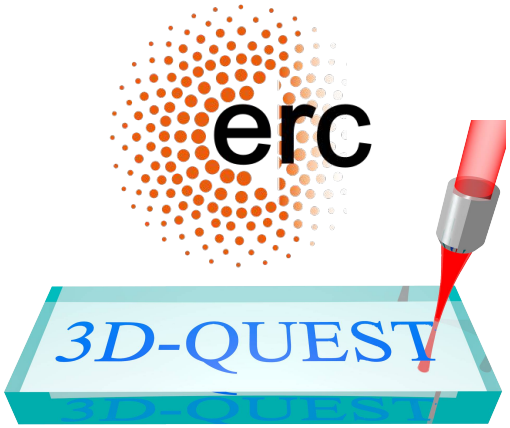
SAPIENZA
UNIVERSITÀ DI ROMA

In the Quantum World – towards the quantum technologies



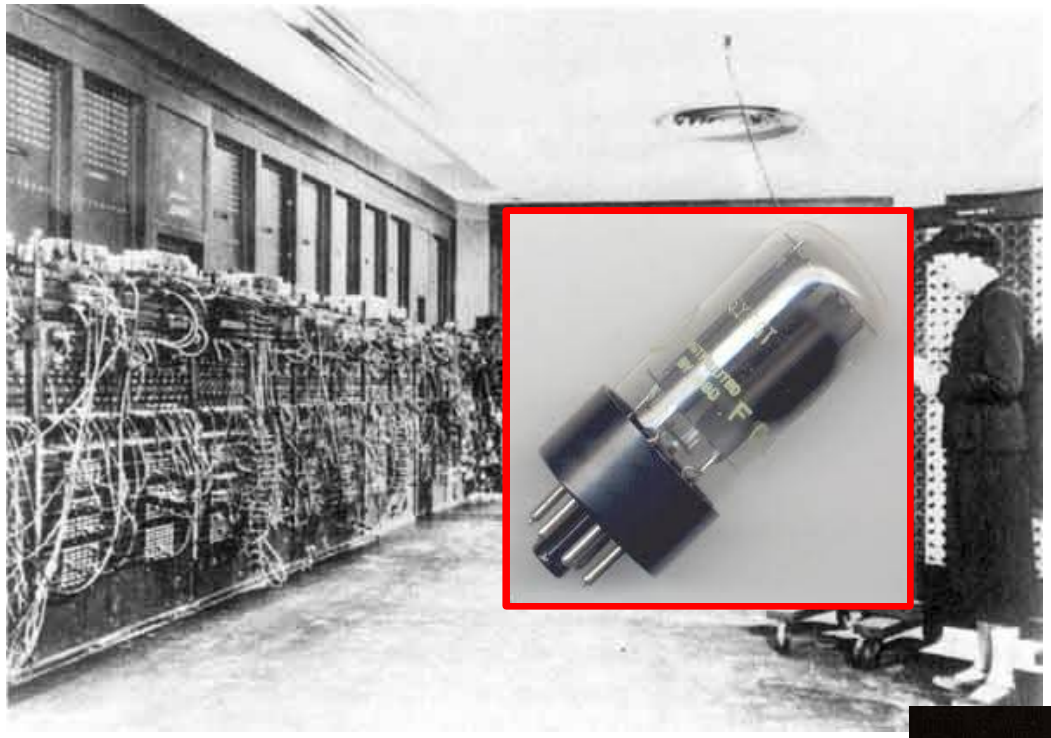
Fabio Sciarrino

Dipartimento di Fisica
Sapienza Università di Roma

QUANTUM OPTICS GROUP
Dipartimento di Fisica, Sapienza Università di Roma

http://quantumoptics.phys.uniroma1.it

www.3dquest.eu



ENIAC (1946)

Electronic Numerical Integrator And Computer

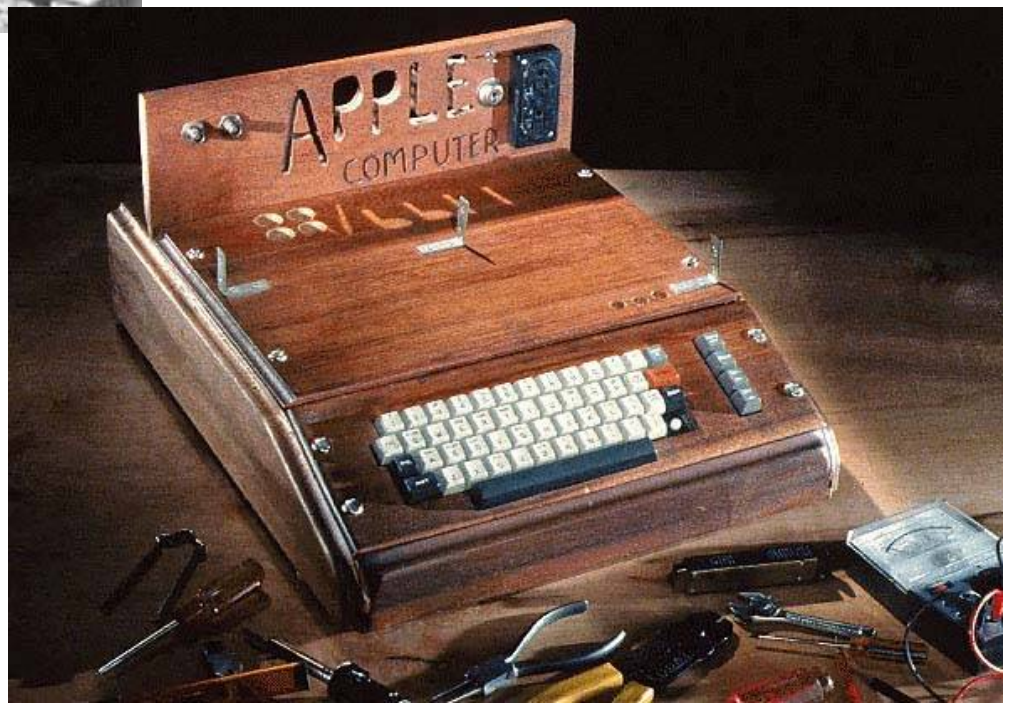
18.000 thermionic valves,

30 tons,

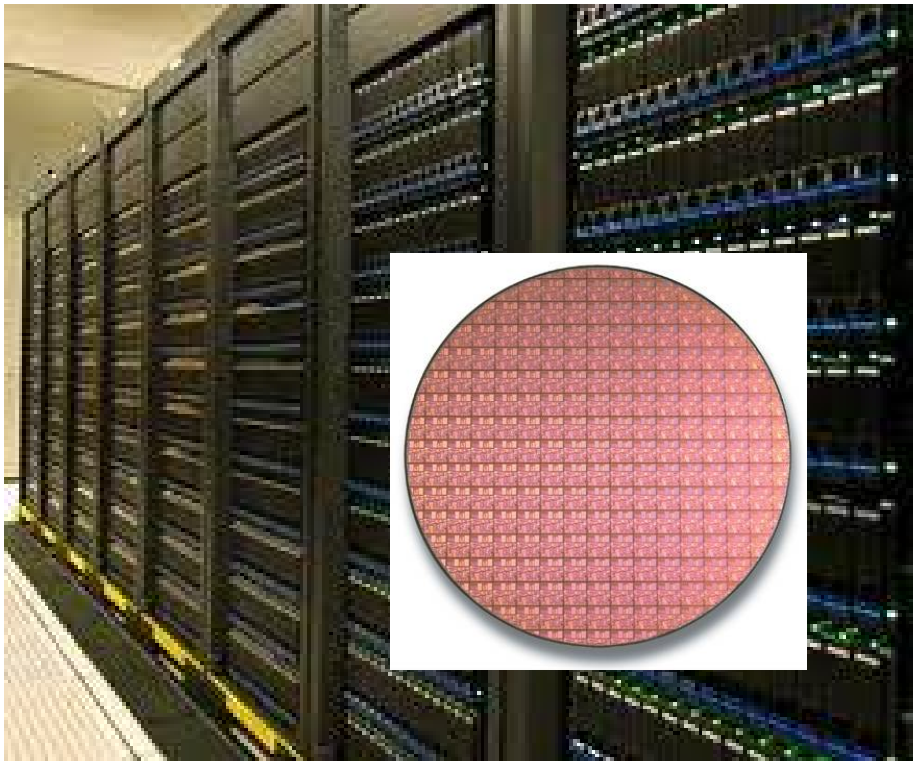
180 mq

Apple I (1976)

.. 4 Kb di Ram...!



TODAY...



Tianhe-1A (2010)

Supercomputer

Operations per second

1 PetaFlops

I-Phone 4s (2012)

RAM 512 Mb

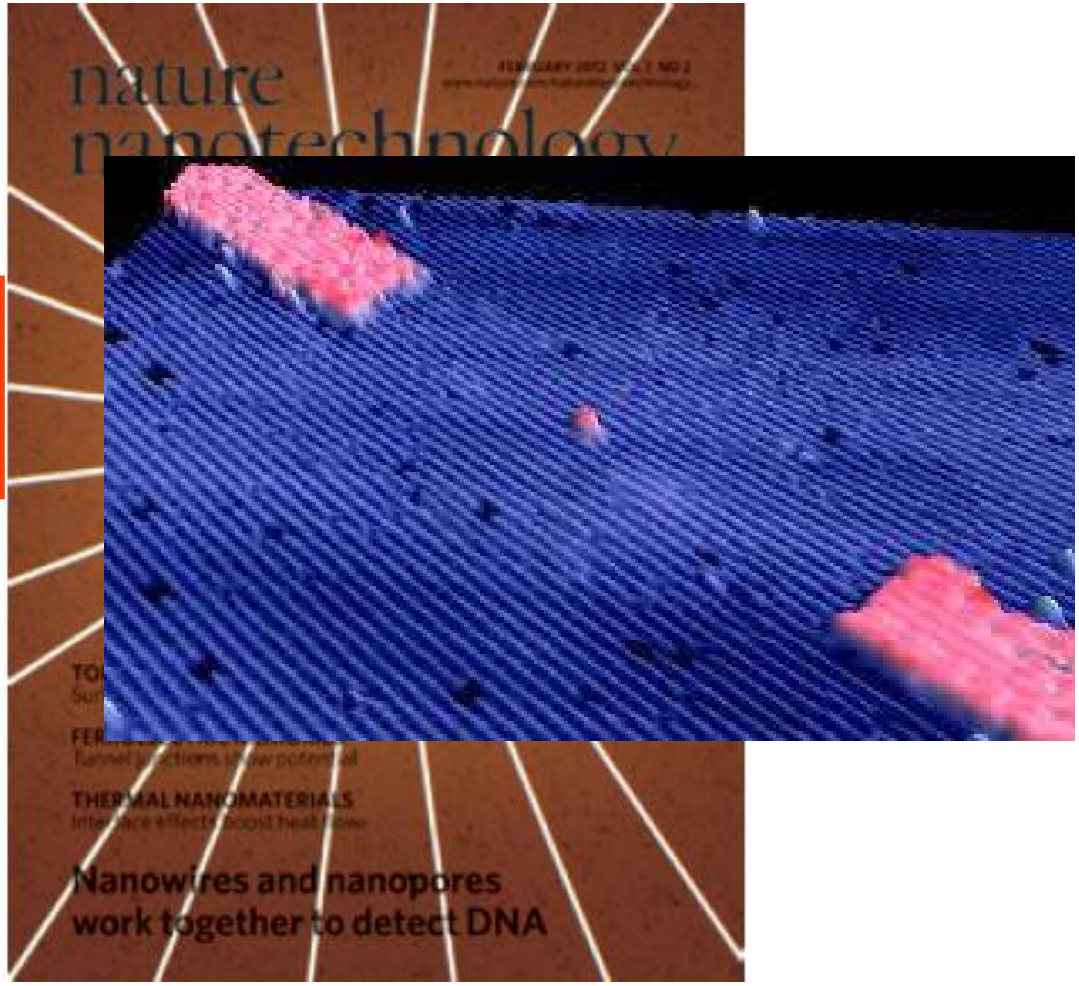
NANOELECTRONICS

Transistors arrive at the atomic limit

A single-atom transistor has been made by positioning a phosphorus atom between metallic electrodes, also made of phosphorus, on a silicon surface.

Gabriel P. Lansbergen

Breaking news!
19 Febbraio 2012



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NANOELECTRONICS

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Gabriel P. Lansbergen

TECNOLOGÍA | Construido en Australia

Un transistor del tamaño de un átomo como antesala del ordenador cuántico

Efe | Sidney

Actualizado lunes 20/02/2012 10:57 horas

EL MUNDO.es

Líder mundial en español | Lunes 20/02/2012. Actualizado 10:57h.

