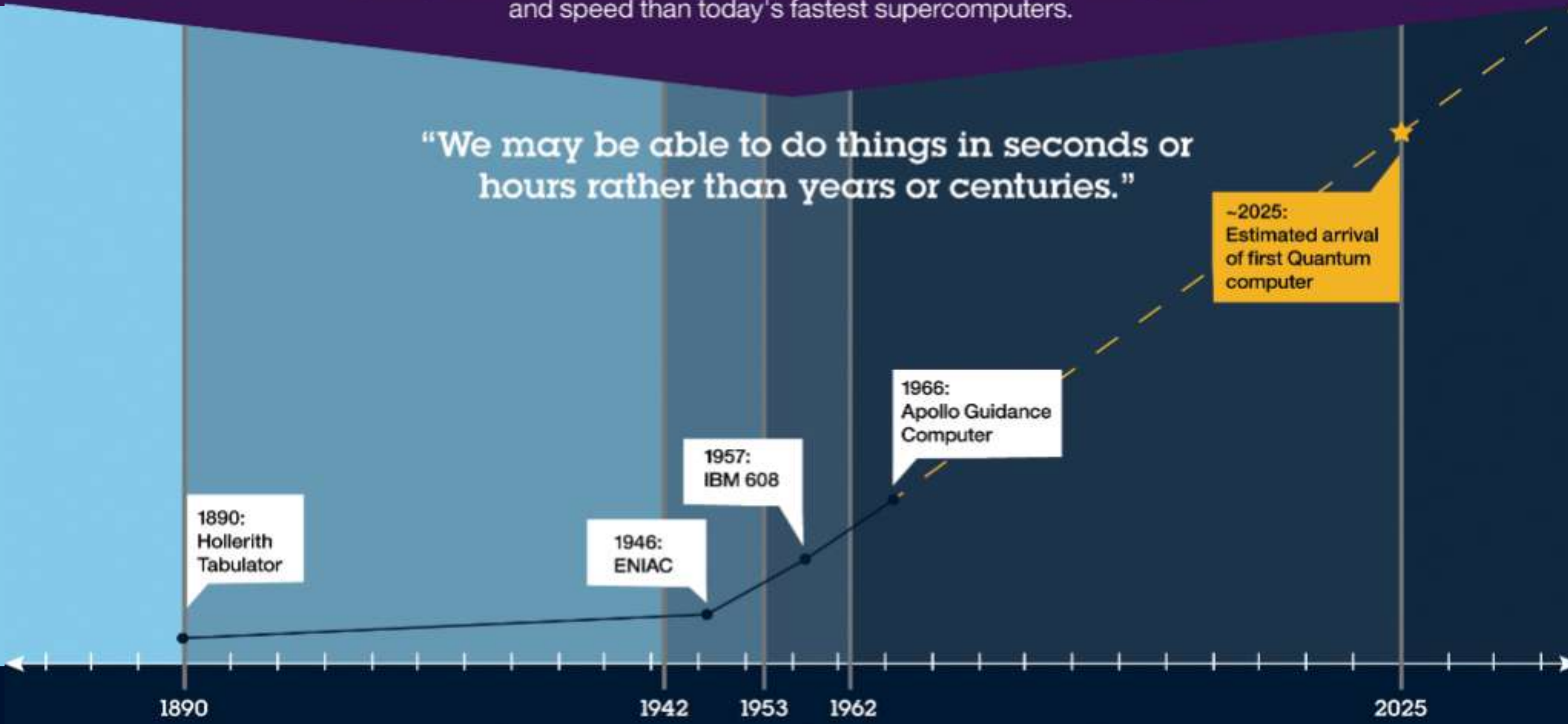
Quantum Technologies Flagship

The Quantum Technologies Flagship aims to place Europe at the forefront of the second quantum revolution, bringing transformative advances to science, industry and society.



THE QUANTUM LEAP

Quantum is a fundamentally new type of computer, based on the principles of quantum mechanics, that promises exponentially more power and speed than today's fastest supercomputers.



1890–1940s
Electromechanical
Used physical relays to perform simple calculations with great speed and reliability.

1942–1950s
Vacuum Tube
Allowed control of electrical current in machines, making the leap to the digital age.

1953–1960s
Transistor
Smaller, more reliable components that used less energy and generated less heat.

1962–2000s
Integrated Circuit
Miniaturized components on a single chip, increasing compute power and reducing cost.

~2025
Quantum
Harness quantum states to represent bits simultaneously for exponential growth in speed and power.

NewScientist Jan. 2019

DAILY NEWS 8 January 2019

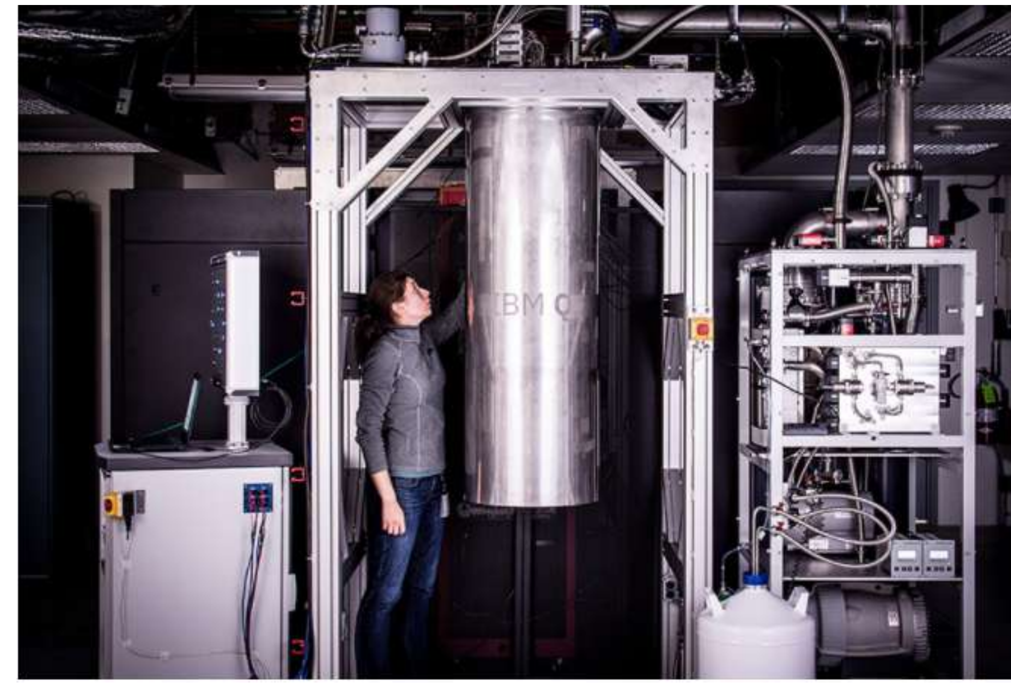
IBM unveils its first commercial quantum computer

IBM's Q System One looks the part

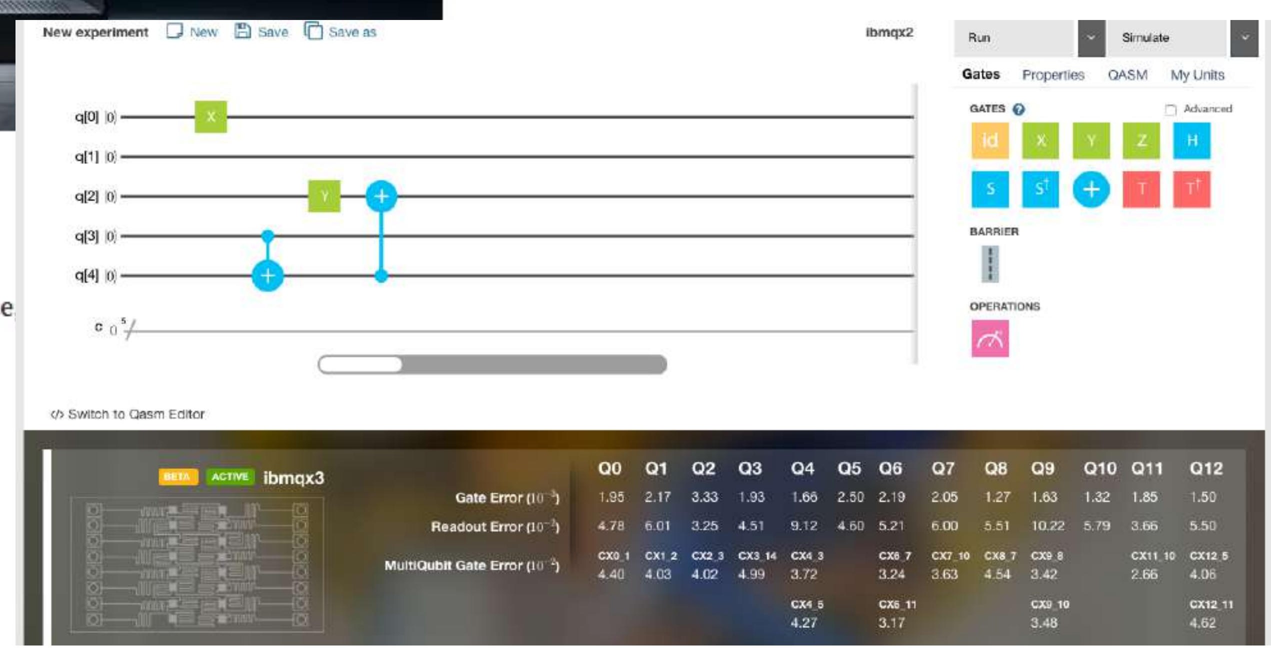
IBM

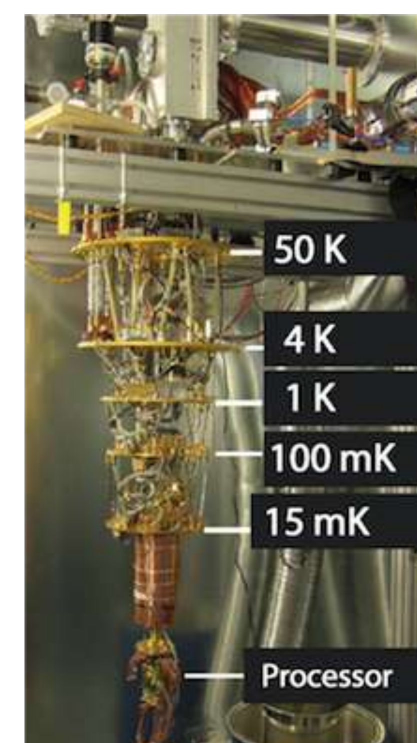
By Jacob Aron

IBM today unveiled its first ever quantum computer designed for commercial use



IBM quantum ide





UNIVERSAL
QUANTUM COMPUTING

GATE MODEL

SUPERCONDUCTING QUBITS
Google 72
IBM 50
rigetti 8

TOPOLOGICAL QUBITS
Microsoft
NONE YET

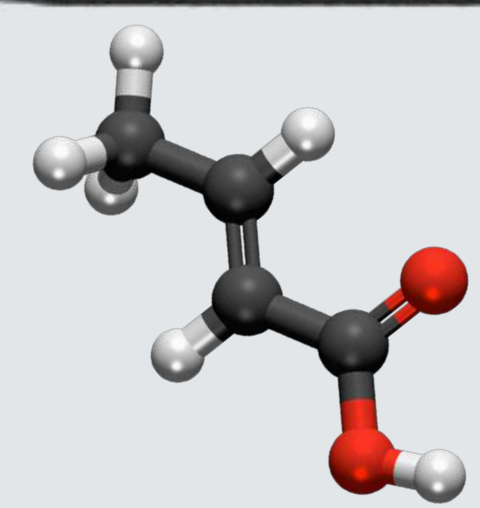
QUANTUM DOTS
intel 2

NOT-UNIVERSAL
QUANTUM COMPUTING

QUANTUM ANNEALING
D:WAVE 2048
The Quantum Computing Company™
Google 2
SUPERCONDUCTING QUBITS

ION TRAP
NIST
University of Maryland 53
MIT 51
HARVARD UNIVERSITY

Brazil



Liquid-state NMR
3 or 4 qubits - Nuclear Spin

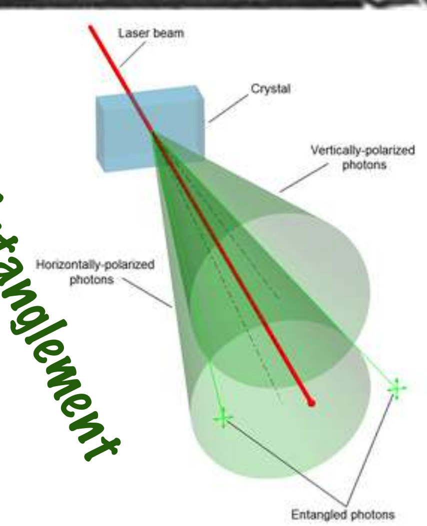
UFABC
CBPF

Hight fidelity universal gates

Single photons
UFABC
UFRJ
UFMG
UFSC

Linear optics

Entanglement



Ground-to-satellite quantum teleportation & quantum cryptograph

nature International weekly journal of science

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News & Comment > News > 2017 > August > Article

NATURE | NEWS

China's quantum satellite clears major hurdle on way to ultrasecure communications

Probe sends entangled photons — which could underpin quantum-based data encryption — over unprecedented distance.