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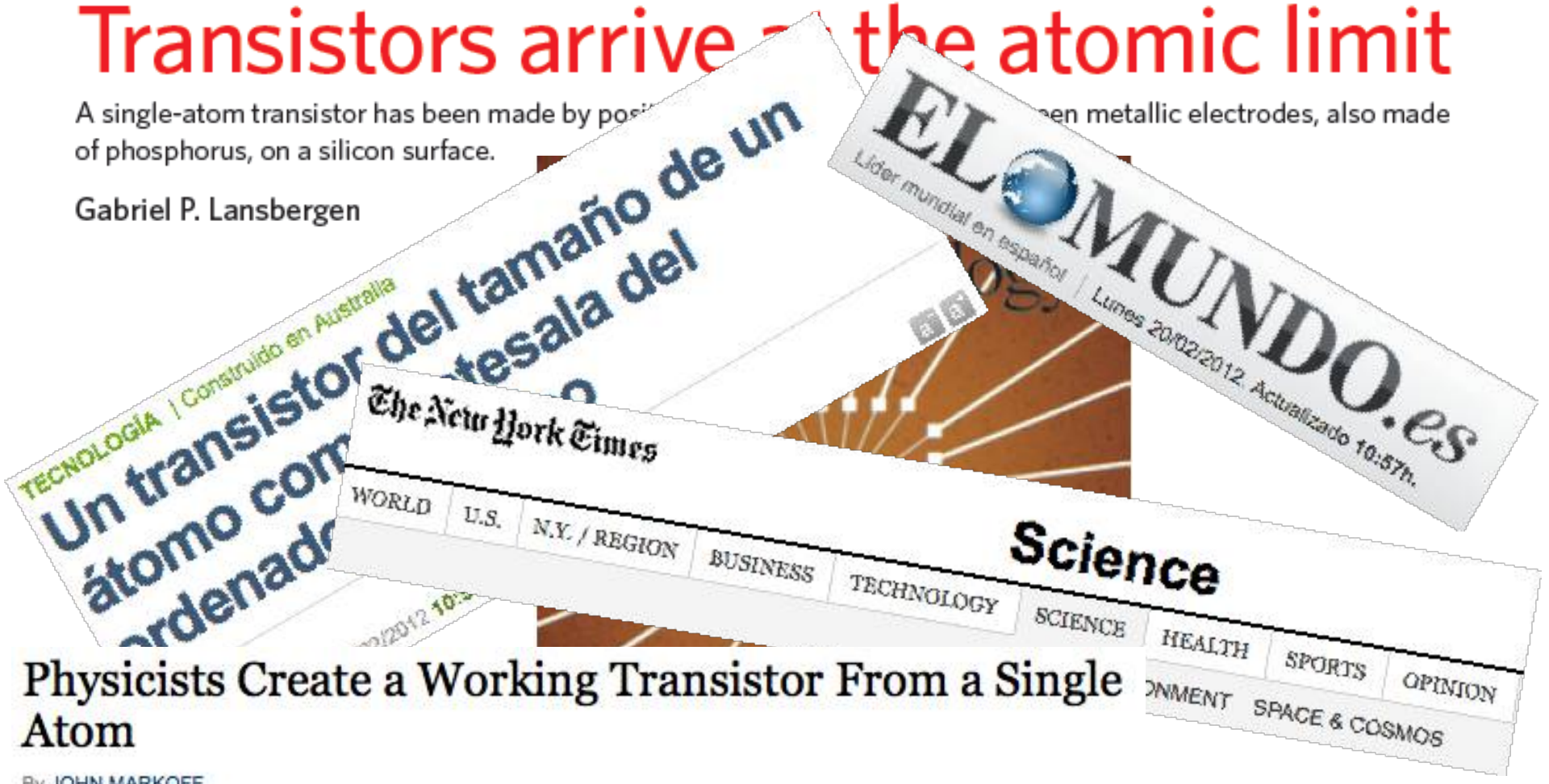


Physicists Create a Working Transistor From a Single Atom

By JOHN MARKOFF
Published: February 19, 2012

Australian and American physicists have built a working transistor from a single phosphorus atom embedded in a silicon crystal.

“ […] Un importante passo in avanti verso i super computer quantistici del futuro, realizzato dai fisici dell'università australiana del Nuovo Galles del Sud a Sydney .”

La Repubblica

“ [...] Científicos australianos han construido el transistor más pequeño del mundo a partir de un único átomo, lo que supone un gran paso hacia el desarrollo de los futuros ordenadores cuánticos.”

El Mundo

“ [...]they had laid the groundwork for a futuristic quantum computer that might one day function in a nanoscale world and would be orders of magnitude smaller and quicker than today’s silicon-based machines.”

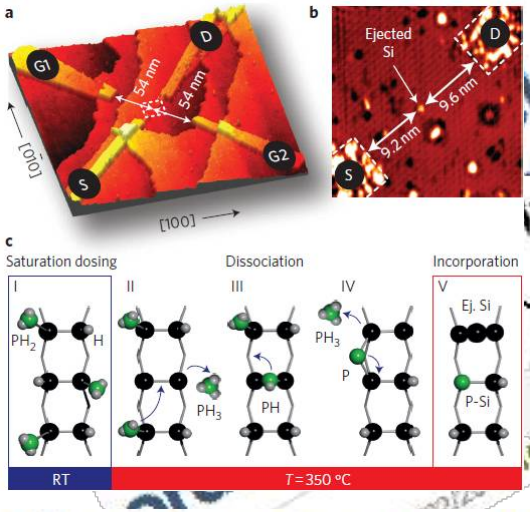
The New York Times

NANOELECTRONICS

Transistors arrive at the atomic limit

A single-atom transistor has been made by positioning between metallic electrodes, also made of phosphorus, on a silicon surface.

Gabriel P. Lansbergen



tamaño de un
tesala del

EL MUNDO.es
Líder mundial en español | Lunes 20/02/2012. Actualizado 10:57h.

The New York Times

U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS

Science

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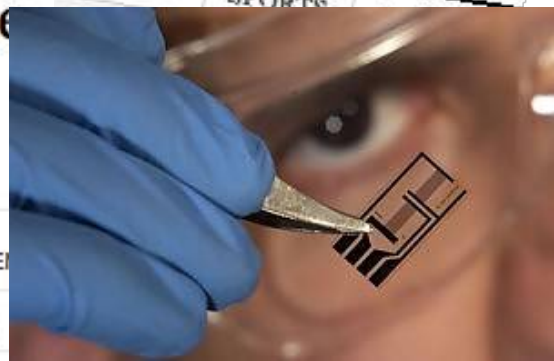
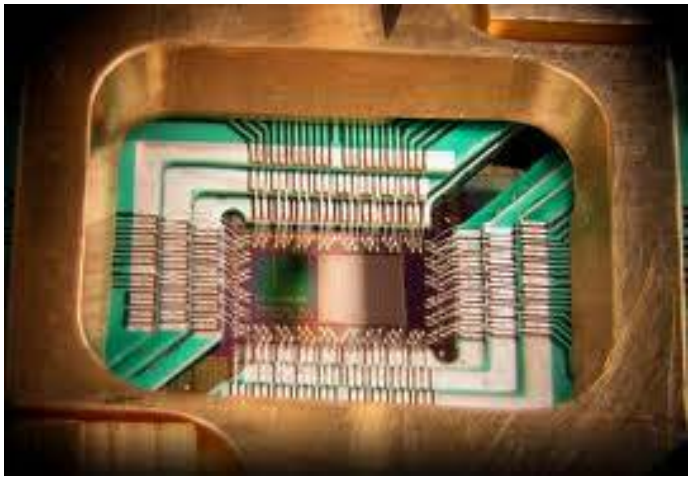
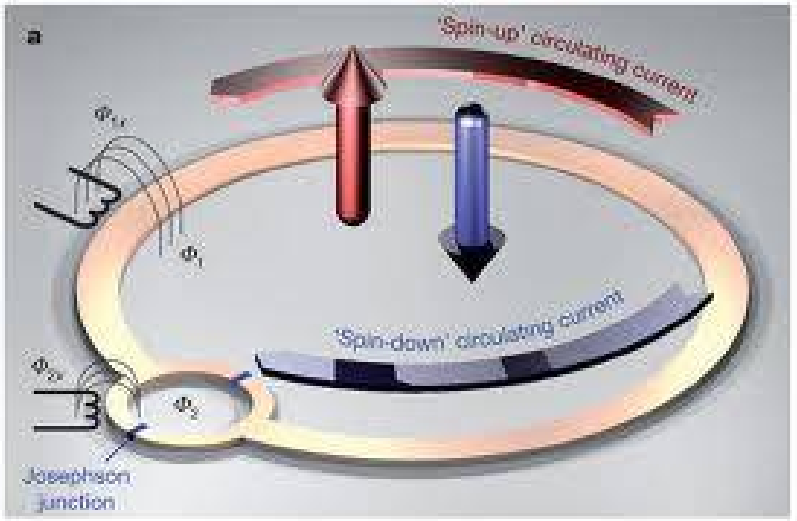
RECOMMEND
TWITTER



D-wave: a commercial quantum computer ?!?

512 qubit....
Cost: 10.000.0000 $
bought from NASA, google..





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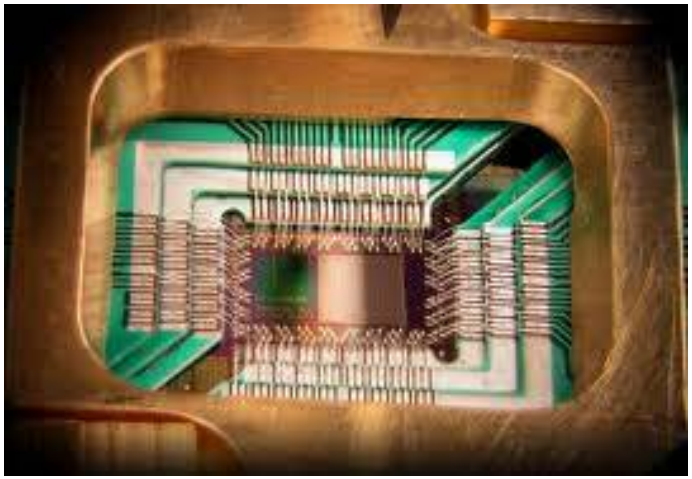


Is it"truly" quantum?
And more powerfull
than a classical computer?

Results of Classical Physics:

At the end of 1800...

The predominant physical theory acknowledged as the only constituents of the Universe **matter** and **radiation**

made of particles perfectly localizable, subject to Newton's law

has a wave-like behavior and obeys the laws of electrodynamics of Maxwell;

The equations of classical physics ....

$$\begin{cases} \mathbf{F} = m\mathbf{a} \\ \mathbf{M} = \dfrac{d\mathbf{L}}{dt} \end{cases}$$

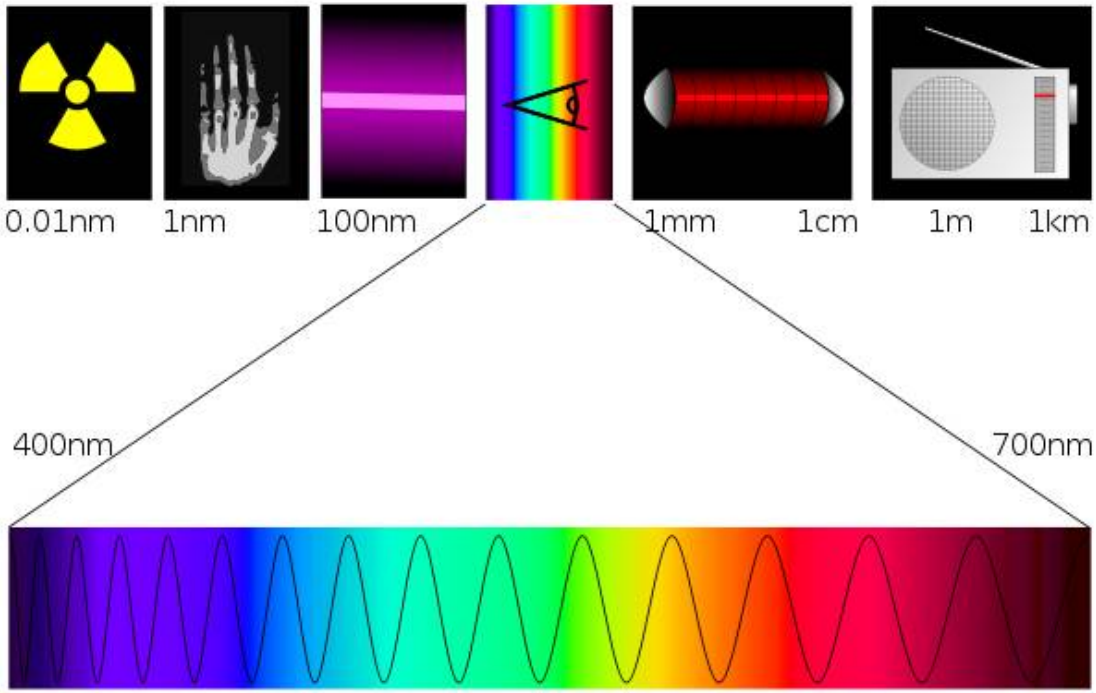
The equations of classical physics ....

The kinematics of the bodies

$$\mathbf{F} = m\mathbf{a}$$

Electromagnetism (Maxwell's equations)

$$\begin{cases} \nabla \cdot \mathbf{D} = \rho \\ \nabla \times \mathbf{E} + \dfrac{\partial \mathbf{B}}{\partial t} = 0 \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \times \mathbf{H} - \dfrac{\partial \mathbf{D}}{\partial t} = \mathbf{J} \end{cases}$$

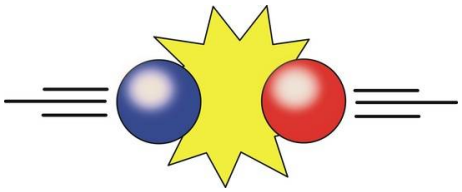


The equations of classical physics ....

Equation | Phenomenon | Description

$$\mathbf{F} = m\mathbf{a}$$

Collision between particles



$$m_1 v_1 + m_2 v_2 = m_1 V_1 + m_2 V_2$$

$$\tfrac{1}{2} m_1 v_1^2 + \tfrac{1}{2} m_2 v_2^2 = \tfrac{1}{2} m_1 V_1^2 + \tfrac{1}{2} m_2 V_2^2$$

Equation | Phenomenon | Description

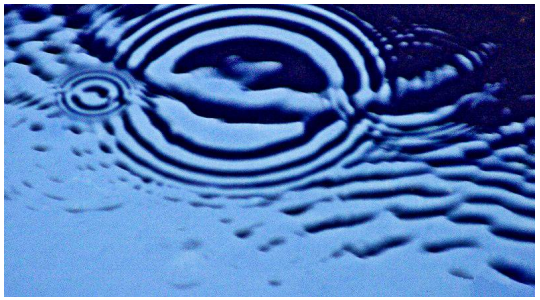
$$\nabla \cdot \mathbf{D} = \rho$$

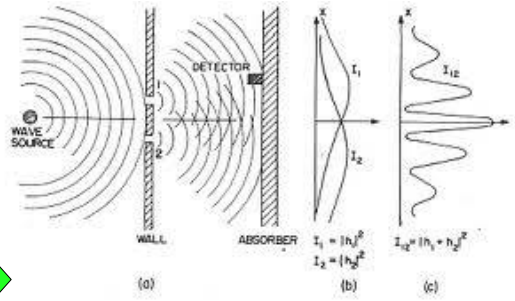
$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}$$

Interference between waves





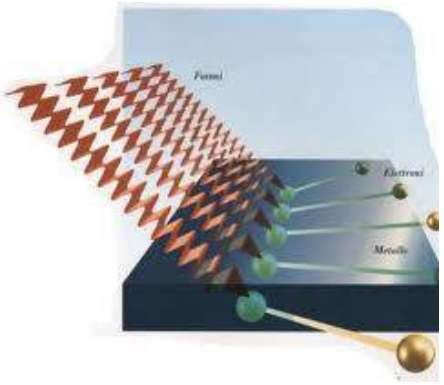
$$I = E^2 = 4\left|E_A^2\right| \cos^2 \frac{kd \sin \alpha}{2}$$

The crisis of classical physics

Classical physics can not explain what happens in the microscopic world ...