Davide Castelvecchi

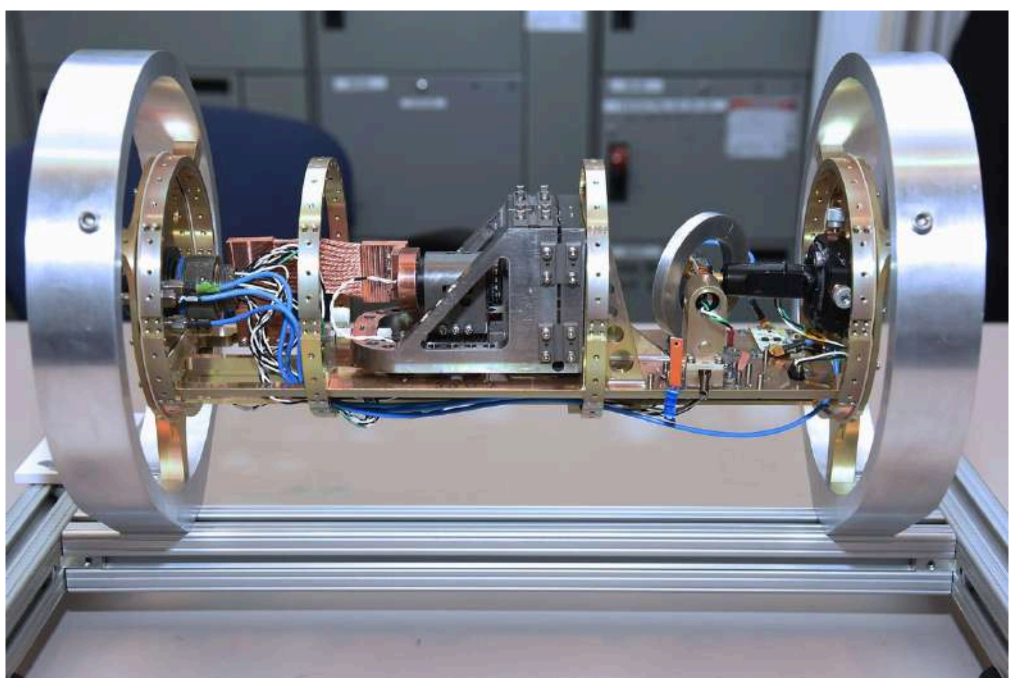
15 June 2017

WIRED

SOPHIA CHEN SCIENCE 11.01.18 08:00 AM

QUANTUM PHYSICISTS FOUND A NEW, SAFER WAY TO NAVIGATE

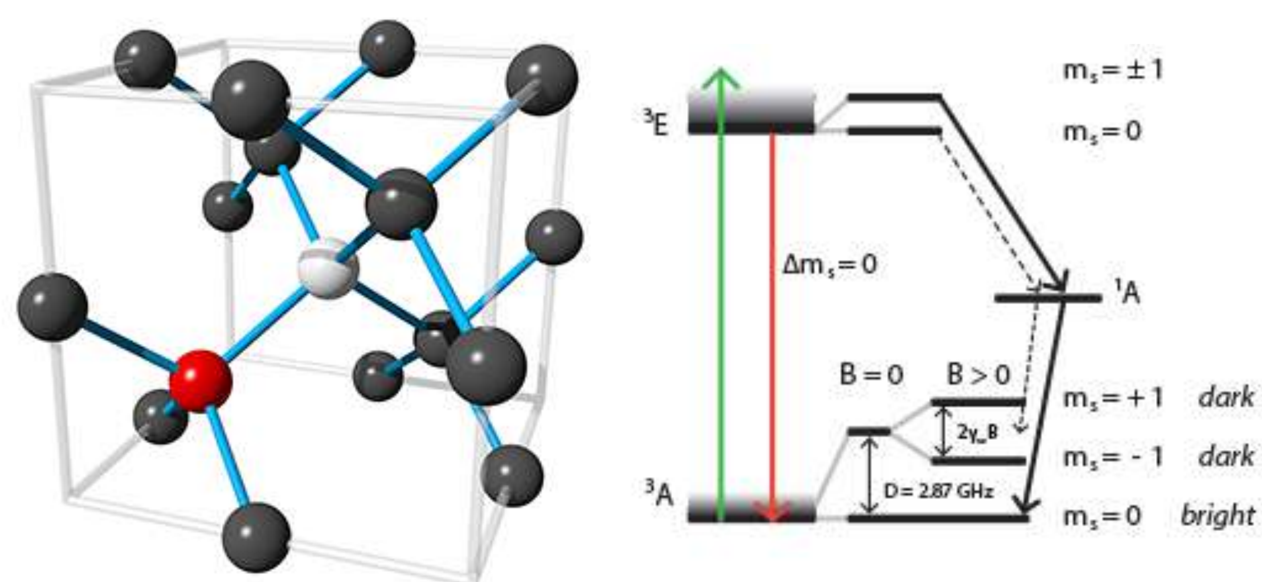
LOCKHEED MARTIN



Quantum magnetometer

After a series of high profile GPS hacks and failures, WIRED reported, the U.S. military and several national labs are working on new **quantum navigators** that could revolutionize global positioning systems by cutting out the need for satellite.

NV center in diamond



Let’s Back to computation

UFABC

Easy and difficult computational tasks

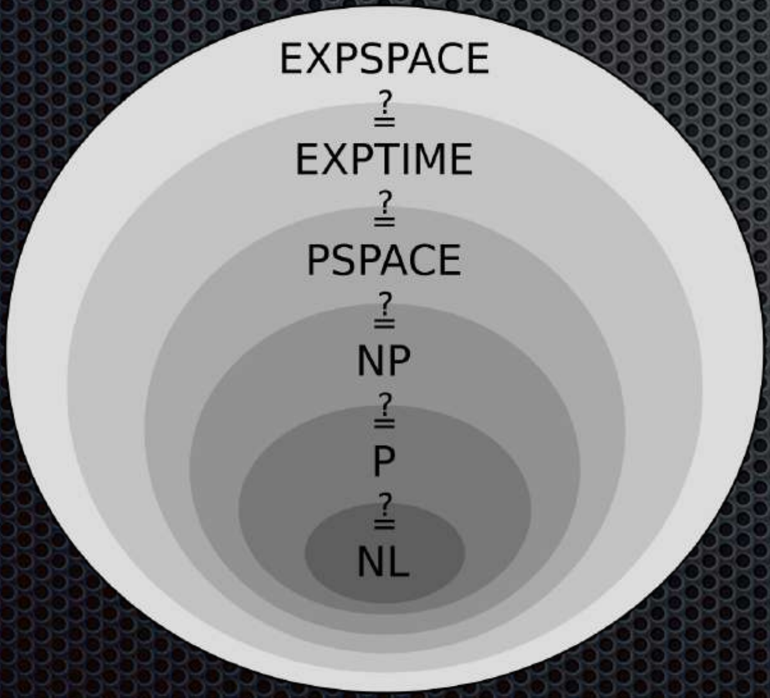
11245 + 33456 — Adding n digits numbers requires n elementary operations