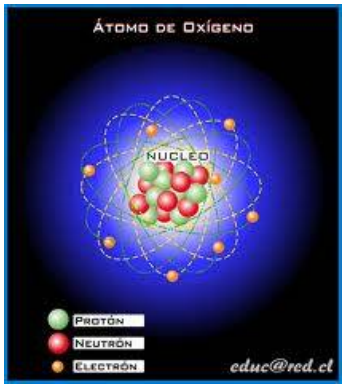
Why an electron does not fall on the nucleus by emitting electromagnetic radiation?

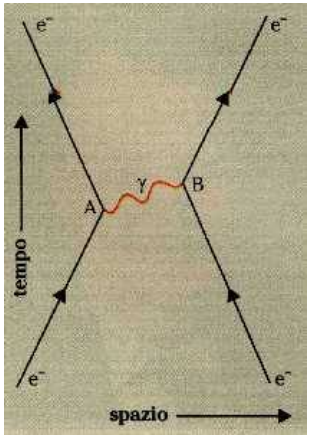
How do you explain the energy emitted from an irradiated metal surface?

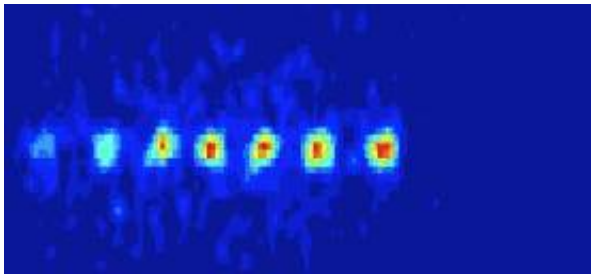


MACROSCOPIC WORLD

MICROSCOPIC WORLD







CLASSICAL PHYSICS

QUANTUM PHYSICS

The answers of Quantum Mechanics ...

The energy, in the same material, has a discontinuous nature being formed by elementary quantity.

QUANTUM THEORY

All the processes of interaction between bodies (the "force fields") are "quantized"

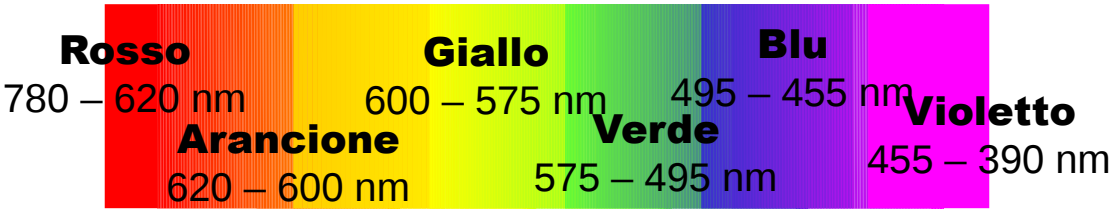
["Building blocks": photons, electrons, etc..]

The quantum of light: the photon

Electromagnetic wave carries energy

Energy changes in a discrete manner:

as the (unit) of energy is the fundamental PHOTON



Photon:

I) Massless

II) Energy

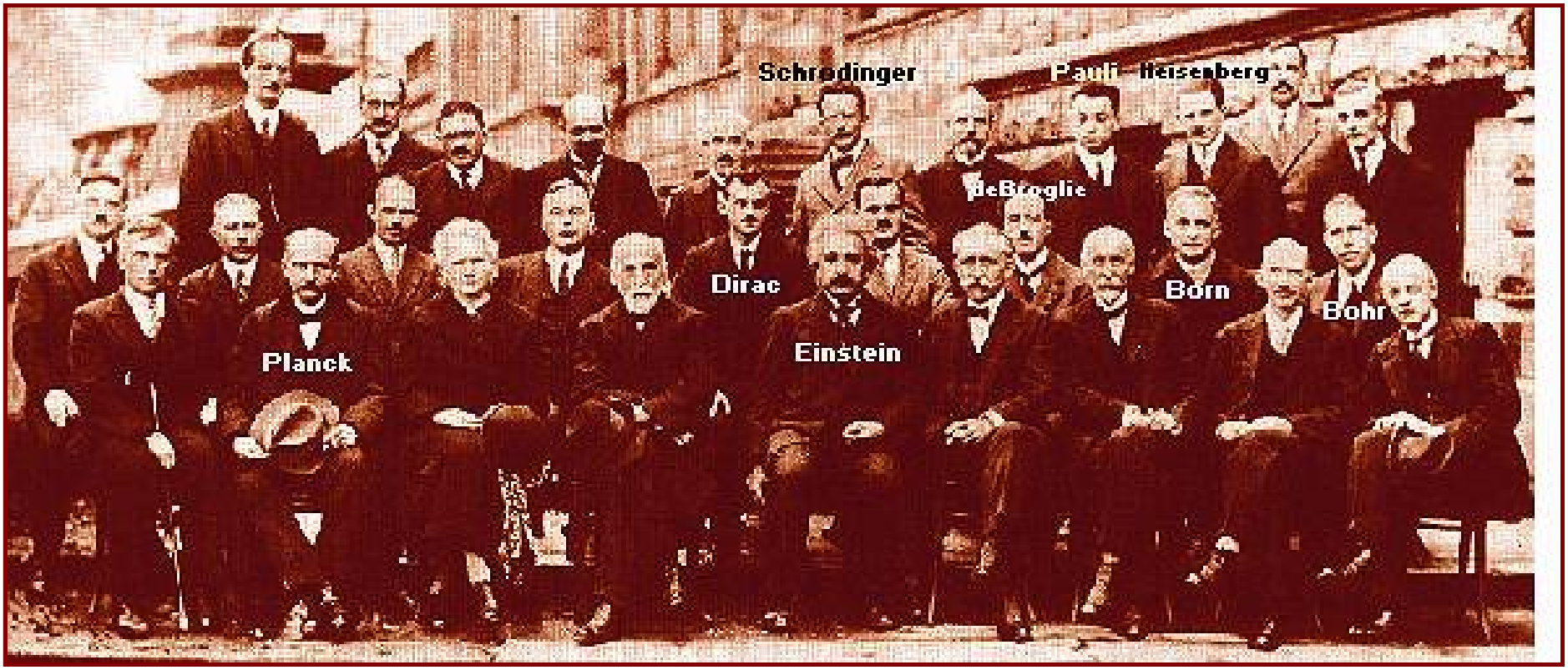
$$E = h\nu$$

Energy

Planck constant

Frequency

The "golden years" of Quantum Mechanics: Solvay Conference (1927)



Quantum physics: Planck, Einstein, Bohr, Dirac, Schroedinger, Heisenberg, Pauli,...

First Principle of dynamic

$$\mathbf{F} = m\,\mathbf{a}$$

First Principle of dynamic

$$\mathbf{F} = m\,\mathbf{a}$$

Force acting on the system

Mass that describes the system

Acceleration: effect of the force

Schroedinger equation

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

Schroedinger equation

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

h Planck constant

Hamiltonian (describes the system considered)

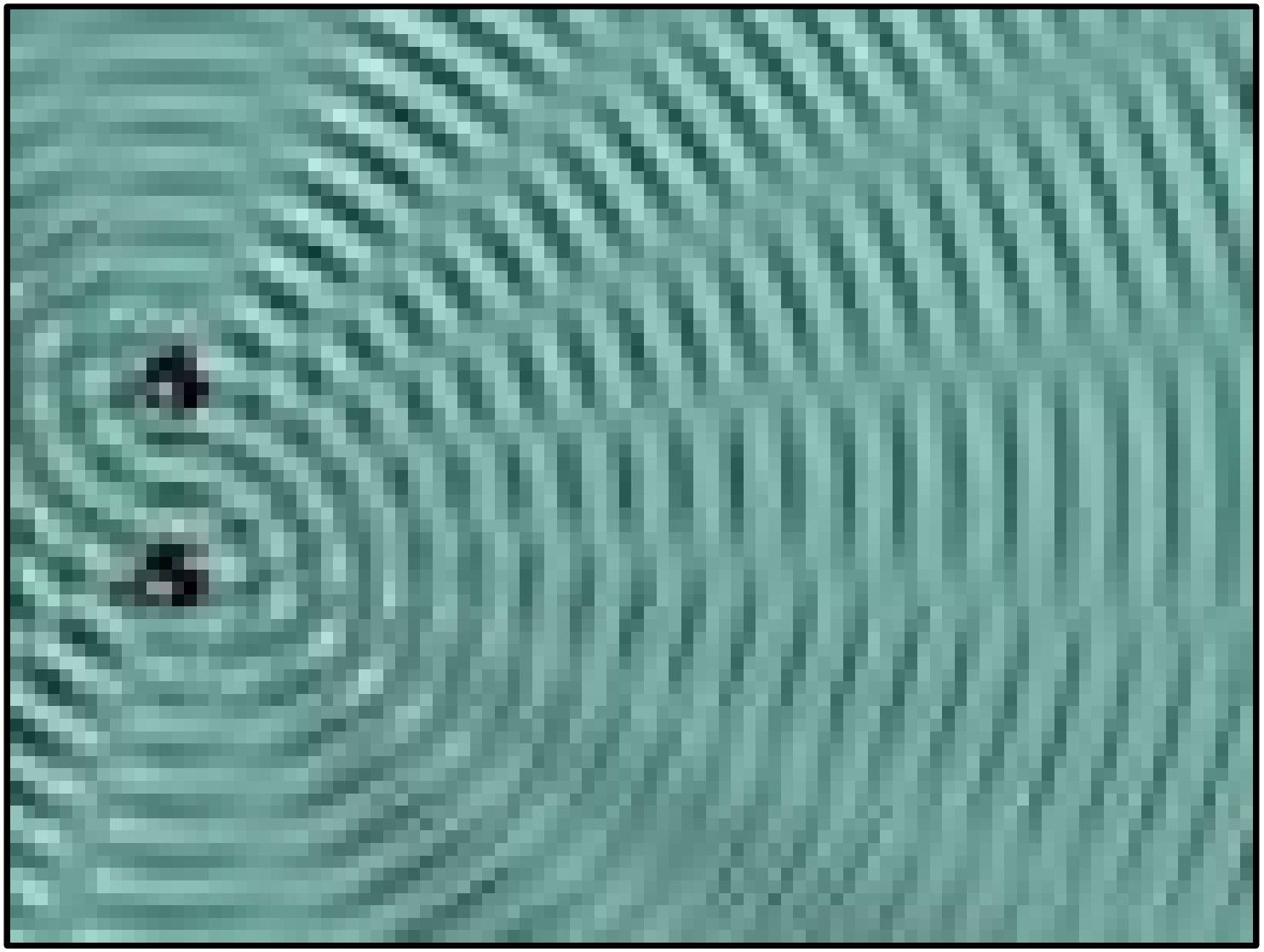
WAVE FUNCTION

Interference

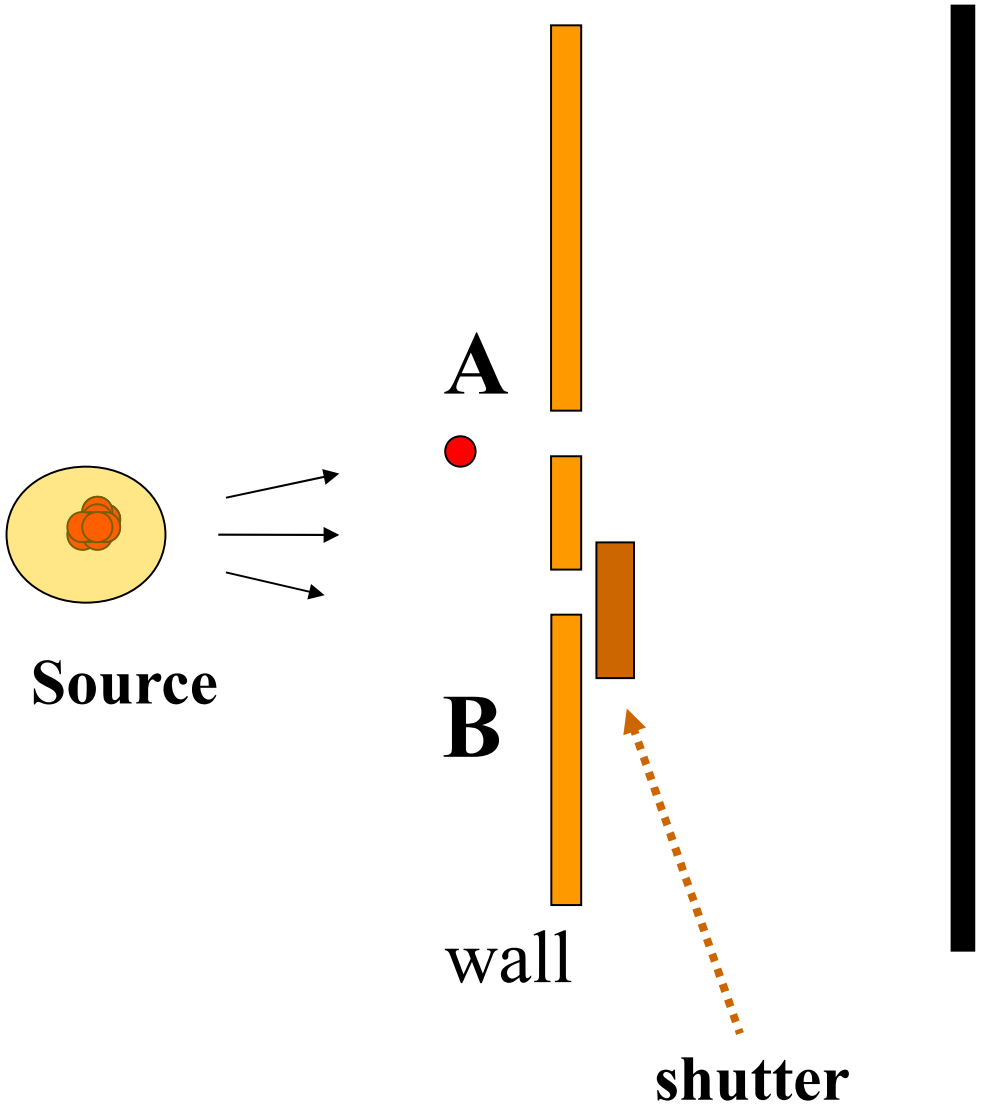
"…the heart of quantum mechanics. In reality it contains the only mystery ..."

R.P. Feynman (1965)

Interference between waves



Single-particle interference



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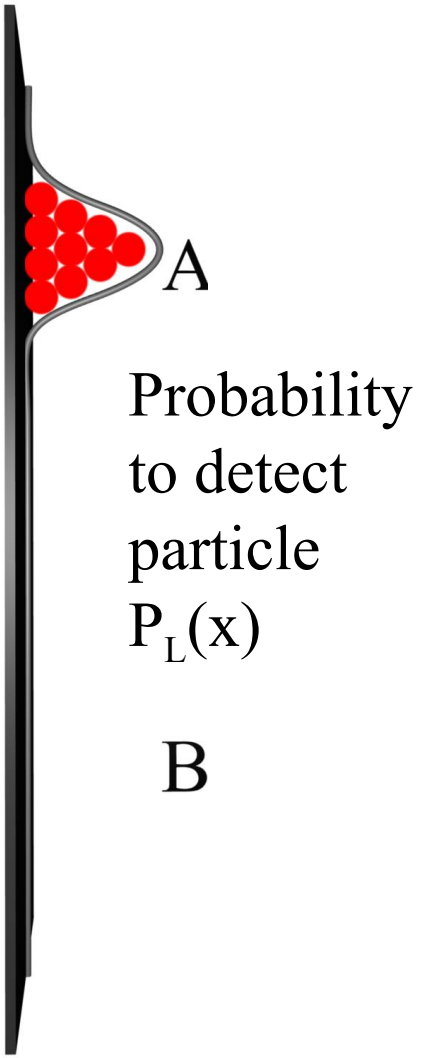

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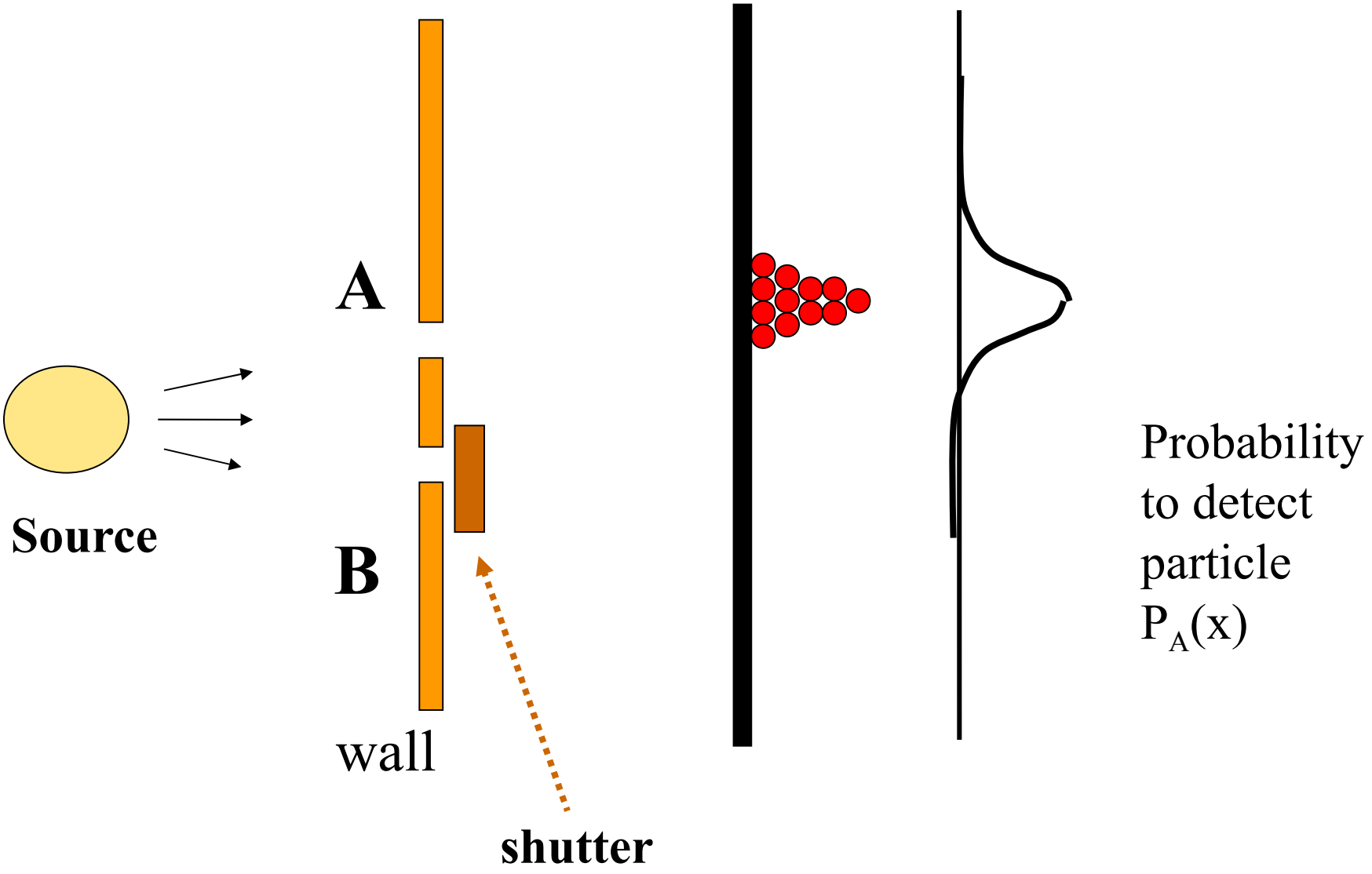

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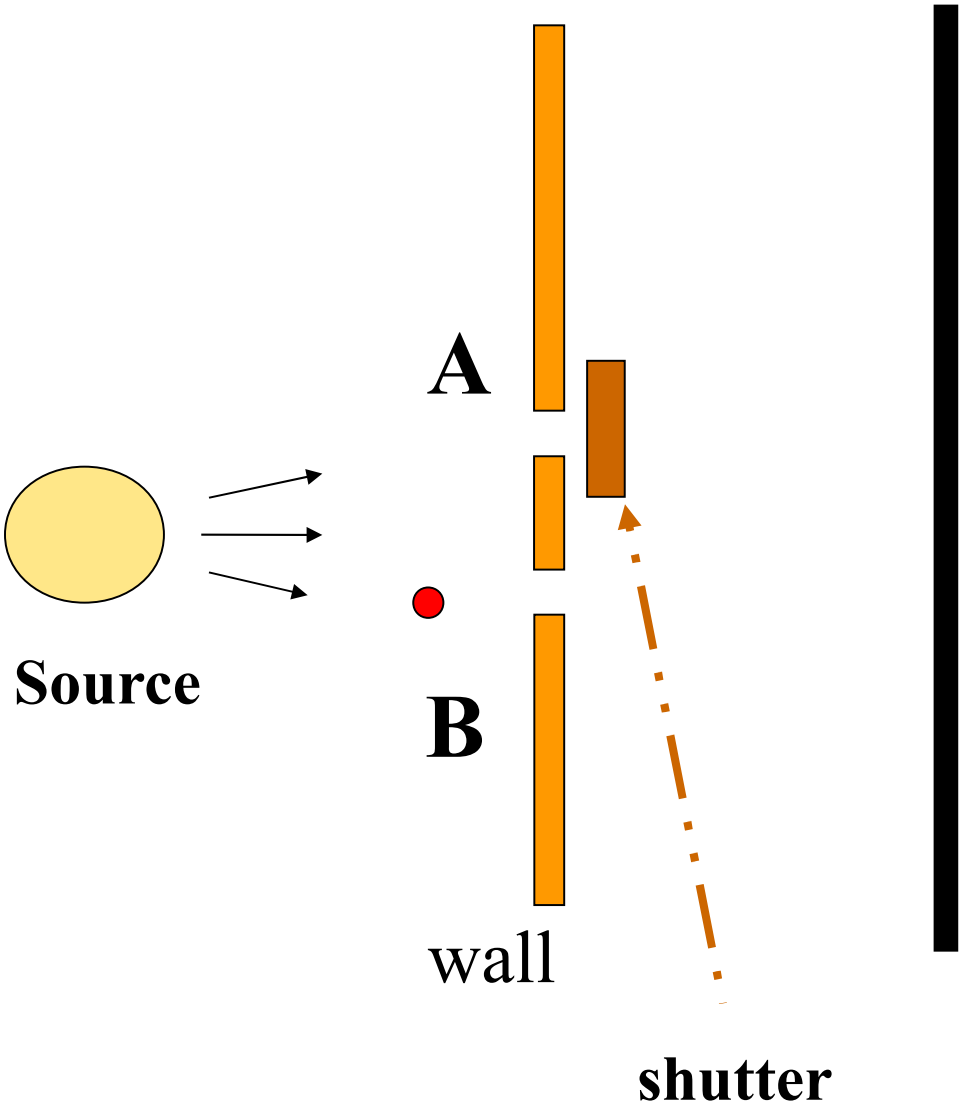

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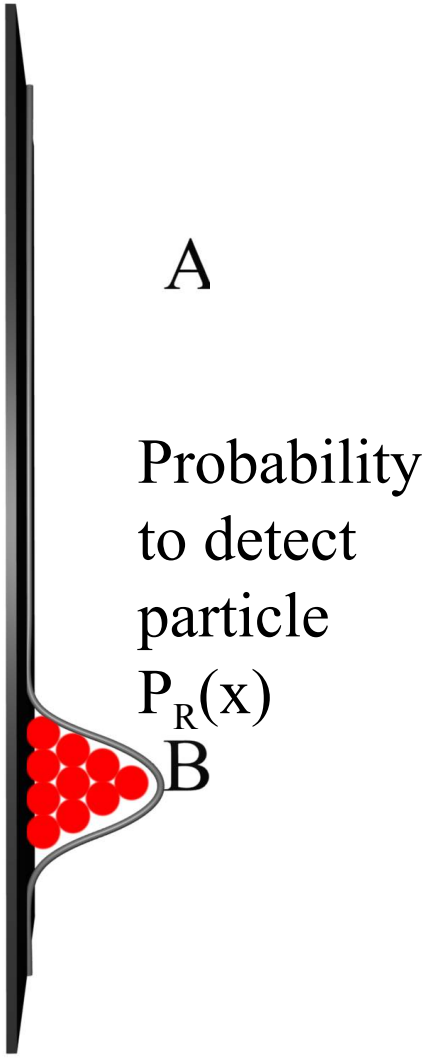
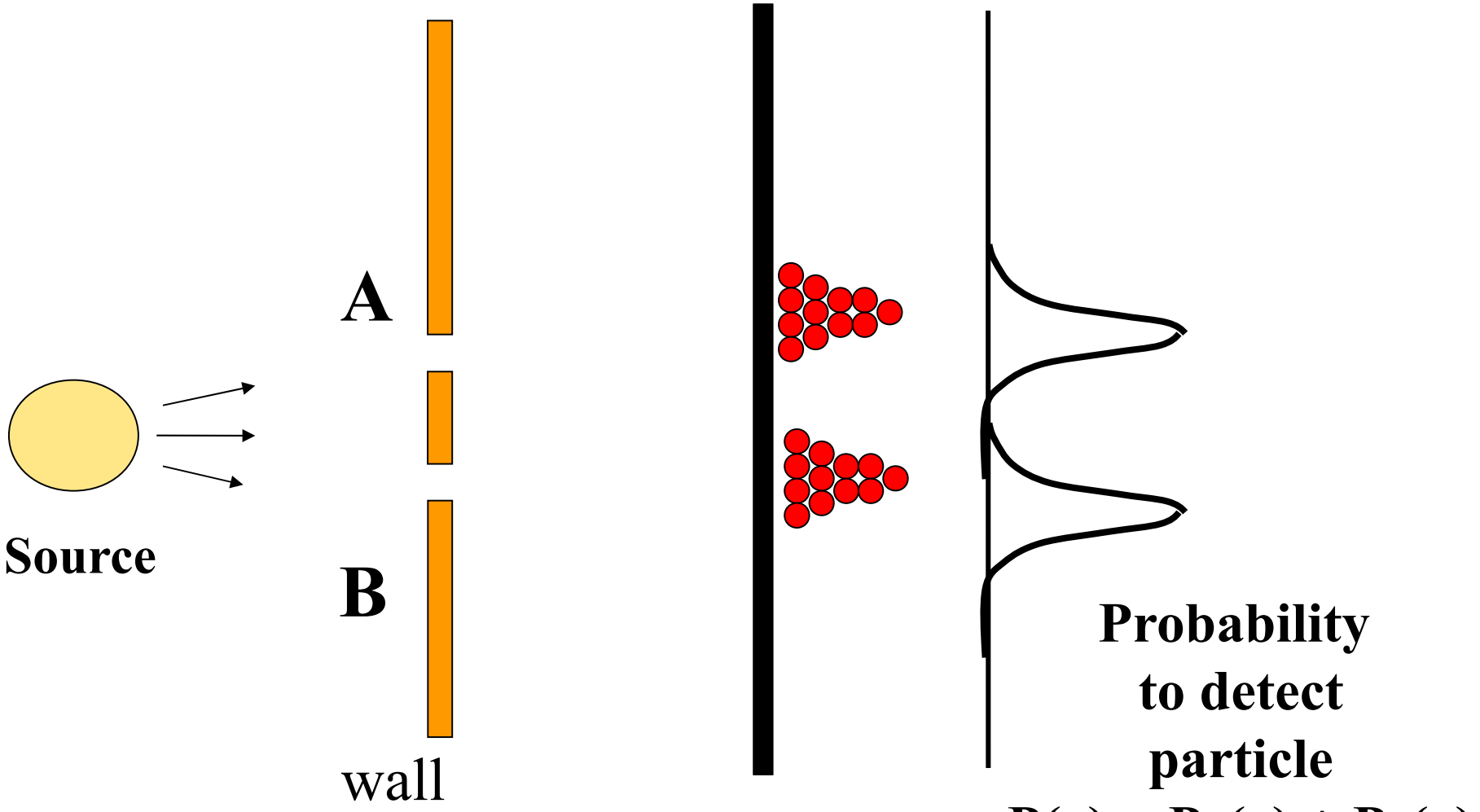