11245 x 33456 — Adding n digits numbers requires n^2 elementary operations

$11245334 = p_1 \times p_2$ — Factoring a n digit number requires

$$\approx \exp\left[\sqrt[3]{\frac{64}{9}\,(\ln n)\,(\ln\ln n)^2}\right] > n^k$$

elementary operations

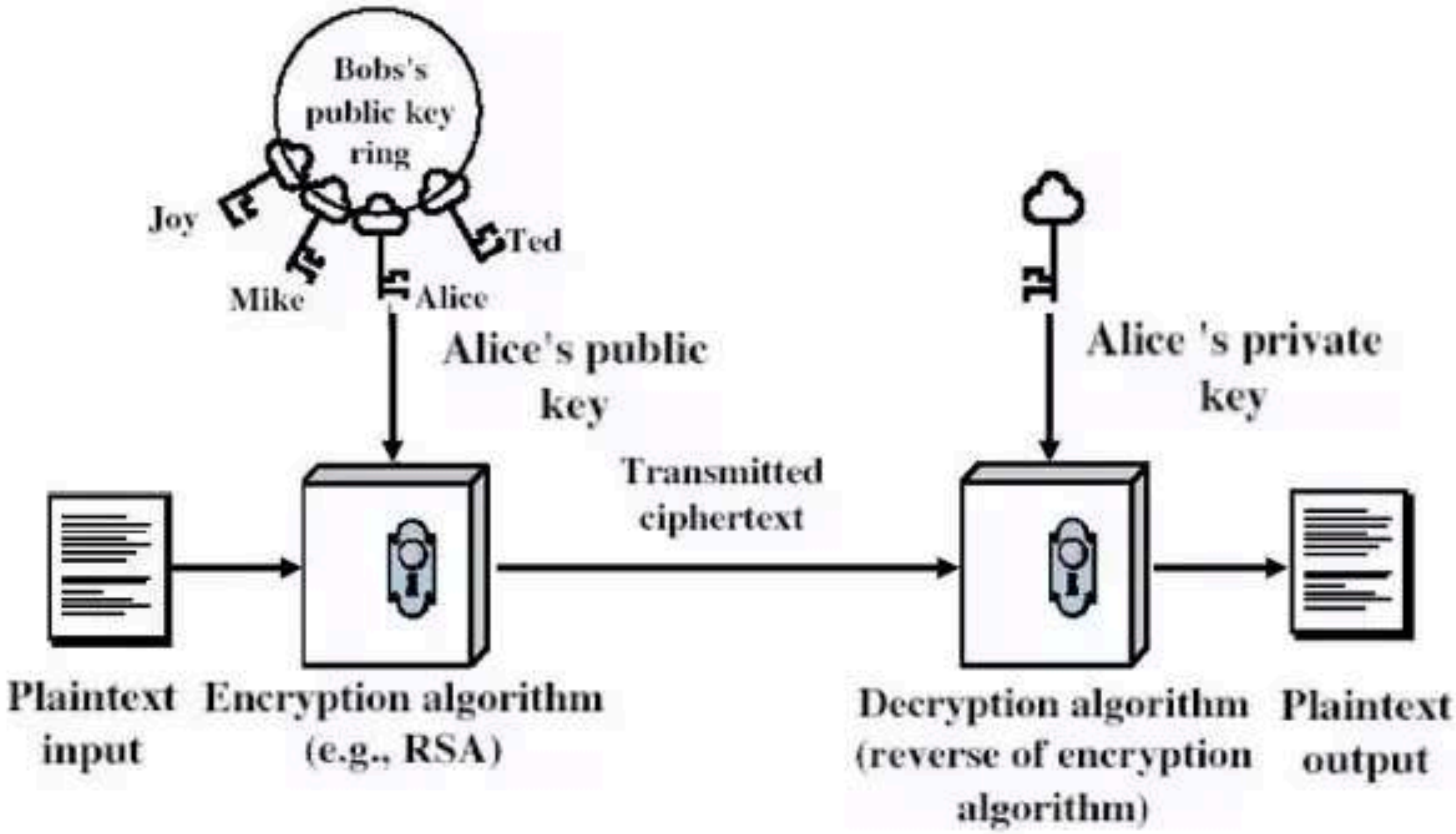


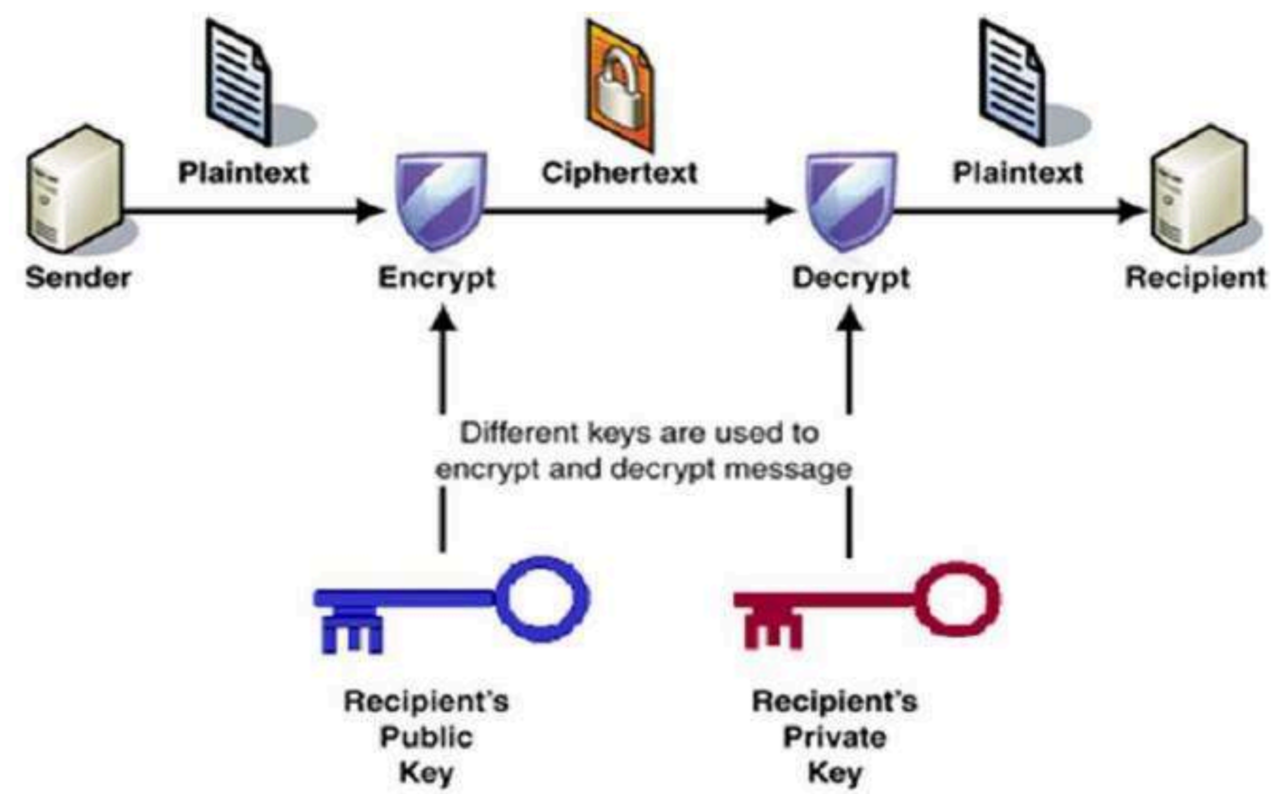
Computational complexity

travelling salesman is a NP problem

3-sat logical clauses satisfability is a NP problem

Public-Key Cryptography

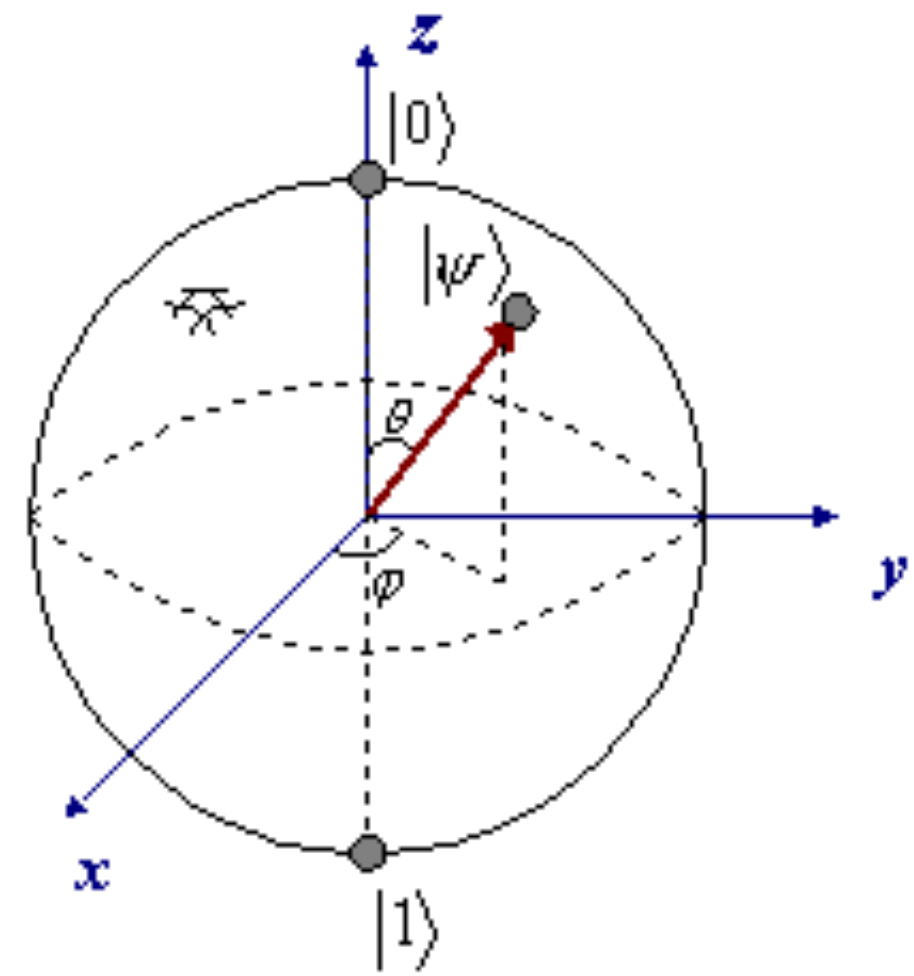




Quantum Computation

The most general state of a quantum bit (qubit)

$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$



$$|0\rangle \rightarrow \begin{pmatrix}1\\0\end{pmatrix} \qquad |1\rangle \rightarrow \begin{pmatrix}0\\1\end{pmatrix} \qquad |\psi\rangle \rightarrow \begin{pmatrix}\cos\theta/2\\ e^{i\varphi}\sin\theta/2\end{pmatrix}$$

$$\vec{v}_B = (x, y, z)$$

$$x = \langle\psi|\hat{\sigma}_x|\psi\rangle,$$
$$y = \langle\psi|\hat{\sigma}_y|\psi\rangle,$$
$$z = \langle\psi|\hat{\sigma}_z|\psi\rangle.$$

$$\hat{\sigma}_x = \begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix},$$

$$\hat{\sigma}_y = \begin{pmatrix}0 & i\\ -i & 0\end{pmatrix},$$

$$\hat{\sigma}_z = \begin{pmatrix}0 & i\\ -i & 0\end{pmatrix},$$

$$Base \ \{|0\rangle, |1\rangle\}$$

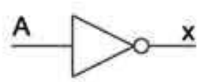
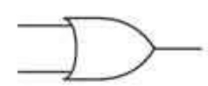
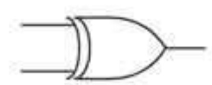
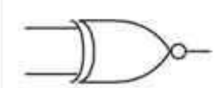
$$M : |\psi\rangle \longrightarrow \vec{v}_B$$

$$\varepsilon \rightarrow \Re^3$$

Classical computational model

UFABC

Logic Gates

Name	NOT	AND	NAND	OR	NOR	XOR	XNOR
Alg. Expr.	$\overline{A}$	AB	$\overline{AB}$	$A+B$	$\overline{A+B}$	$A\oplus B$	$\overline{A\oplus B}$
Symbol							
Truth Table	A X 0 **1** 1 **0**	B A X 0 0 **0** 0 1 **0** 1 0 **0** 1 1 **1**	B A X 0 0 **1** 0 1 **1** 1 0 **1** 1 1 **0**	B A X 0 0 **0** 0 1 **1** 1 0 **1** 1 1 **1**	B A X 0 0 **1** 0 1 **0** 1 0 **0** 1 1 **0**	B A X 0 0 **0** 0 1 **1** 1 0 **1** 1 1 **0**	B A X 0 0 **1** 0 1 **0** 1 0 **0** 1 1 **1**

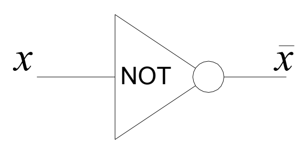
Classical 1 bit logic gate

a	not a
0	1
1	0

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \xrightarrow{X} |\psi\rangle = \alpha|1\rangle + \beta|0\rangle$$

$$X \equiv \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad X\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} \beta \\ \alpha \end{pmatrix}$$

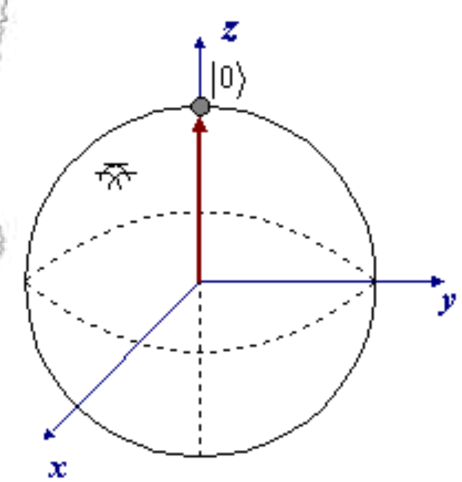
Hadamard quantum logic gate $H \equiv \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$ $\quad H\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} \alpha+\beta \\ \alpha-\beta \end{pmatrix}$



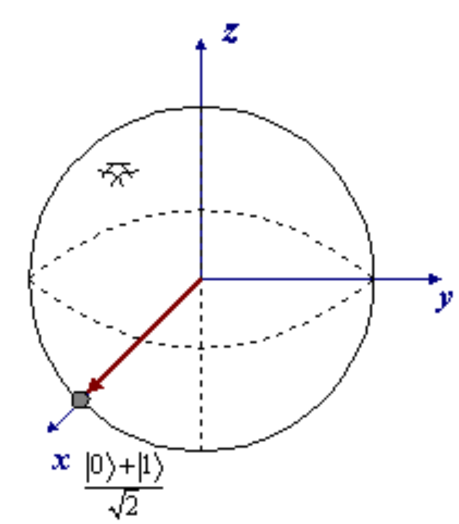
$$\alpha|0\rangle + \beta|1\rangle \; \boxed{X} \; \beta|0\rangle + \alpha|1\rangle$$

$$\alpha|0\rangle + \beta|1\rangle \; \boxed{Z} \; \alpha|0\rangle - \beta|1\rangle$$

$$\alpha|0\rangle + \beta|1\rangle \; \boxed{H} \; \frac{\alpha+\beta}{\sqrt{2}}|0\rangle + \frac{\alpha-\beta}{\sqrt{2}}|1\rangle$$



$$|0\rangle \xrightarrow{\textit{Hadamard}} \frac{|0\rangle + |1\rangle}{\sqrt{2}}$$



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Qubit rotations

$$\boxed{\hat{R}_{\vec{n}}(\theta) = \exp\left(-i\frac{\theta}{2}\vec{n}\cdot\hat{\vec{\sigma}}\right) = \cos\left(\frac{\theta}{2}\right)\hat{1} - i\sin\left(\frac{\theta}{2}\right)\vec{n}\cdot\hat{\vec{\sigma}}}$$

$$R_X(\theta) \equiv \cos\left(\frac{\theta}{2}\right)\hat{1} - i\sin\left(\frac{\theta}{2}\right)\hat{X} = \begin{bmatrix} \cos\left(\frac{\theta}{2}\right) & -i\sin\left(\frac{\theta}{2}\right) \\ -i\sin\left(\frac{\theta}{2}\right) & \cos\left(\frac{\theta}{2}\right) \end{bmatrix}$$

$$R_Y(\theta) \equiv \cos\left(\frac{\theta}{2}\right)\hat{1} - i\sin\left(\frac{\theta}{2}\right)\hat{Y} = \begin{bmatrix} \cos\left(\frac{\theta}{2}\right) & -\sin\left(\frac{\theta}{2}\right) \\ \sin\left(\frac{\theta}{2}\right) & \cos\left(\frac{\theta}{2}\right) \end{bmatrix}$$

$$R_Z(\theta) \equiv \cos\left(\frac{\theta}{2}\right)\hat{1} - i\sin\left(\frac{\theta}{2}\right)\hat{Z} = \begin{bmatrix} e^{-i\theta/2} & 0 \\ 0 & e^{i\theta/2} \end{bmatrix}$$

Some identities

$HXH = Z$ $\qquad$ $HYH = -Y$ $\qquad$ $HZH = X$

$$\boxed{H = \frac{1}{\sqrt{2}}(X + Z) = R_Y\left(\frac{\pi}{2}\right)}$$

No-cloning theorem

It is impossible to copy unknown quantum information

Suppose that, we want to copy the state psi to a blank state of an auxiliary system

$$|\psi\rangle_S \otimes |B\rangle_M .$$

A unitary operation can produce the copy as

$$|\psi\rangle_S \otimes |B\rangle_M \xrightarrow{U} \hat{U}\left(|\psi\rangle_S \otimes |B\rangle_M\right) = |\psi\rangle_S \otimes |\psi\rangle_M .$$

A universal copy machine should work for a different state, let us say phi

$$\hat{U}\left(|\psi\rangle_S \otimes |B\rangle_M\right) = |\psi\rangle_S \otimes |\psi\rangle_M ,$$
$$\hat{U}\left(|\varphi\rangle_S \otimes |B\rangle_M\right) = |\varphi\rangle_S \otimes |\varphi\rangle_M .$$

What happens when we apply this unitary to a superposition state?