“classical” behaviour



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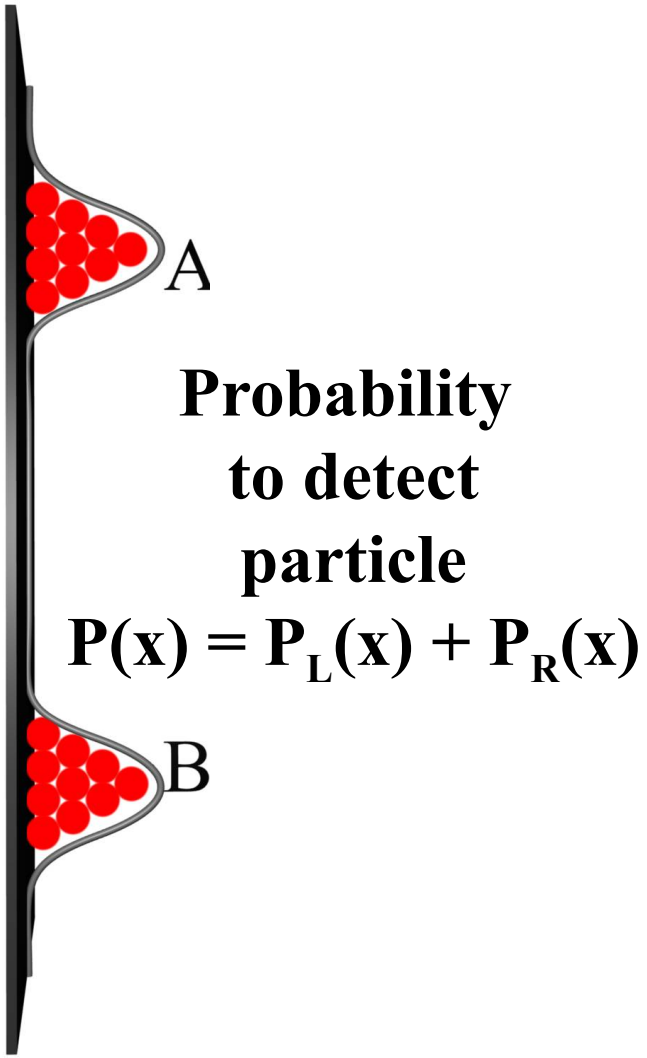
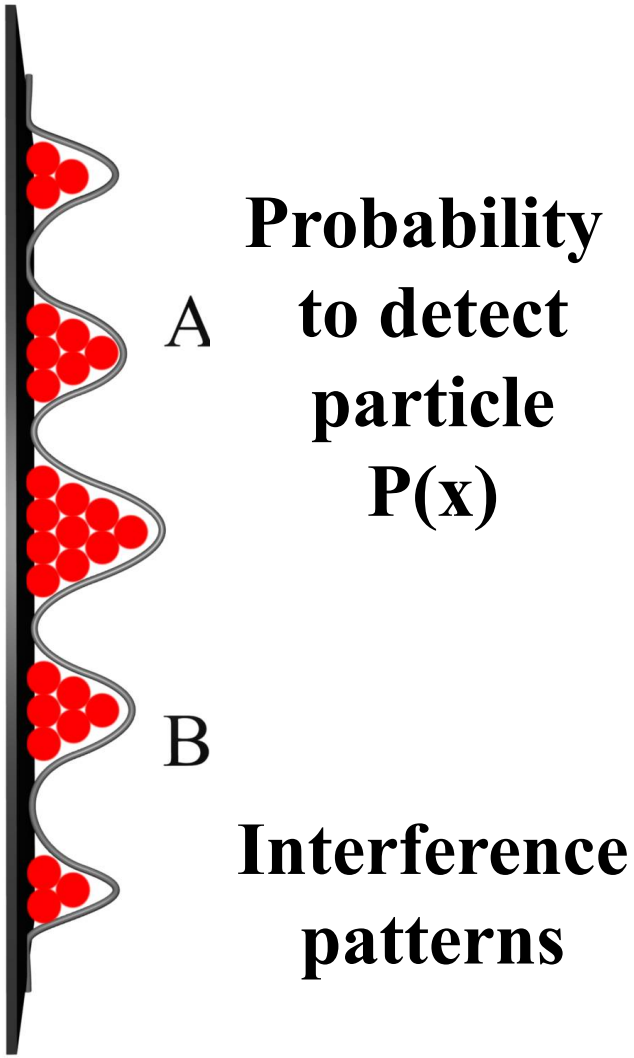


Probability to detect particle

$$P(x) = P_L(x) + P_R(x)$$

Quantum interference



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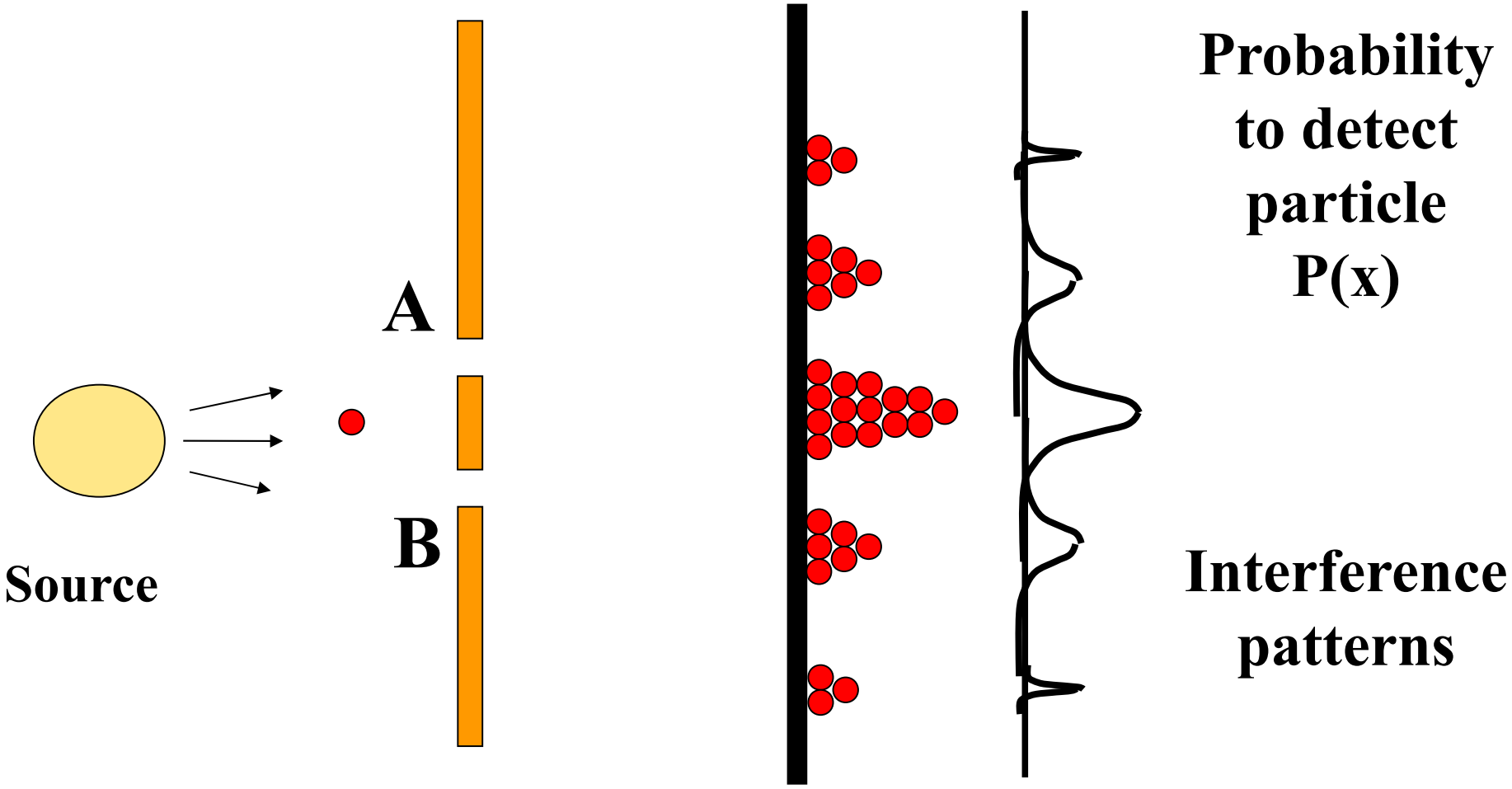

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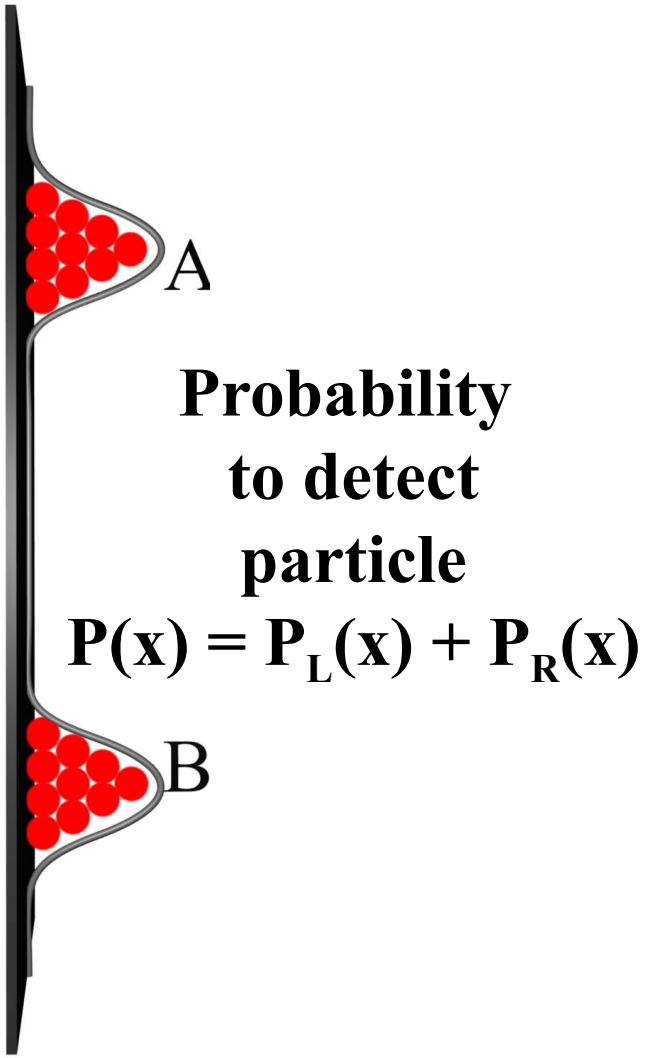

Probability to detect particle

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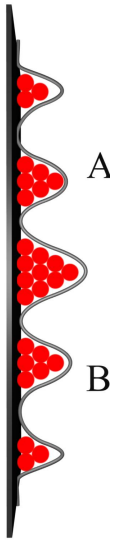
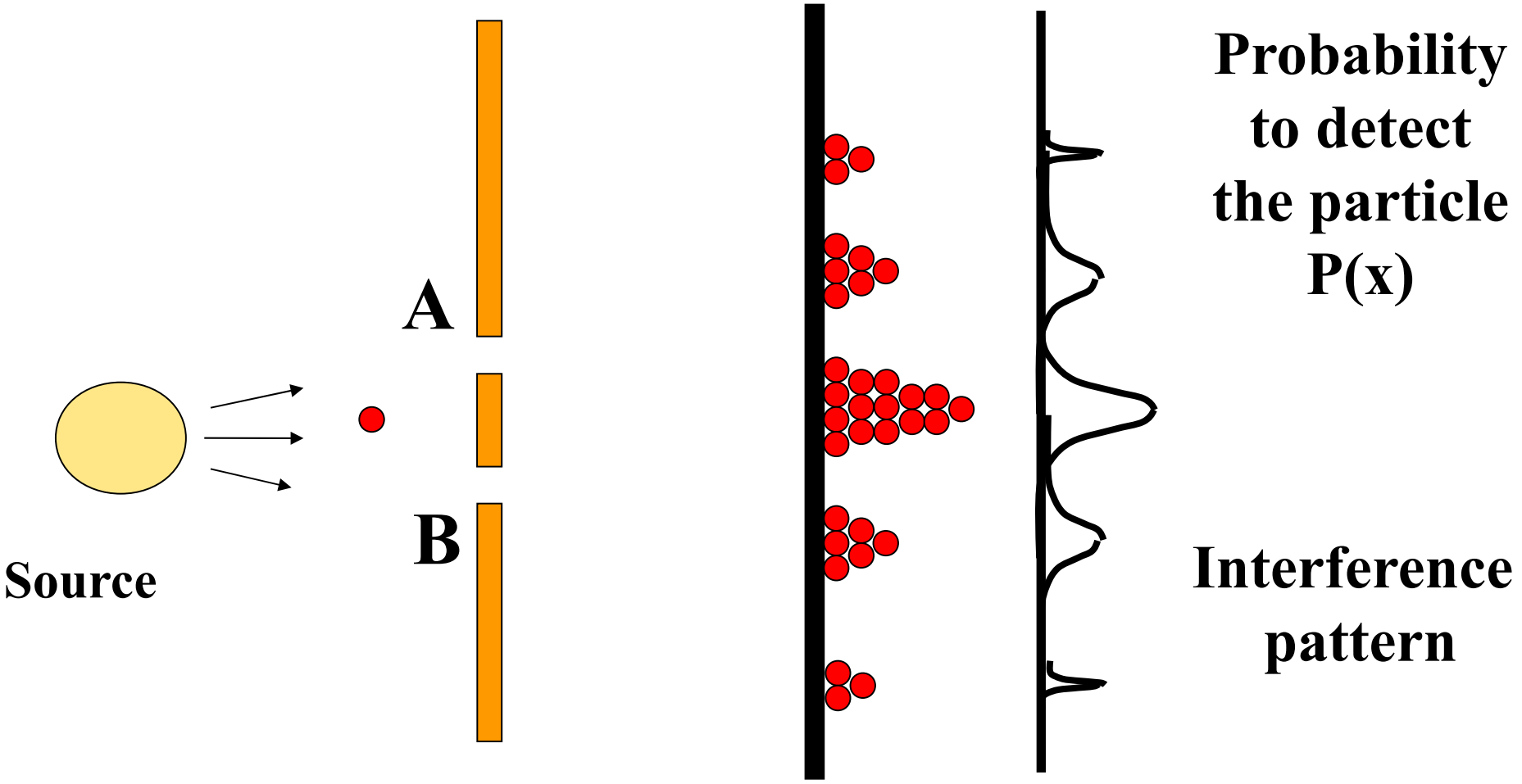
Wavefunction



From which slit the photon is going through ?