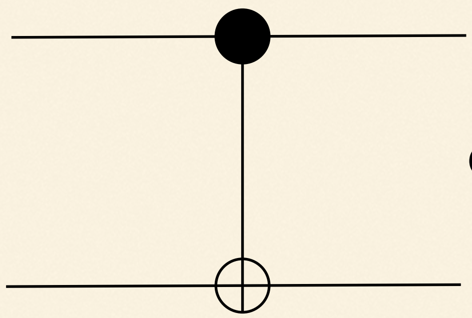
$$\begin{aligned}\hat{U}\left[\left(|\psi\rangle_S + |\varphi\rangle_S\right) \otimes |B\rangle_M\right] &= \hat{U}\left(|\psi\rangle_S \otimes |B\rangle_M\right) + \hat{U}\left(|\varphi\rangle_S \otimes |B\rangle_M\right) \\ &= |\psi\rangle_S \otimes |\psi\rangle_M + |\varphi\rangle_S \otimes |\varphi\rangle_M \\ &\neq \left(|\psi\rangle_S + |\varphi\rangle_S\right) \otimes \left(|\psi\rangle_M + |\varphi\rangle_M\right)\end{aligned}$$

This is not a copy
It is in fact an entangled state

W. K. Wootters and W. H. Zurek, Nature 299, 802 (1982); D. Dieks, Phys. Lett. A 92,. 271 (1982).

Two qubit logic gates

The control not gate (equivalent to the XOR)



Computacional basis $\{|00\rangle\,,\ |01\rangle\,,\ |10\rangle\,,\ |11\rangle\}$

$$|0\rangle\langle 0| \otimes \mathbb{1} + |1\rangle\langle 1| \otimes \sigma_x$$

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

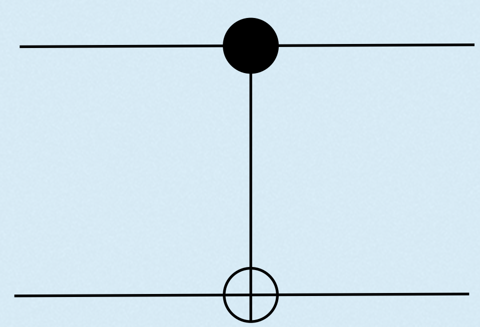
Example:

Input state

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

$$|0\rangle$$

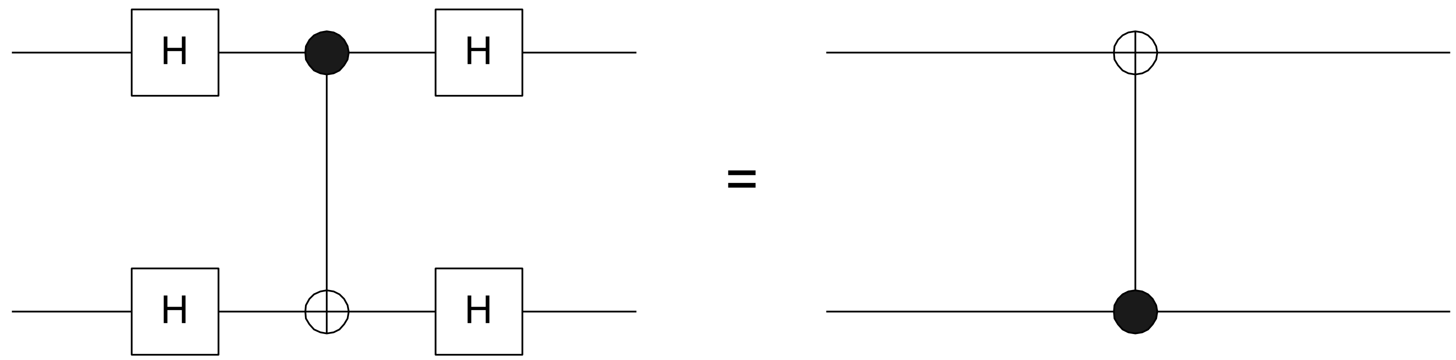
Cnot gate

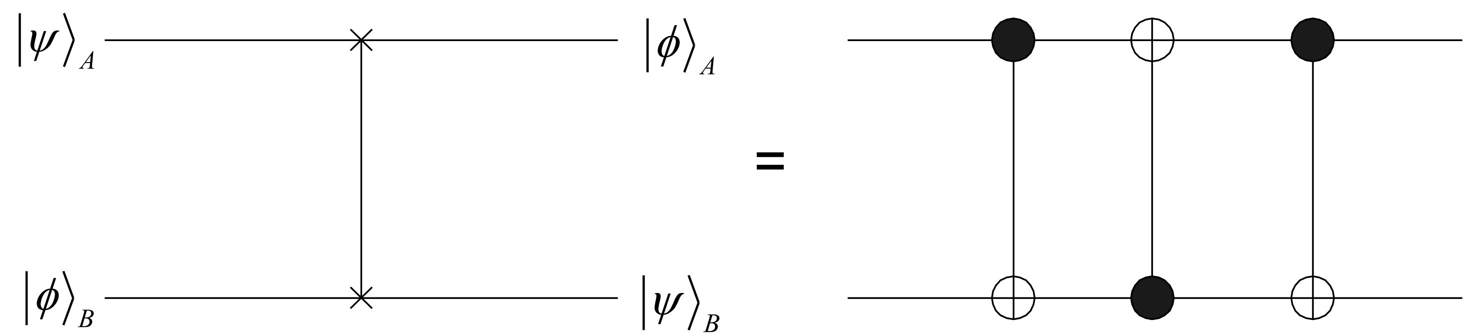


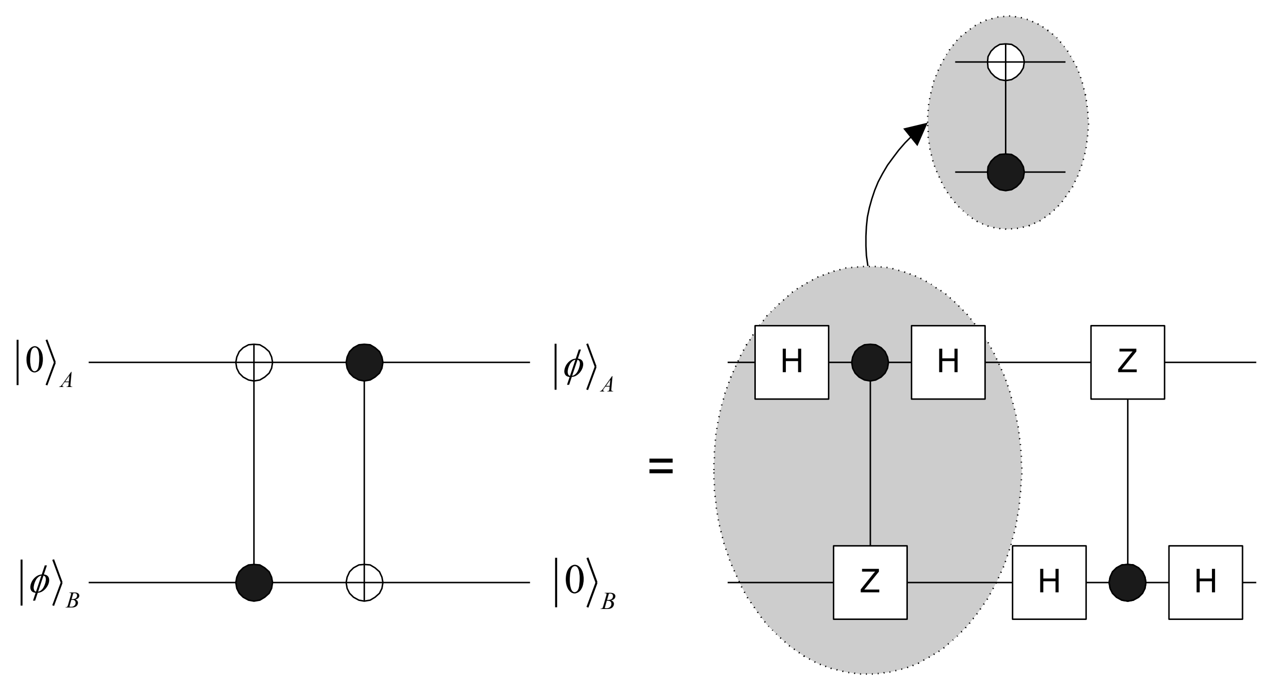
Output state

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

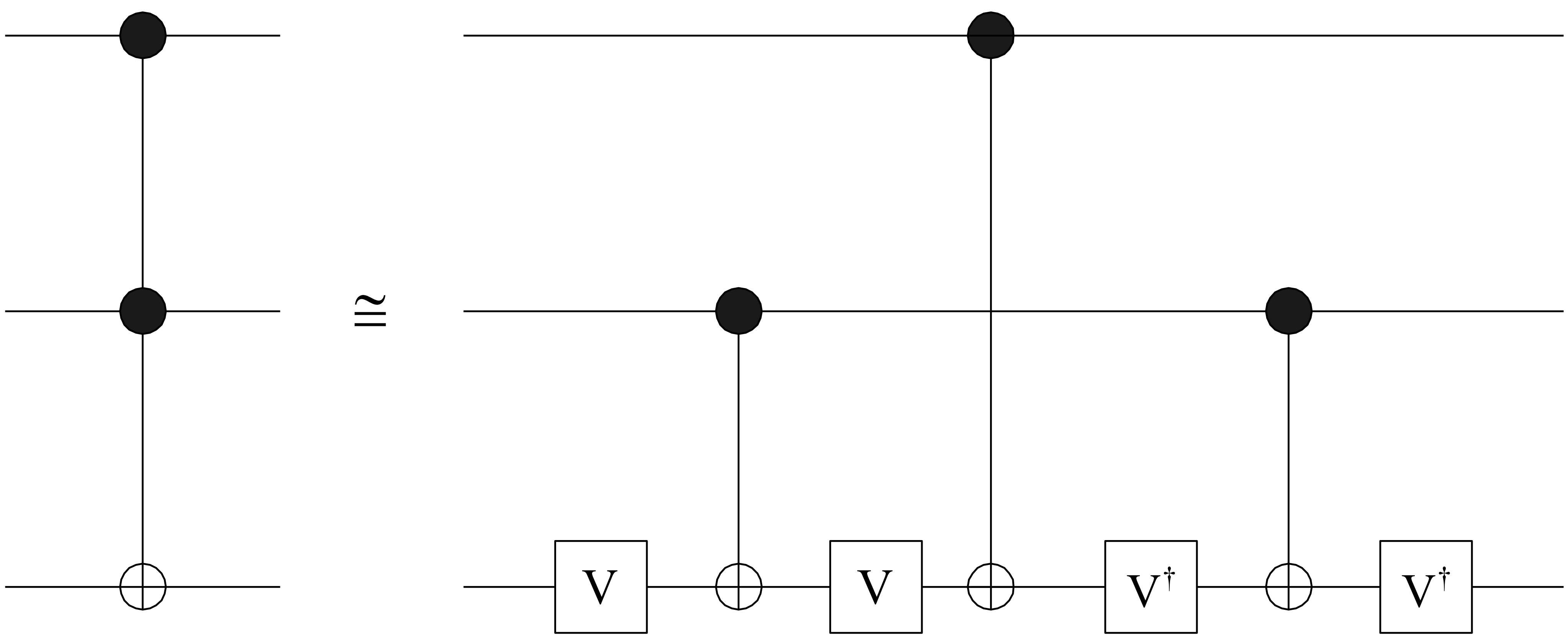
Some quantum gates identities







One qubit operations and Cnot gates are universal



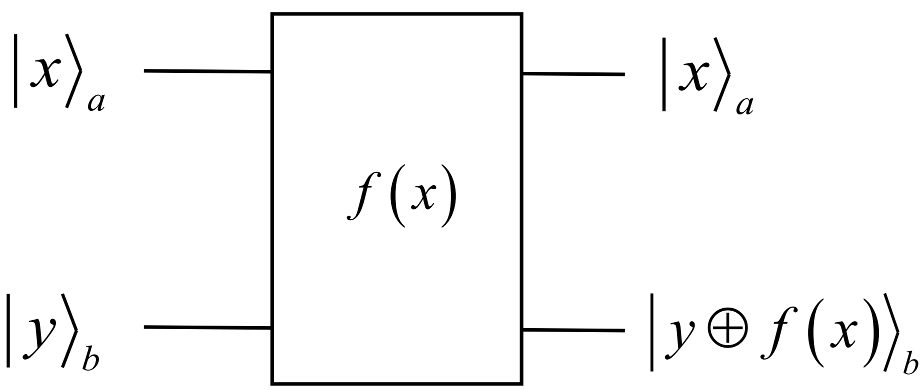
Deutsch Algorithm

quantum parallelism

D. Deutsch, Proc. R. Soc. London A **400**, 97 (1985).

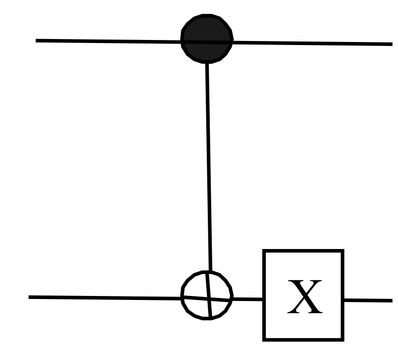
Let us consider the 1-bit function $f(x) : \{0,1\} \to \{0,1\}$

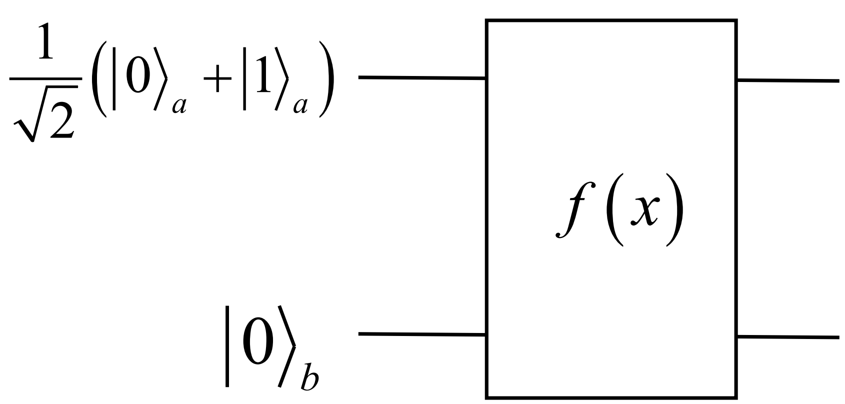
The function f (x) is computed by a oracle that you have no access



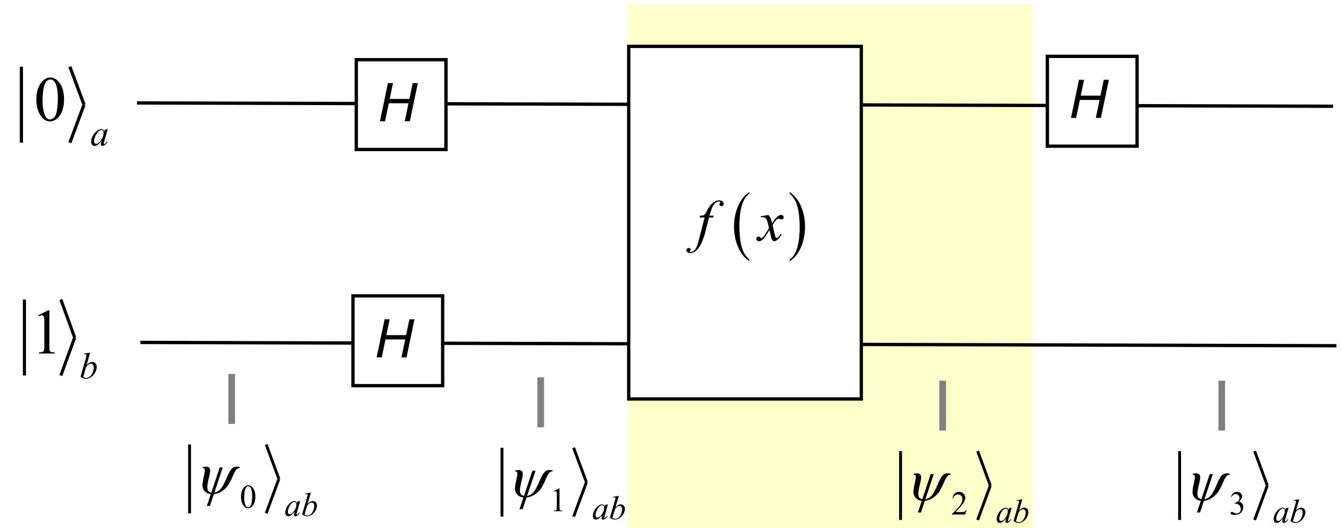
Ex.

$$f(x) = \bar{x} = \begin{cases} 1, & if \quad x = 0 \\ 0, & if \quad x = 1 \end{cases}$$





$$\frac{1}{\sqrt{2}}\left(|0\rangle_a |f(0)\rangle_b + |1\rangle_a |f(1)\rangle_b\right)$$



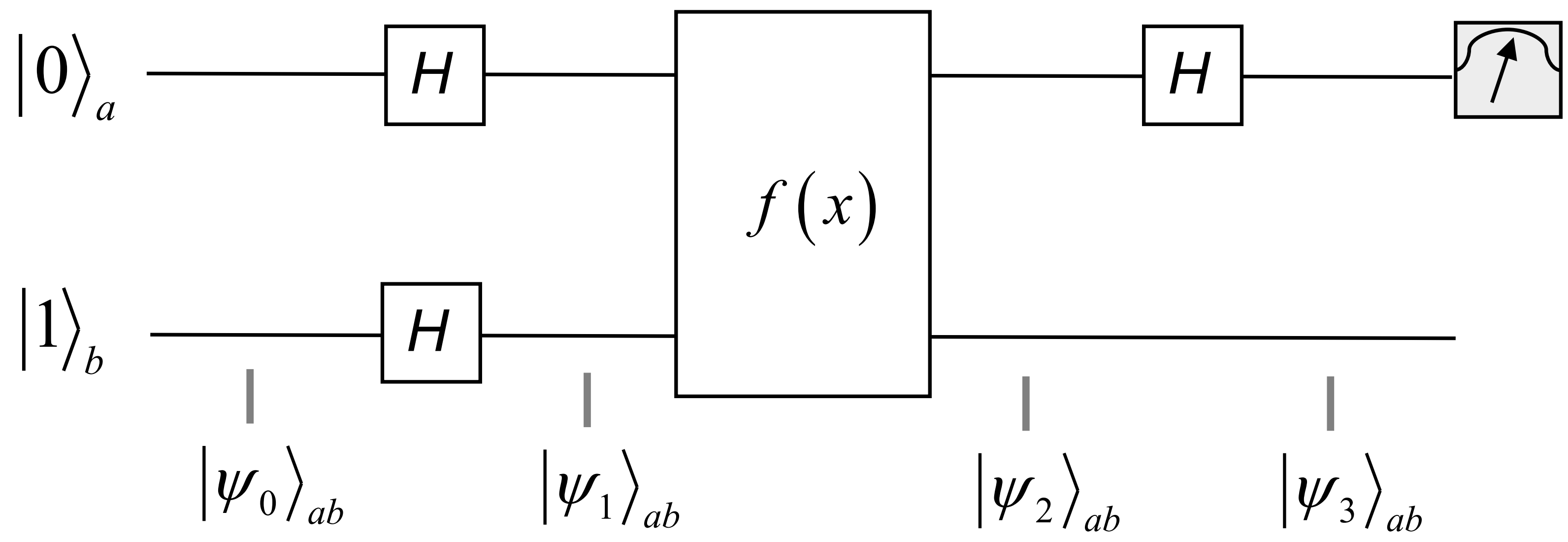
0 $|\psi_0\rangle_{ab} = |0\rangle_a |1\rangle_b$

1 $|\psi_1\rangle_{ab} = H^{\otimes 2}|0\rangle_a |1\rangle_b = \frac{1}{2}\left(|0\rangle_a + |1\rangle_a\right) \otimes \left(|0\rangle_b - |1\rangle_b\right)$

$\boxed{H^{\otimes 2} = H^{(a)} \otimes H^{(b)}}$

2 $$|\psi_2\rangle_{ab} = \frac{1}{2}\hat{U}^{ab}_{f(x)}\left[|0\rangle_a \left({}_a|0\rangle_b - |1\rangle_b\right) + |1\rangle_a \left(|0\rangle_b - |1\rangle_b\right)\right]$$
$$= \frac{1}{2}\left[(-1)^{f(0)}|0\rangle_a \left({}_a|0\rangle_b - |1\rangle_b\right) + (-1)^{f(1)}|1\rangle_a \left(|0\rangle_b - |1\rangle_b\right)\right]$$

$$|\psi_2\rangle_{ab} = \begin{cases} \frac{1}{2}(-1)^{f(0)}\left(|0\rangle_a + |1\rangle_a\right)\left({}_a|0\rangle_b - |1\rangle_b\right), & if \quad f(0) = f(1) \\ \frac{1}{2}(-1)^{f(0)}\left(|0\rangle_a - |1\rangle_a\right)\left({}_a|0\rangle_b - |1\rangle_b\right), & if \quad f(0) \neq f(1) \end{cases}$$



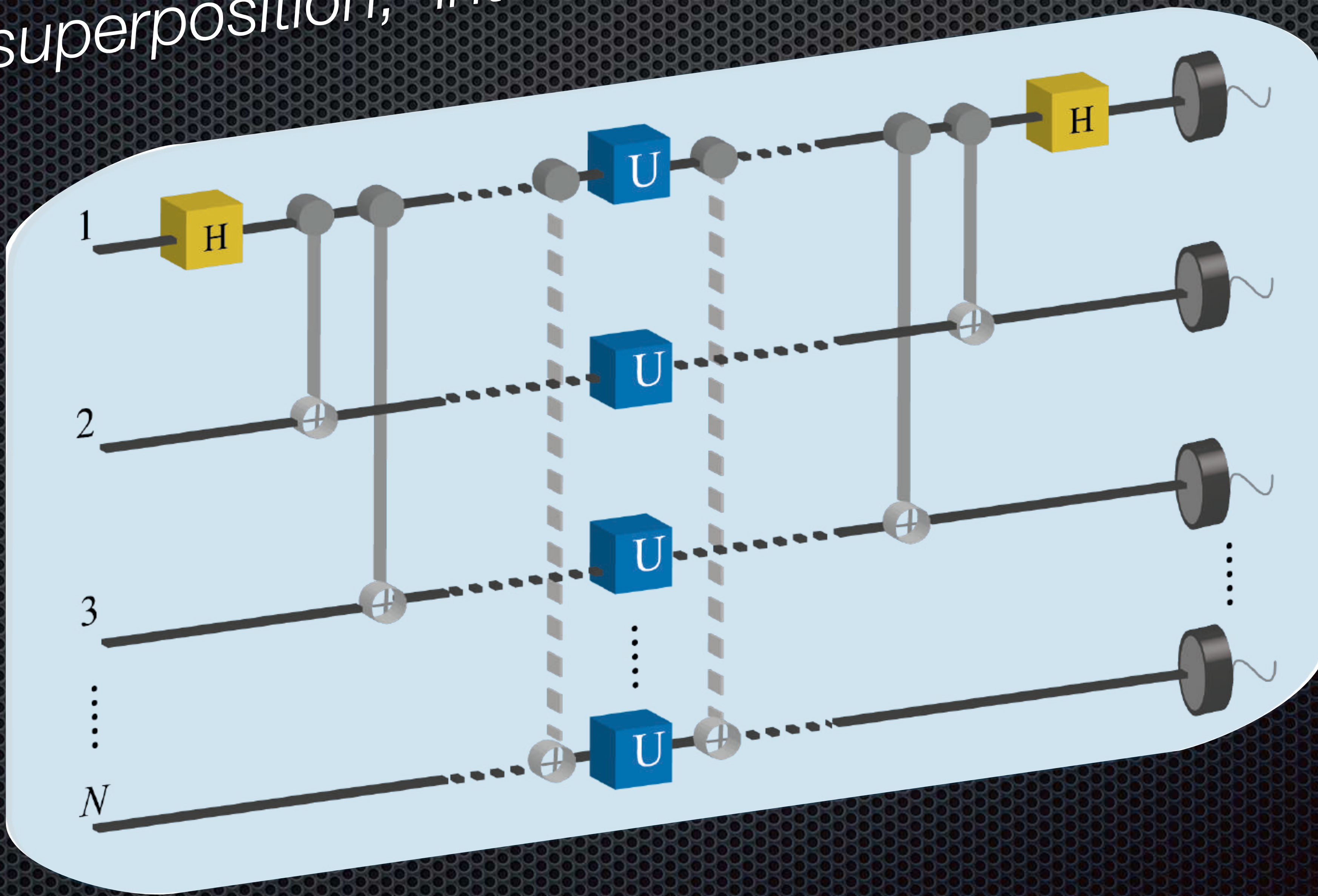
3 $$|\psi_3\rangle_{ab} = H^{(a)}|\psi_2\rangle_{ab} = \begin{cases} \frac{1}{\sqrt{2}}(-1)^{f(0)}|0\rangle_a\left({}_a|0\rangle_b - |1\rangle_b\right), & if \quad f(0) = f(1) \\ \frac{1}{\sqrt{2}}(-1)^{f(0)}|1\rangle_a\left({}_a|0\rangle_b - |1\rangle_b\right), & if \quad f(0) \neq f(1) \end{cases}$$

$$|\psi_3\rangle_{ab} = (-1)^{f(0)}|f(0)\oplus f(1)\rangle_a \frac{1}{\sqrt{2}}\left(|0\rangle_b - |1\rangle_b\right)$$

$$f(0)\oplus f(1) = \begin{cases} 0, & if \quad f(0) = f(1) \\ 1, & if \quad f(0) \neq f(1) \end{cases}$$