It is as if the photon follows the two paths at the same time

Quantum interference



The photon “goes through” the two slits

Quantum interference

Classical physics: a particle can travel along path A **or** B along the way

Quantum physics: "a particle can travel along path A **and** B along the way "

Quantum interference

Classical physics: a particle can travel
along path A **or** B along the way

Quantum physics: "a particle can travel
along path A **and** B along the way "

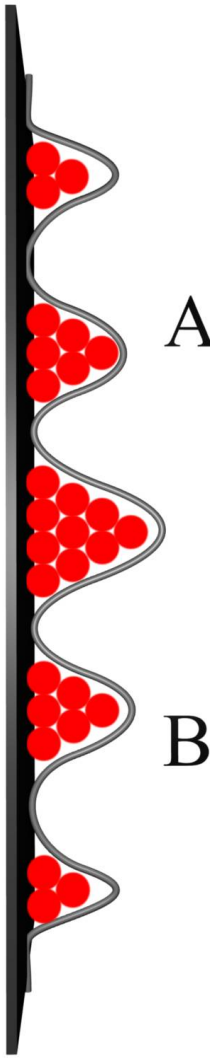
The particle is in a superposition state
of the two trajectories.

The wave function that characterizes the system can be written .....

WAVE FUNCTION

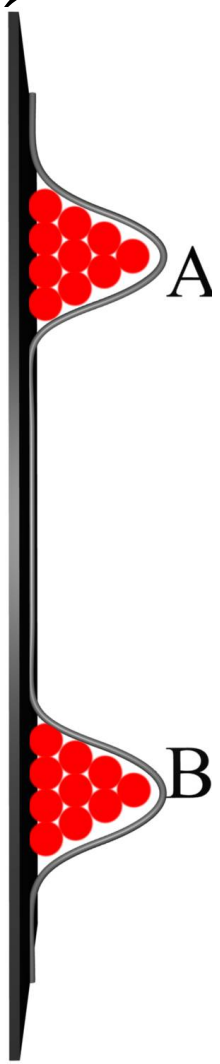
$$|\,fotone\ in\ A\rangle + |\,fotone\ in\ B\rangle$$

$$|\,fotone\ in\ \ A\rangle + |\,fotone\ in\ \ B\rangle$$



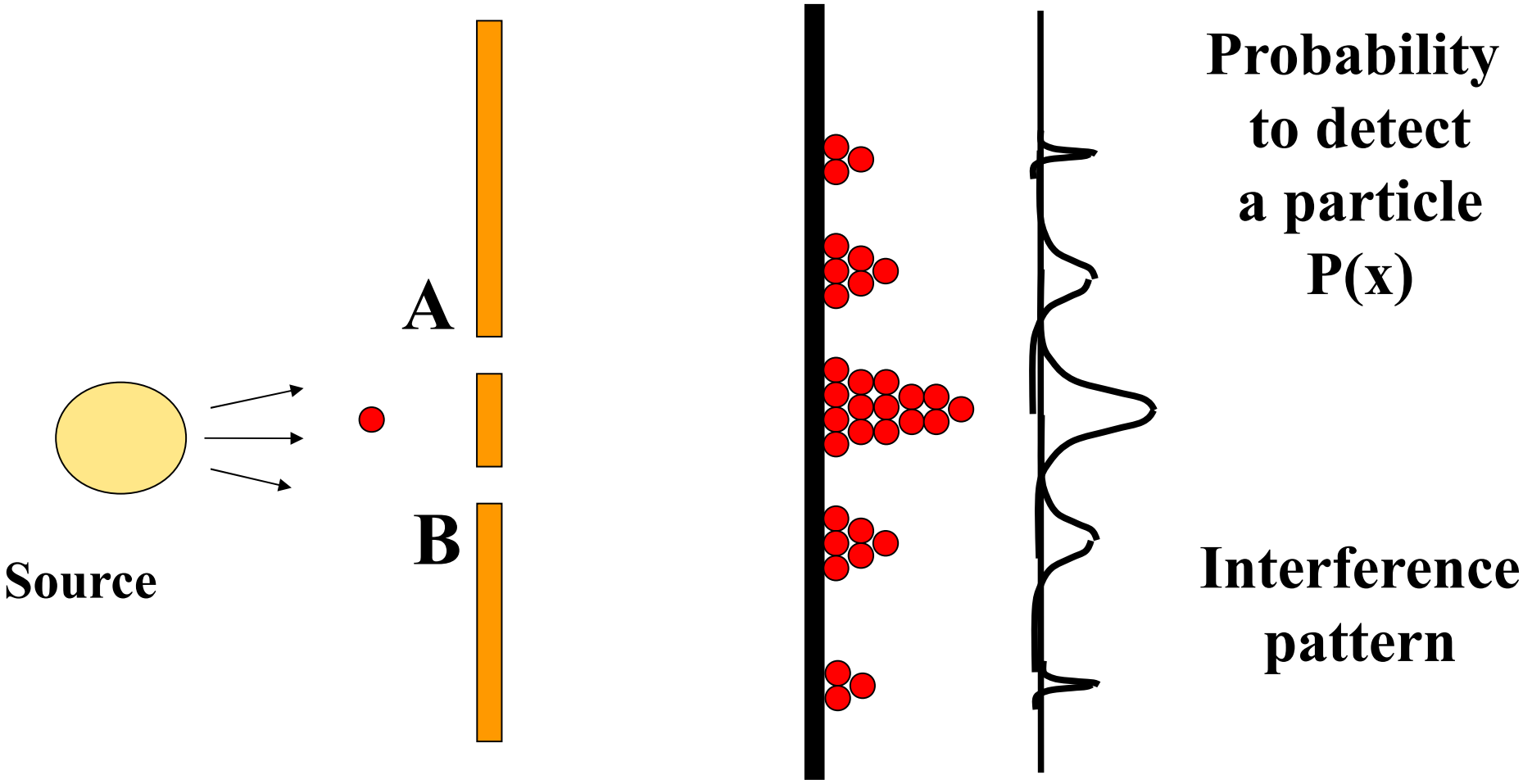
Observation

where the particle is going?

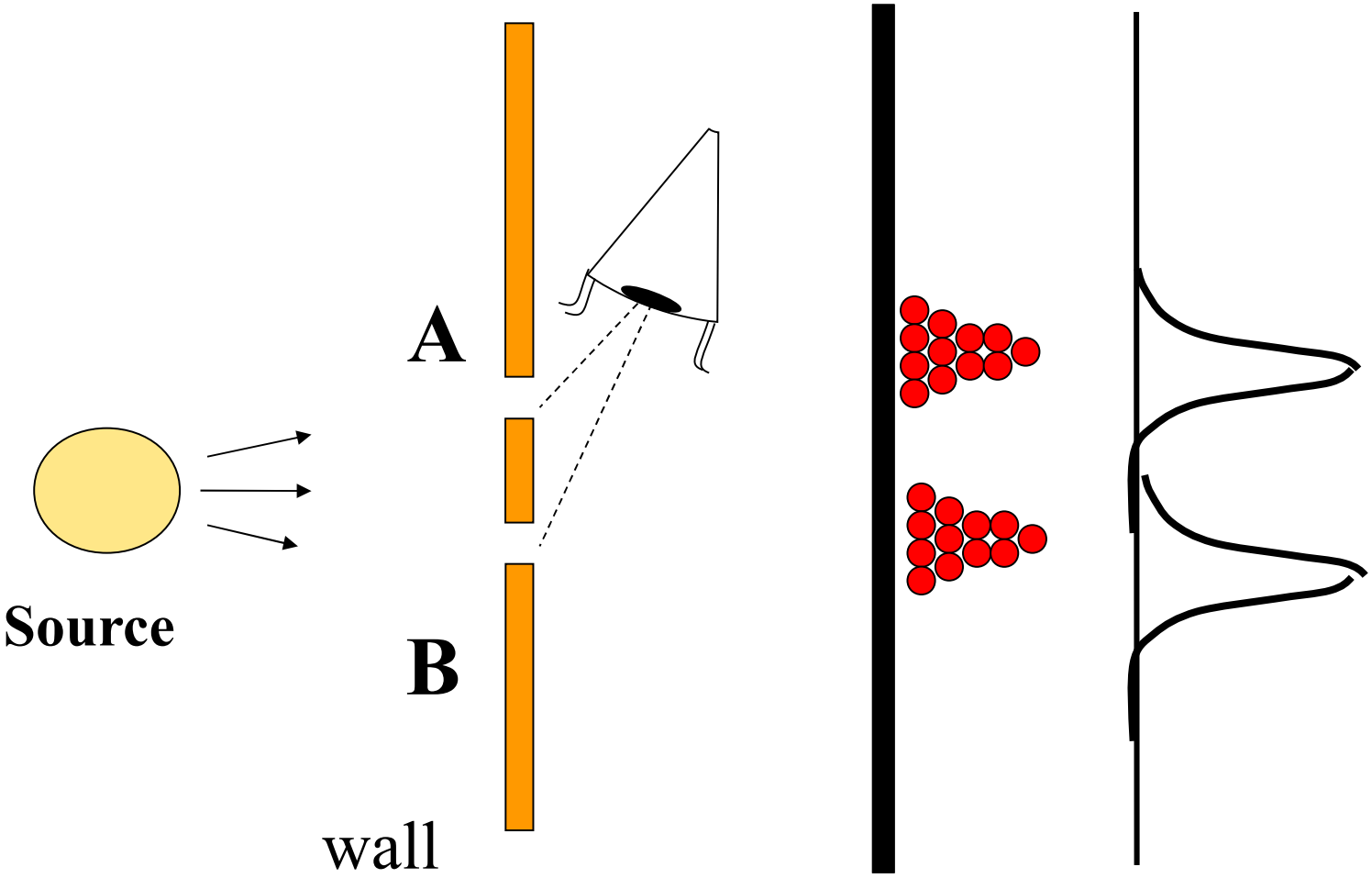


The interference patterns disappear!

Where the particle is going?

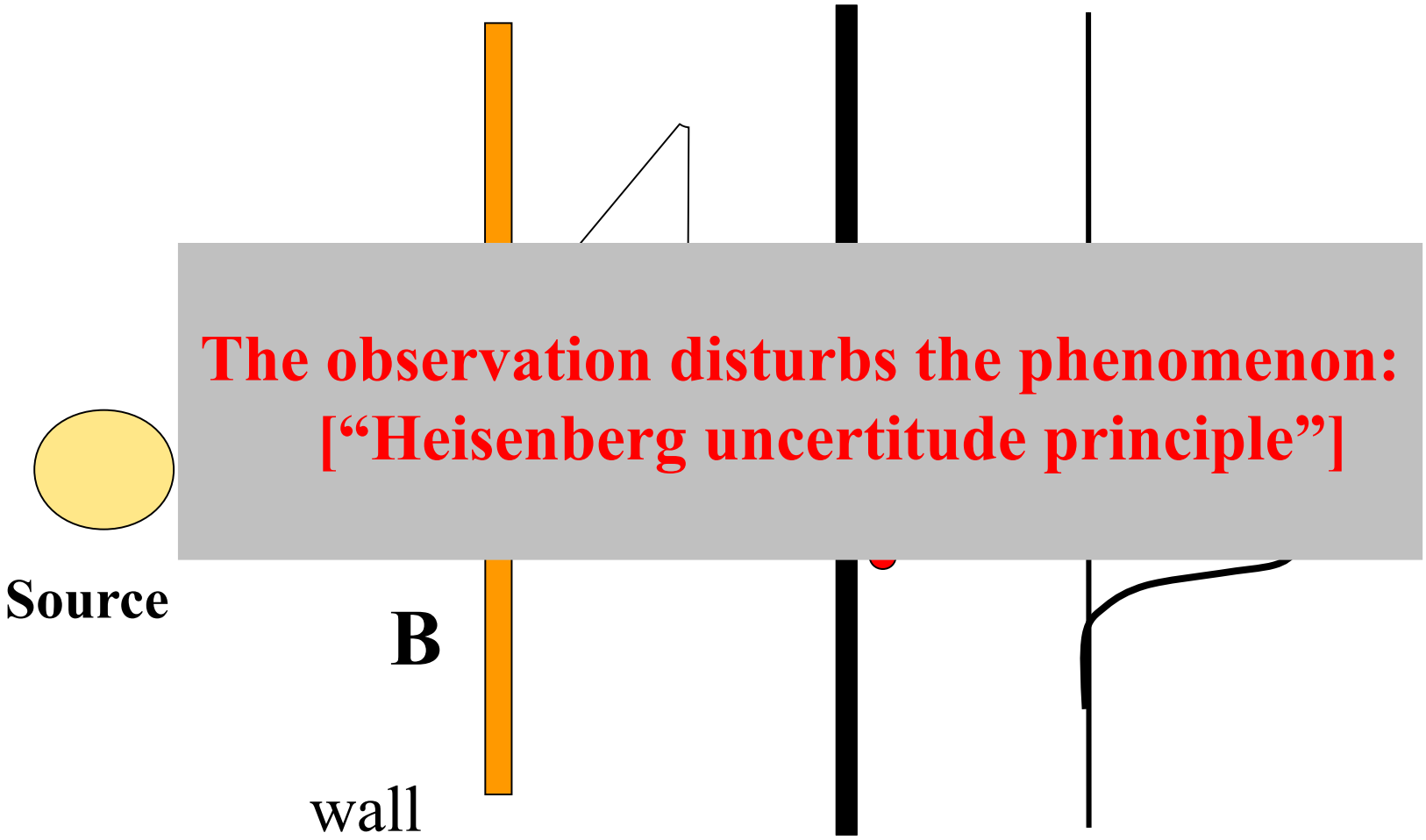


Observation



The interference patterns disappear!

Observation



The interference patterns disappear!