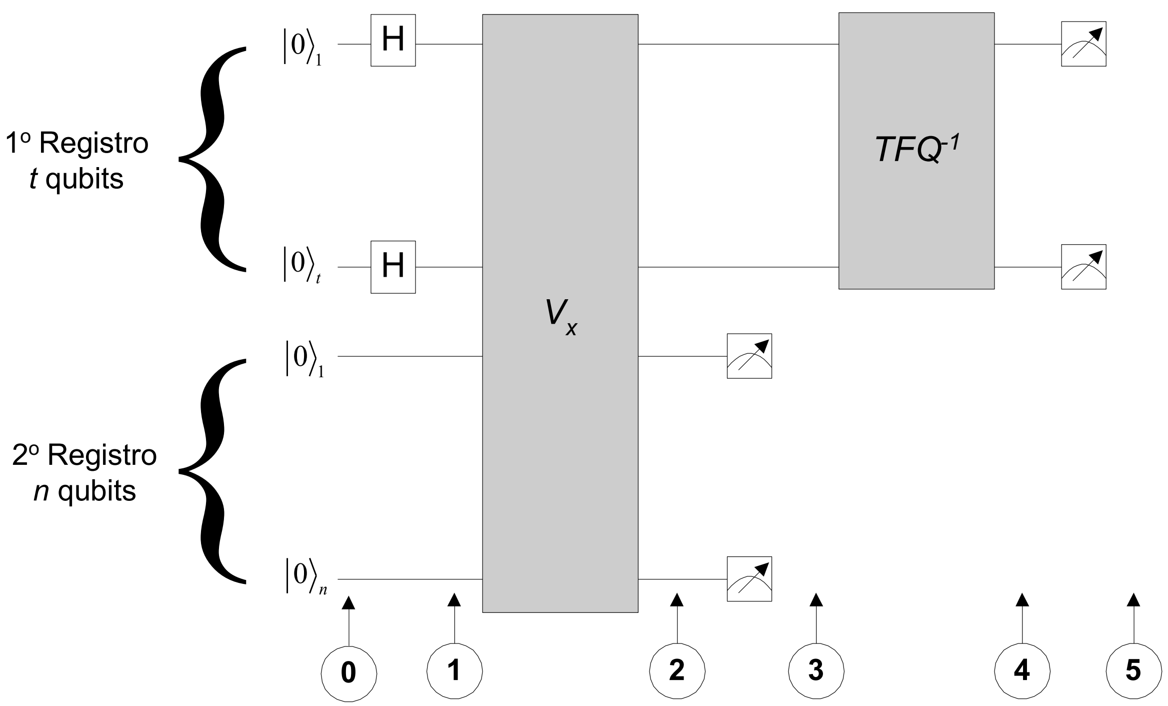
Quantum algorithms

superposition, interference , entanglement

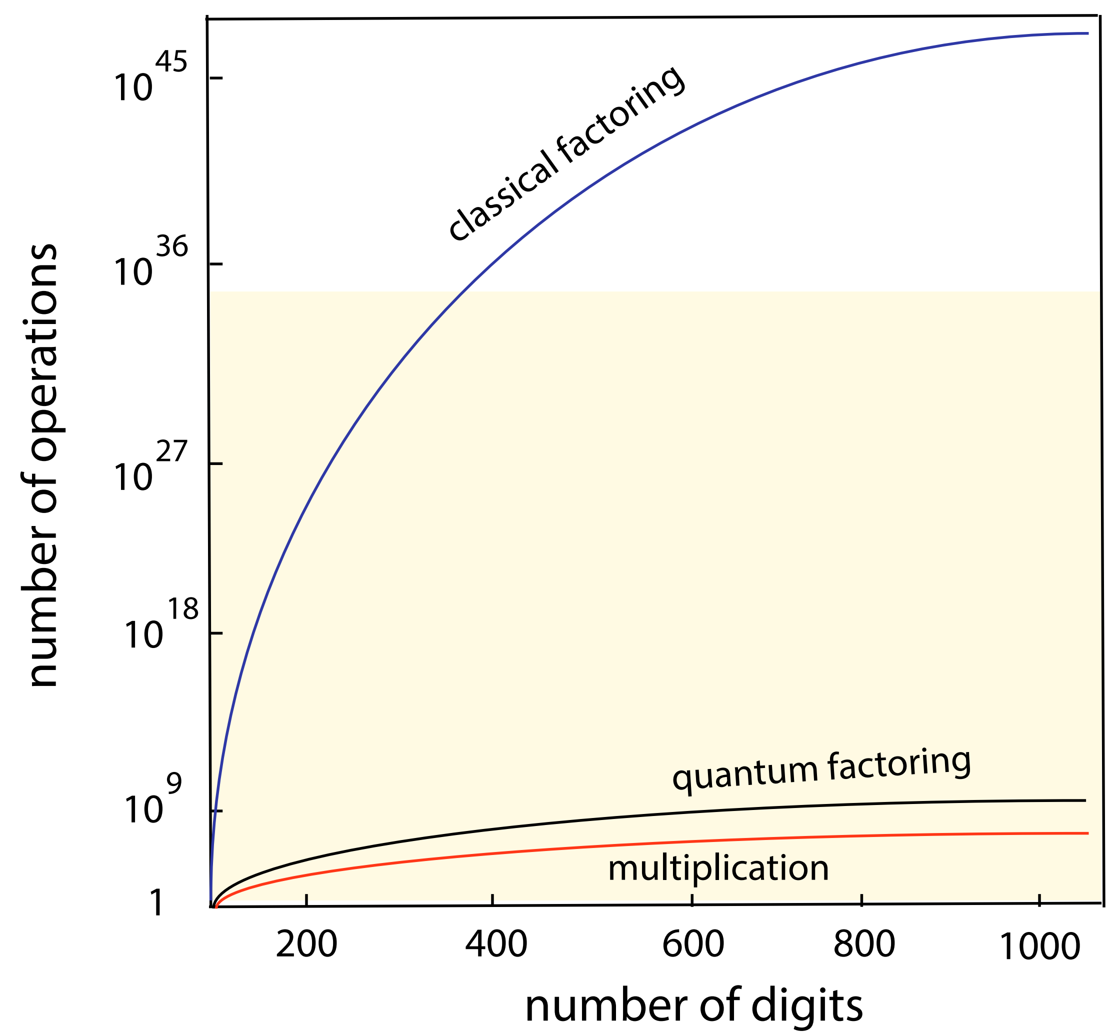


UFABC

Shor's factoring algorithm



about n^3 elementary operations

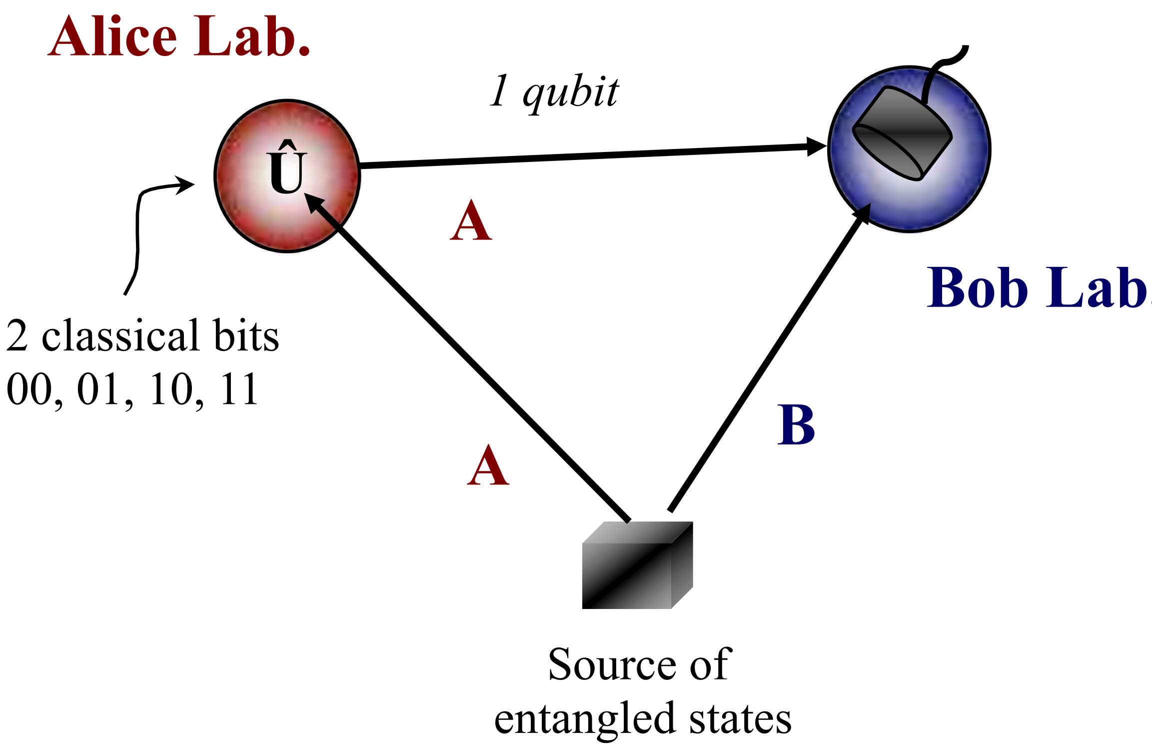


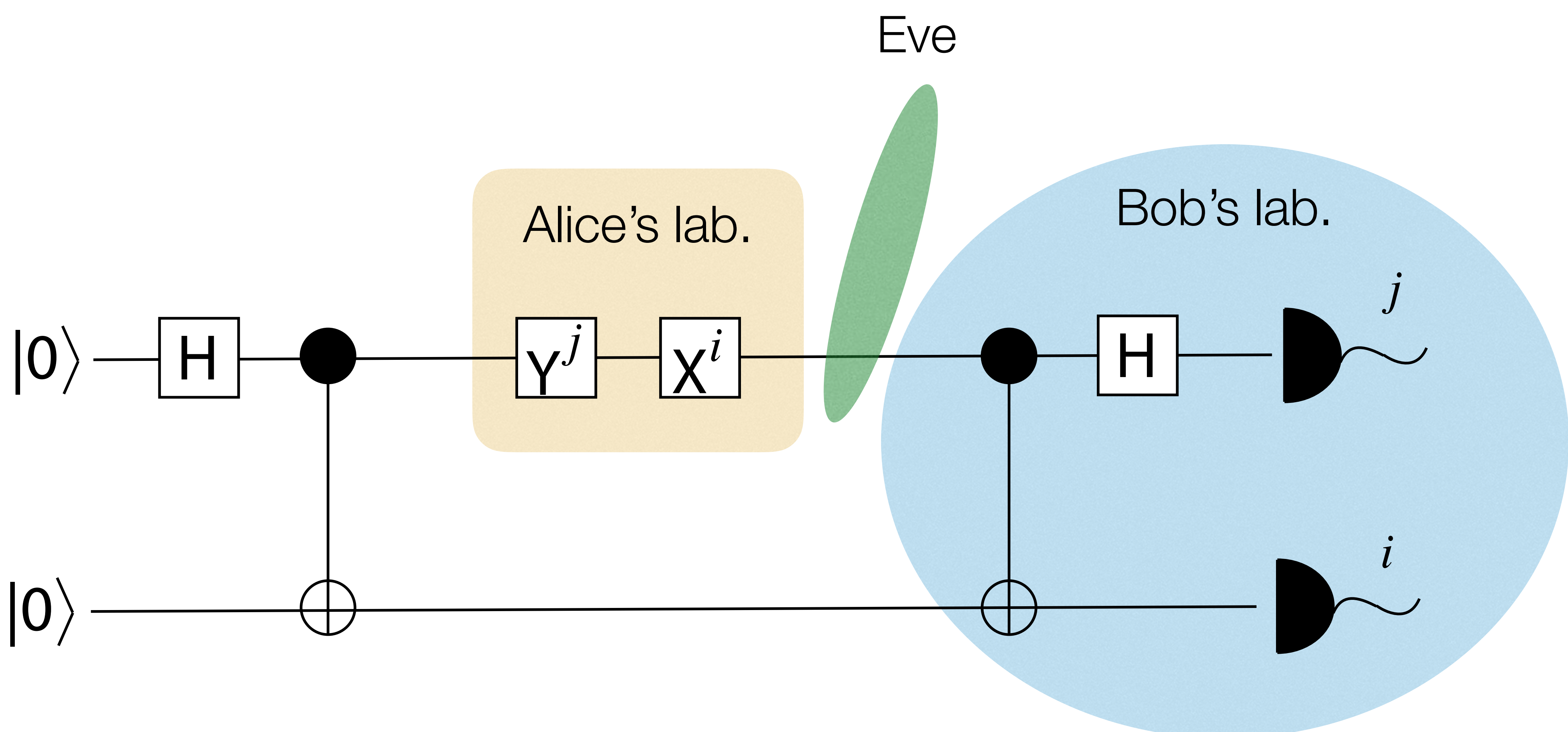
Exponential complexity reduction

Quantum communication

Superdense Coding

One-time pad cryptograph





In the Bob's lab

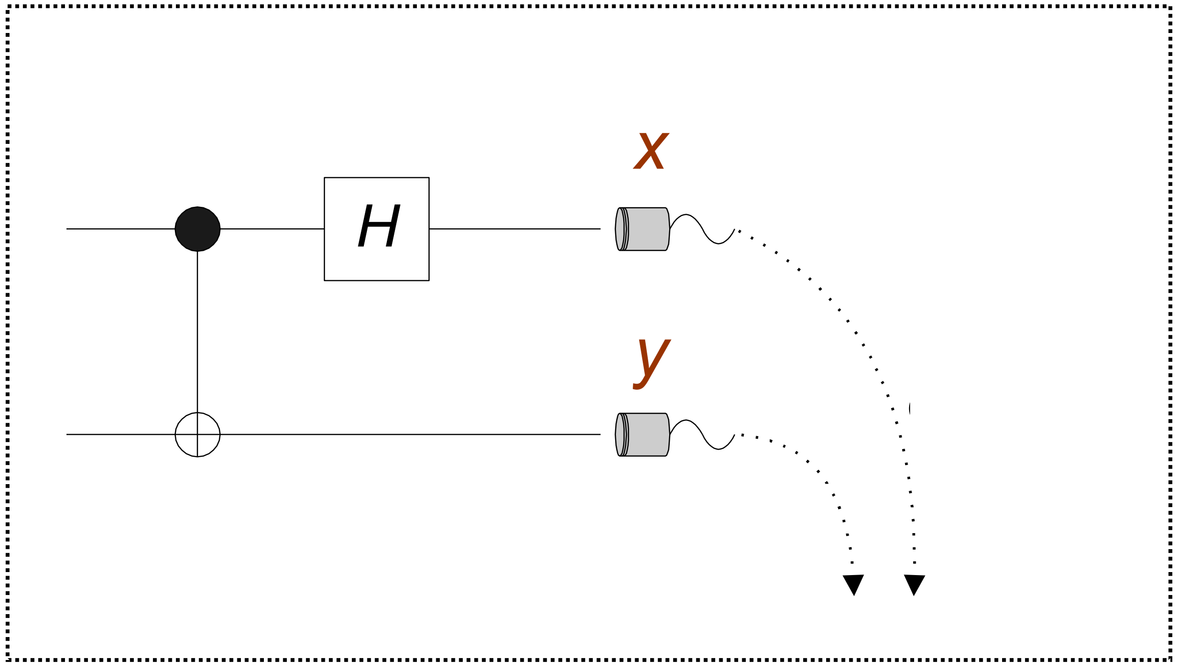
$$\left|B_{x,y}\right\rangle_{ab} = \frac{1}{\sqrt{2}}\left(\left|0\right\rangle_a \left|y\right\rangle_b + (-1)^x \left|1\right\rangle_a \left|\bar{y}\right\rangle_b\right)$$

$$\left|B_{0,0}\right\rangle_{ab} = \frac{1}{\sqrt{2}}\left(\left|0\right\rangle_a \left|0\right\rangle_b + \left|1\right\rangle_a \left|1\right\rangle_b\right) = \left|\Phi^+\right\rangle_{ab}$$

$$\left|B_{1,0}\right\rangle_{ab} = \frac{1}{\sqrt{2}}\left(\left|0\right\rangle_a \left|0\right\rangle_b - \left|1\right\rangle_a \left|1\right\rangle_b\right) = \left|\Phi^-\right\rangle_{ab}$$

$$\left|B_{0,1}\right\rangle_{ab} = \frac{1}{\sqrt{2}}\left(\left|0\right\rangle_a \left|1\right\rangle_b + \left|1\right\rangle_a \left|0\right\rangle_b\right) = \left|\Psi^+\right\rangle_{ab}$$

$$\left|B_{1,1}\right\rangle_{ab} = \frac{1}{\sqrt{2}}\left(\left|0\right\rangle_a \left|1\right\rangle_b - \left|1\right\rangle_a \left|0\right\rangle_b\right) = \left|\Psi^-\right\rangle_{ab}$$



$$\begin{aligned}
\left|input\right\rangle_{ab} &= \left|B_{x,y}\right\rangle_{ab} \\
&= \frac{1}{\sqrt{2}}\left(\left|0\right\rangle_a \left|y\right\rangle_b + (-1)^x \left|1\right\rangle_a \left|\bar{y}\right\rangle_b\right) \\
&\xrightarrow{CNOT_{ab}} \frac{1}{\sqrt{2}}\left(\left|0\right\rangle_a \left|y\right\rangle_b + (-1)^x \left|1\right\rangle_a \left|1\oplus\bar{y}\right\rangle_b\right) \\
&\xrightarrow{H_a} \frac{1}{\sqrt{2}}\left[\left(\frac{1+(-1)^x}{\sqrt{2}}\right)\left|0\right\rangle_a \left|y\right\rangle_b + \left(\frac{1-(-1)^x}{\sqrt{2}}\right)\left|1\right\rangle_a \left|1\oplus\bar{y}\right\rangle_b\right]
\end{aligned}$$

$$\boxed{1\oplus\bar{y} = y}$$

$x = 0$

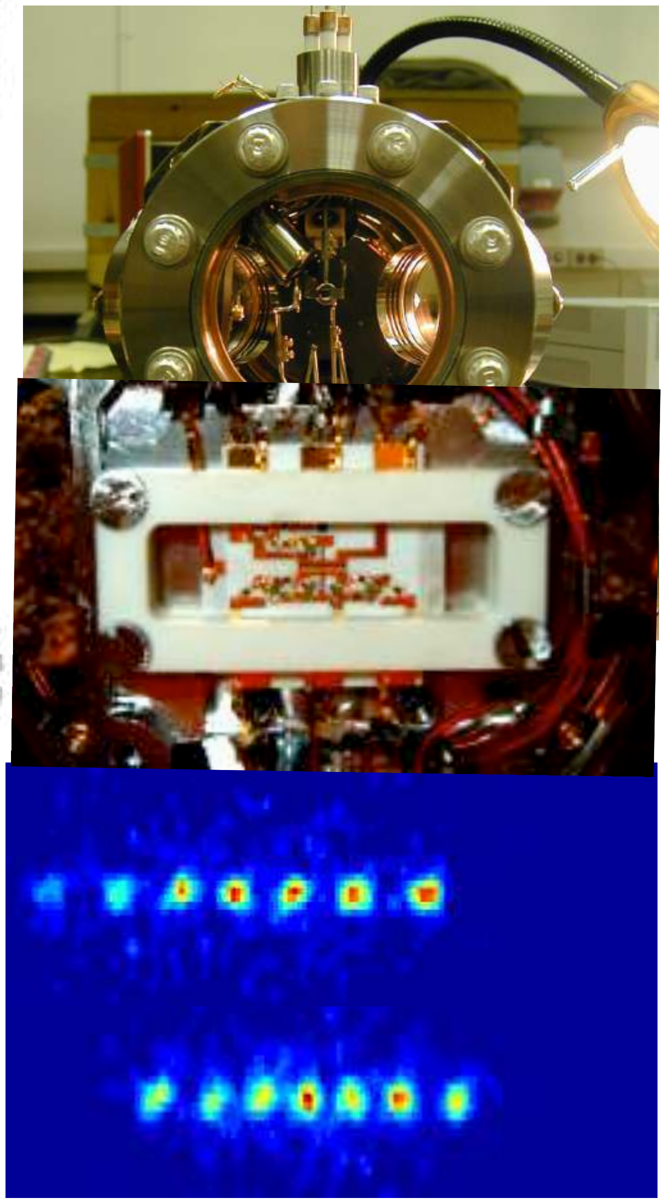
$$\left|output\right\rangle = \left|0\right\rangle_a \left|y\right\rangle_b = \begin{cases} \left|0\right\rangle_a \left|0\right\rangle_b, & y = 0 \rightarrow \left|input\right\rangle = \left|\Phi^+\right\rangle \\ \left|0\right\rangle_a \left|1\right\rangle_b, & y = 1 \rightarrow \left|input\right\rangle = \left|\Psi^+\right\rangle \end{cases}$$

$x = 1$

$$\left|output\right\rangle = \left|1\right\rangle_a \left|y\right\rangle = \begin{cases} \left|1\right\rangle_a \left|0\right\rangle_b, & y = 0 \rightarrow \left|input\right\rangle = \left|\Phi^-\right\rangle \\ \left|1\right\rangle_a \left|1\right\rangle_b, & y = 1 \rightarrow \left|input\right\rangle = \left|\Psi^-\right\rangle \end{cases}$$

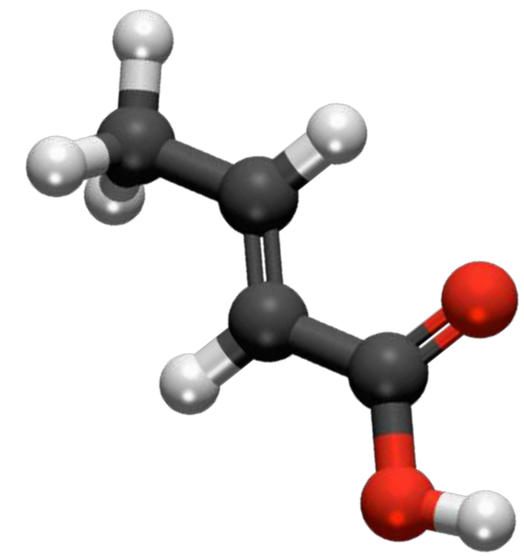
How to implement qubits in physical systems

Traped Ions

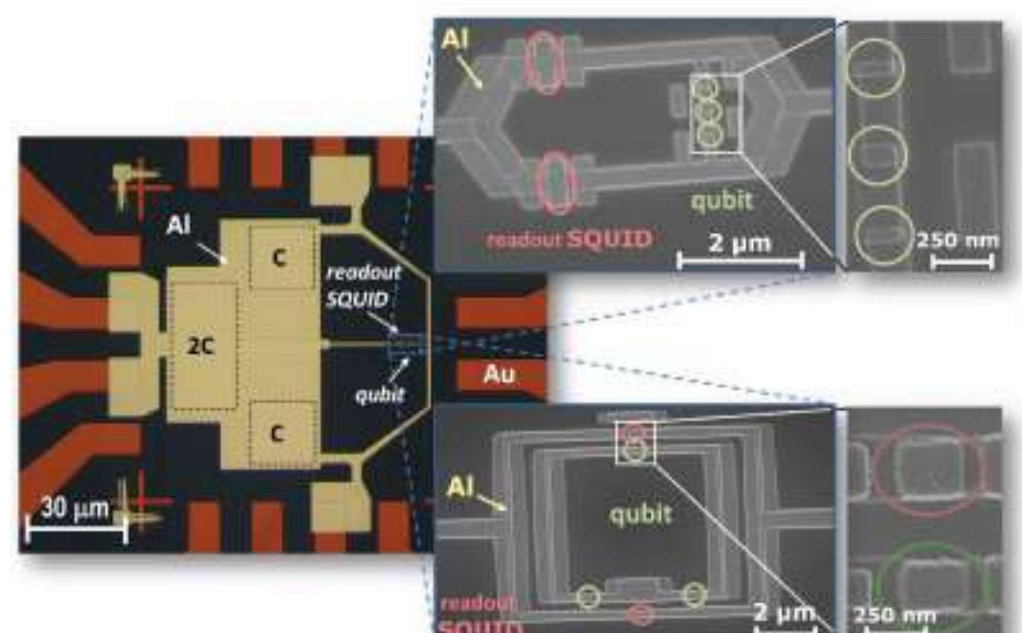


Photonic systems

Nuclear spins - NMR



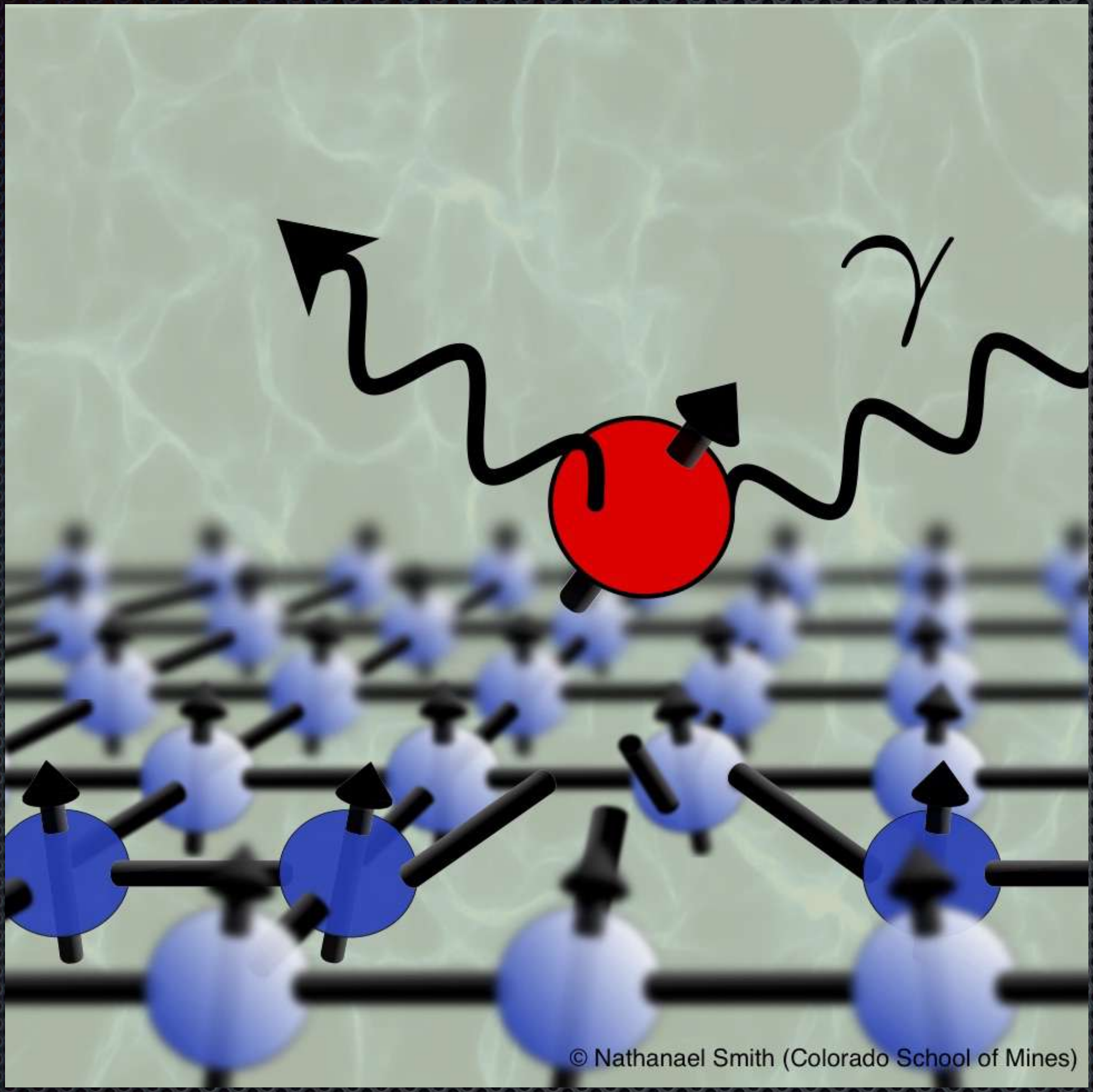
Superconducting Circuit electrodynamics



Many others candidates

Open Quantum System - Master Equation

two level system interacting with a Markovian heat reservoir



System environment interaction

$$
\begin{aligned}
H = & \hbar \frac{\omega_0}{2} \\
& + \sum_k \omega_k a^\dagger a \\
& + \sum_k g_k (\sigma_+ a + \sigma_- a^\dagger)
\end{aligned}
$$

Initially uncorrelated

$$\rho_{SR}(0) = \rho_S(0) \otimes \rho_R(0)$$

Open Quantum System - Master Equation

two level system interacting with a Markovian heat reservoir

$$\frac{d}{dt}\rho(t) = -\frac{i}{\hbar}\left[H(t), \rho(t)\right] + \gamma_{\downarrow}\left[\Gamma_{\downarrow}\rho(t)\Gamma_{\uparrow}^{\dagger} - \frac{1}{2}\left\{\rho(t), \Gamma_{\uparrow}^{\dagger}\Gamma_{\downarrow}\right\}\right] + \gamma_{\uparrow}\left[\Gamma_{\uparrow}\rho(t)\Gamma_{\downarrow}^{\dagger} - \frac{1}{2}\left\{\rho(t), \Gamma_{\downarrow}^{\dagger}\Gamma_{\uparrow}\right\}\right]$$

where

$$\gamma_{\downarrow} = \gamma_0\left(N_{\mathrm{BE}} + 1\right) \qquad \gamma_{\uparrow} = \gamma_0 N_{\mathrm{BE}}$$

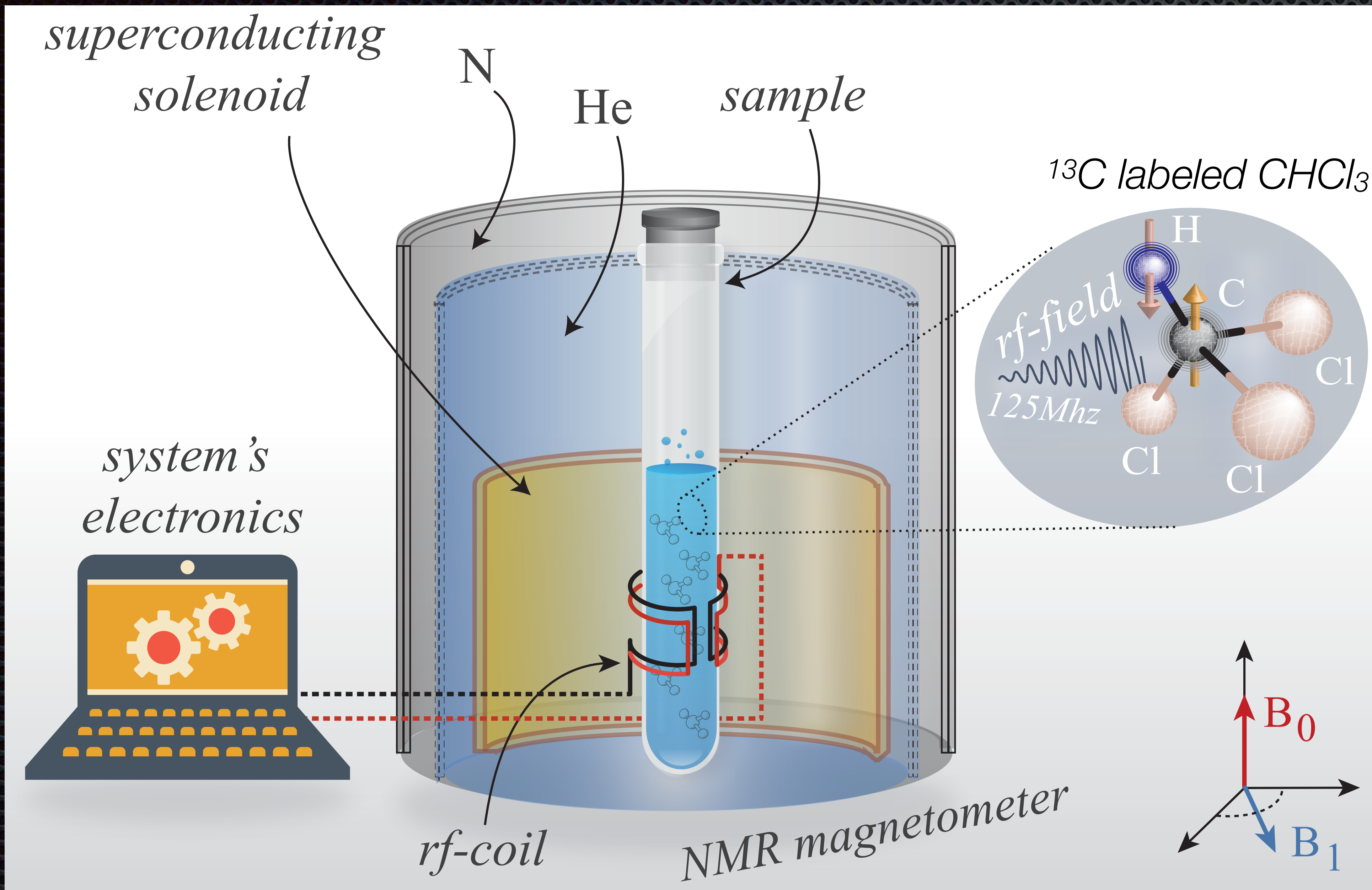
$N_{\mathrm{BE}} = \left(e^{\beta\hbar\omega} - 1\right)^{-1}$ is the Bose-Einstein distribution

γ_0 is the vacuum decay rate

Quantum information w/ Nuclear Spins

UFABC

Liquid state NMR experimental setup



Trichloromethane diluted in acetone d_6

NMR @ 500 Mhz UFABC, São Paulo

nucleus	^{1}H	^{2}H	^{13}C	^{19}F	^{31}P
ν_0 [MHz]	500	77	126	470	202
spin (nat. abund.)	1/2 (99%)	1 (1%)	1/2 (1%)	1/2 (100%)	1/2 (100%)

Thank you for your attention

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