“It from bit”

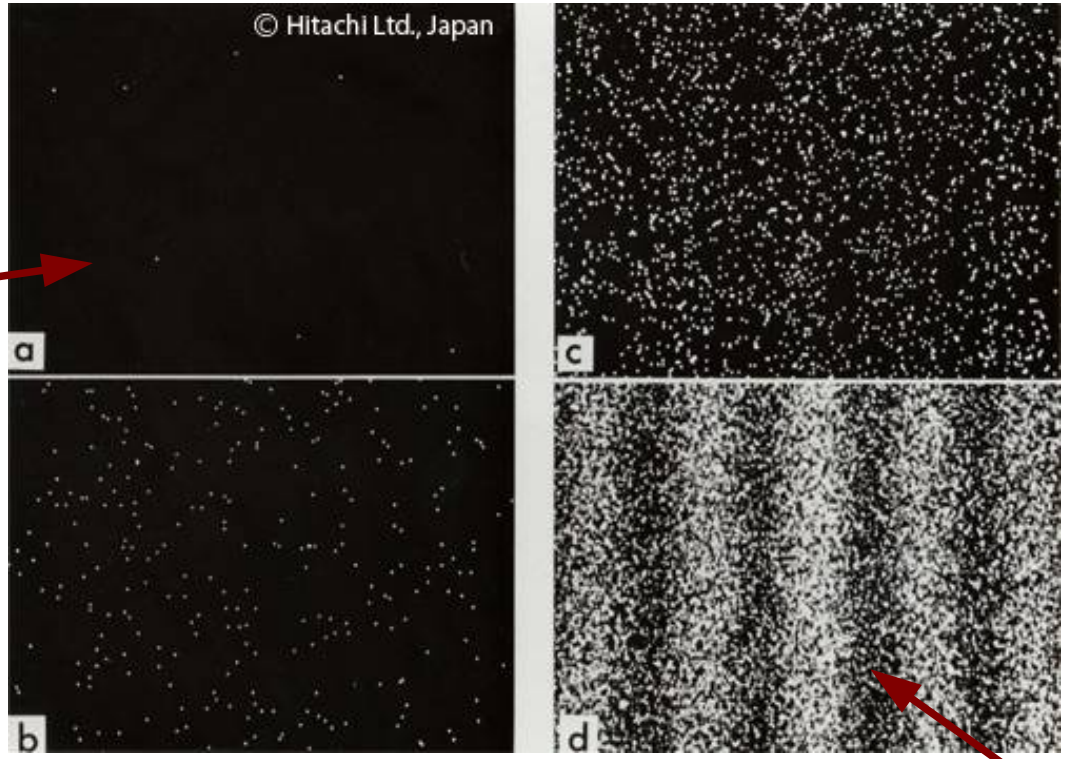
J.A.Wheeler

The reality is also created by our questions, or from information gained.

The observation disturbs the phenomenon: [“Heisenberg uncertitude principle”]

Interference with massive particles: electrons

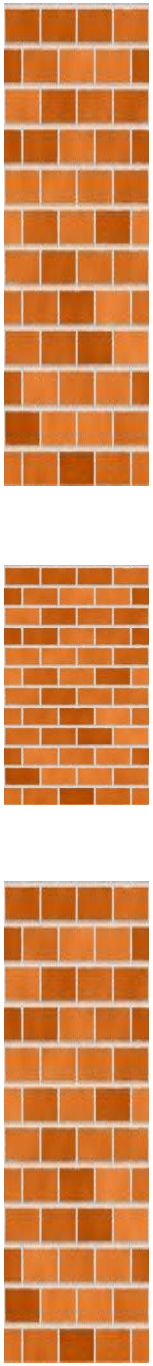
8
electrons



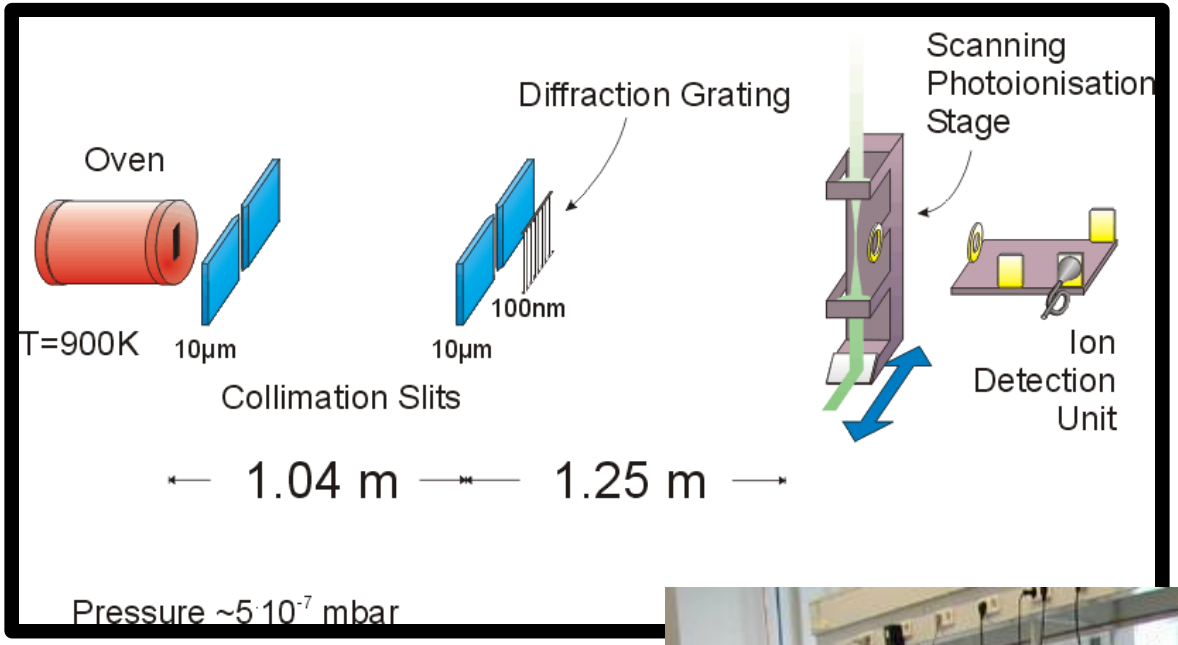
60.000
electrons

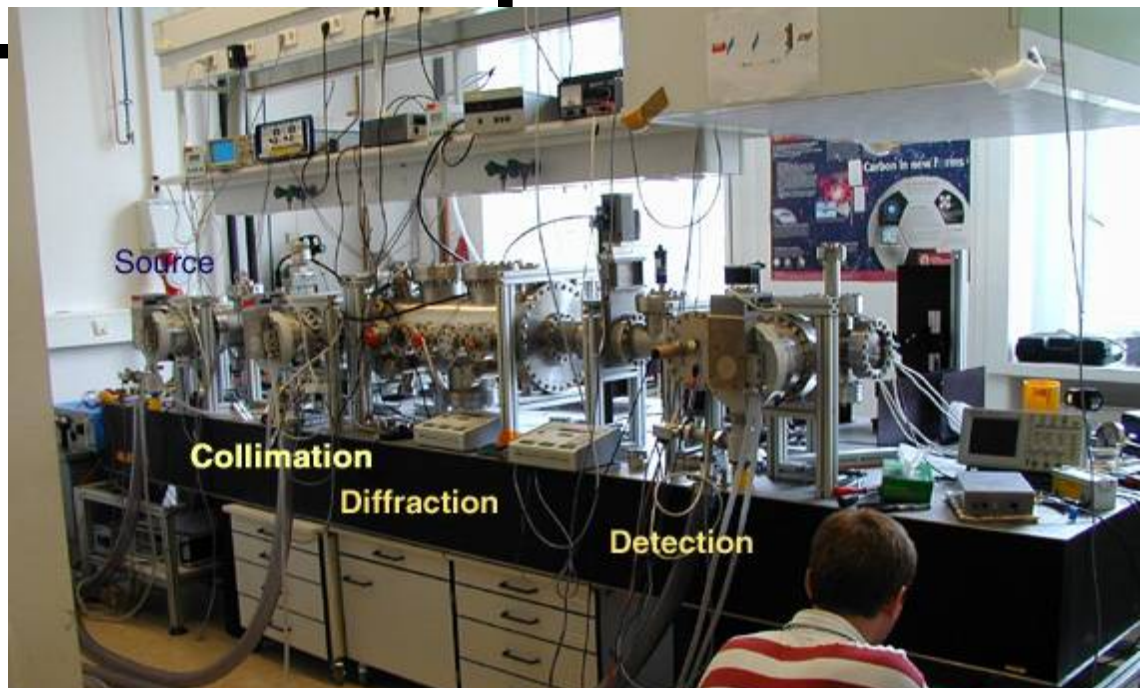

10

Fullerene C_{60}



?

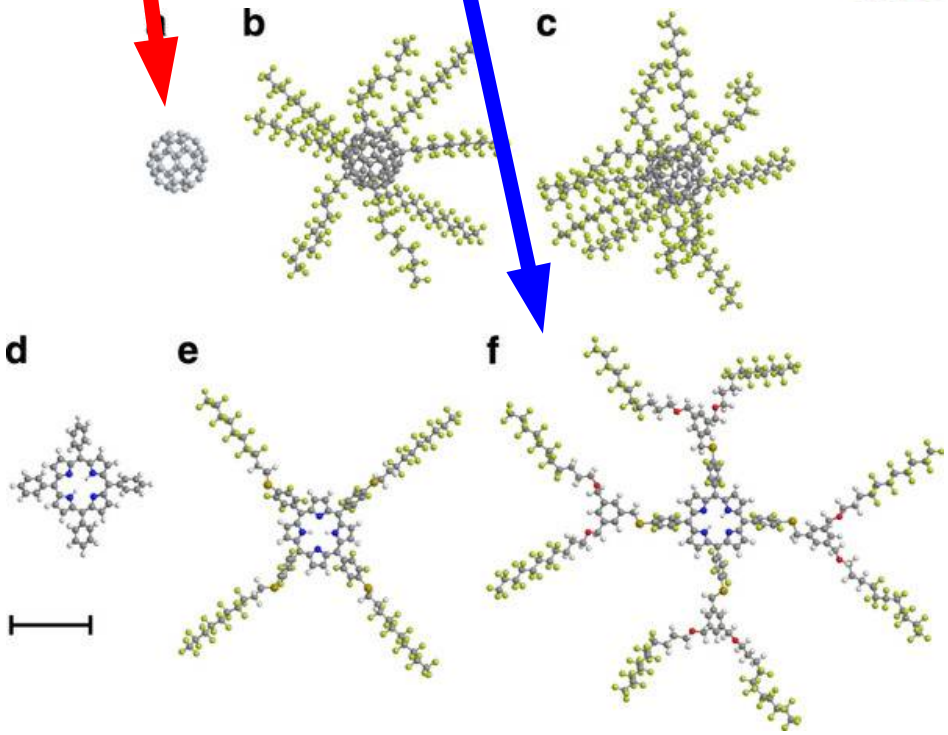

Oven
T=900K
10µm
Diffraction Grating
100nm
10µm
Collimation Slits
Scanning
Photoionisation
Stage
Ion
Detection
Unit
1.04 m
1.25 m
Pressure ~5·10-7 mbar


Source
Collimation
Diffraction
Detection

Fullerene C_{60}

$C_{168}H_{94}F_{152}O_8N_4S_4$

430 atomi

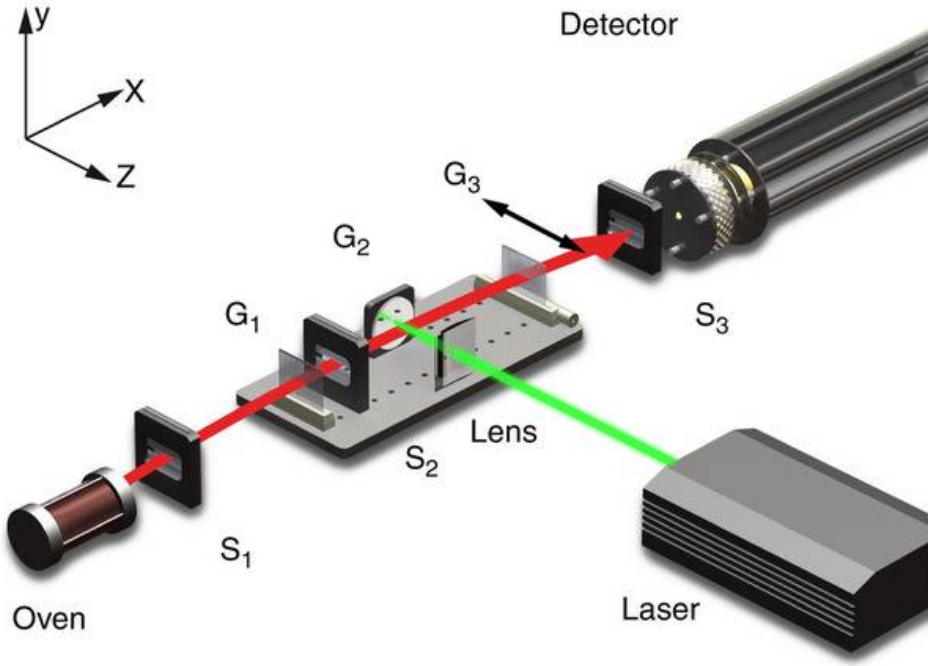


NATURE COMMUNICATIONS | ARTICLE OPEN

Quantum interference of large organic molecules

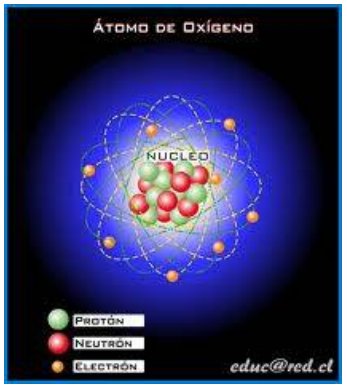
Stefan Gerlich, Sandra Eibenberger, Mathias Tomandl, Stefan Nimmrichter, Klaus Hornberger, Paul J. Fagan, Jens Tüxen, Marcel Mayor & Markus Arndt

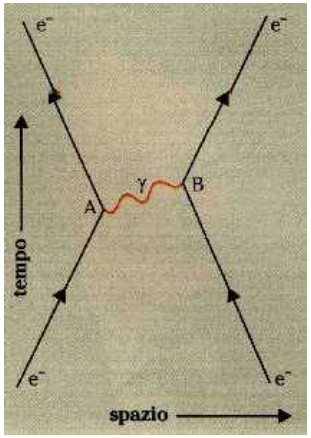
Nature Communications **2**, Article number: 263
doi:10.1038/ncomms1263
Received 05 January 2011 Accepted 02 March 2011

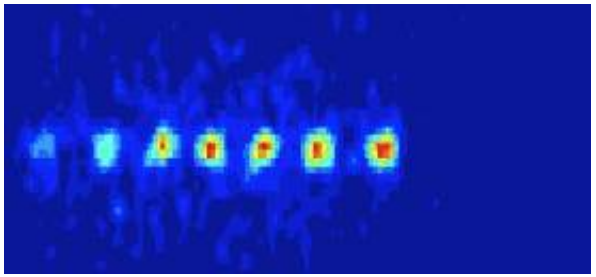


MACROSCOPIC WORLD

MICROSCOPIC WORLD





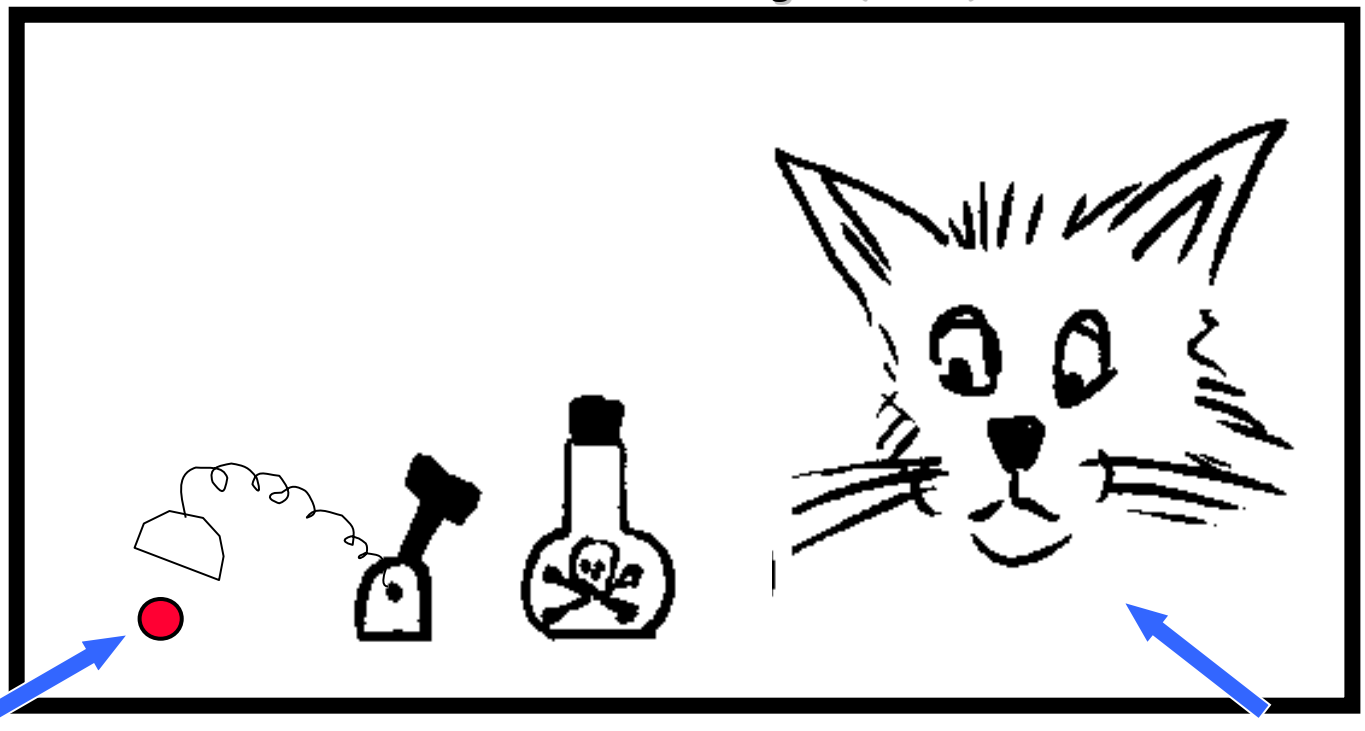


CLASSICAL PHYSICS

QUANTUM PHYSICS

The paradox of Schroedinger's cat

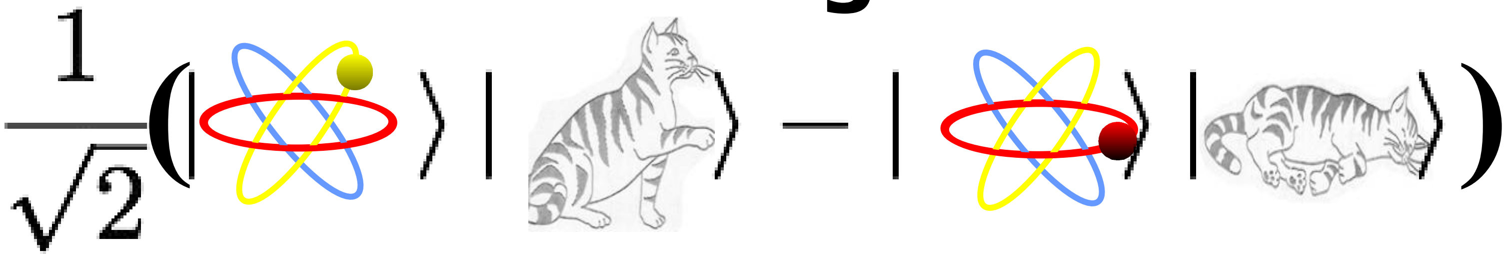
E. Schrödinger (1935)



Oggetto quantistico – particella radioattiva.
50% probabilità di decadimento in un'ora.
Il decadimento causa la rottura della fiala con veleno

Oggetto classico: gatto

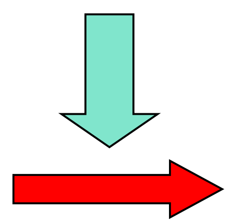
The paradox of Schroedinger's cat



Atom not decayed — Alive cat — Atom decayed — Dead cat

Not observed cats living and dead at the same time!

Interaction with the environment: loss of coherence

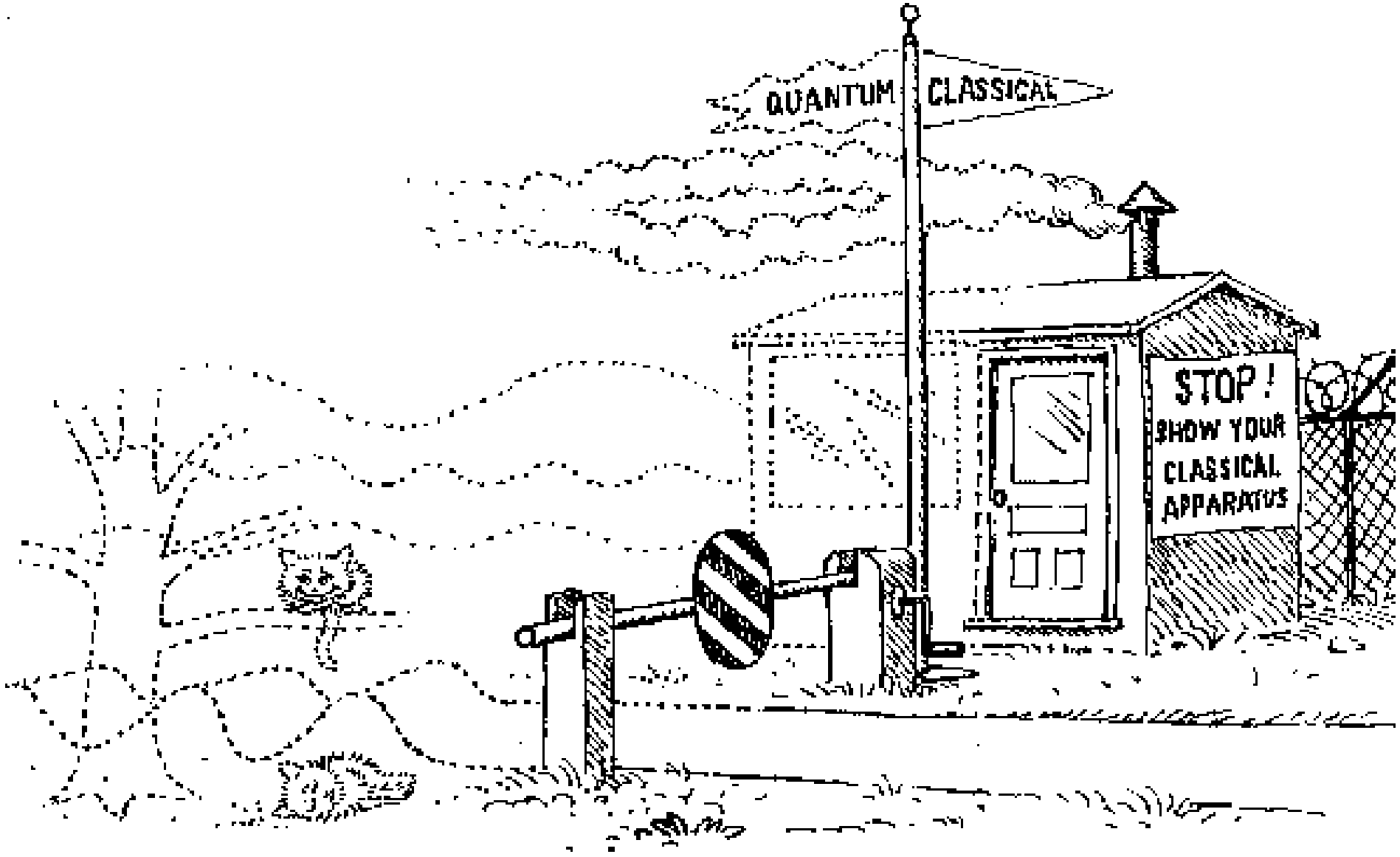


Superposition state *(alive* *__and__* *dead)* → Statistical mixture *(alive* *__or__* *dead)*

Computing: superposition states of many qubits

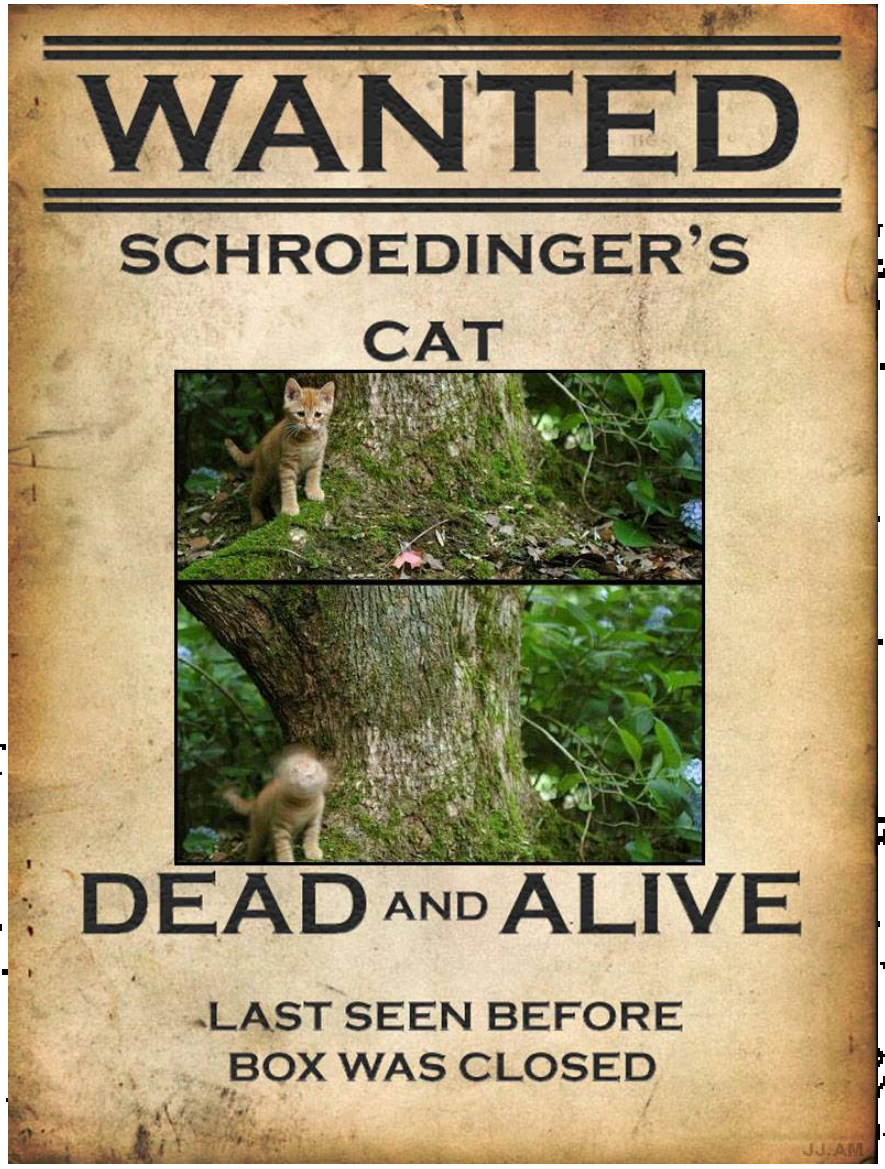
Techniques for Quantum Error Correction

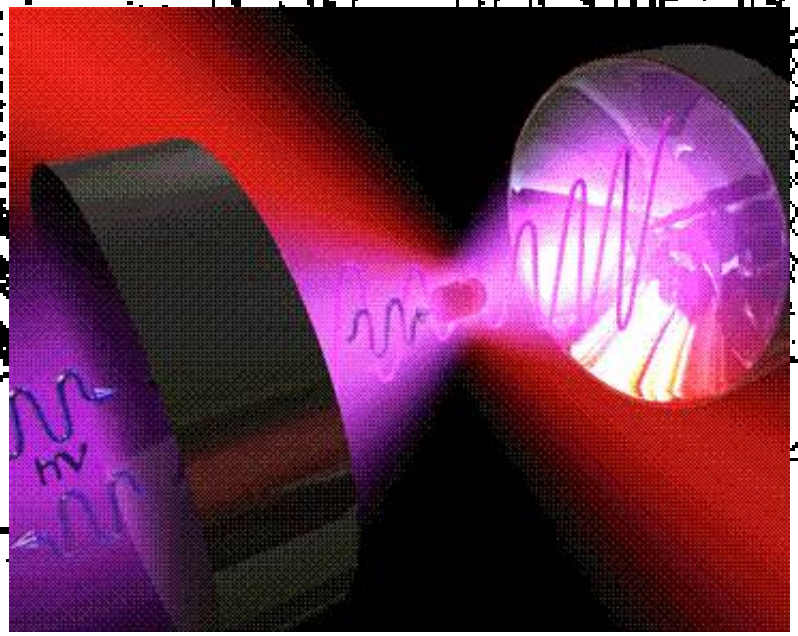
The border between the classical and quantum world



Zurek, Physics Today, October 1991, page 38

The border between the classical and quantum world





Zurek, Physics Today, October 1991, page 38

“A phenomenon is not a phenomenon until is a measured phenomenon…”

J. A. Wheeler

“Is there a moon in the sky if I do not look at?”

A. Einstein

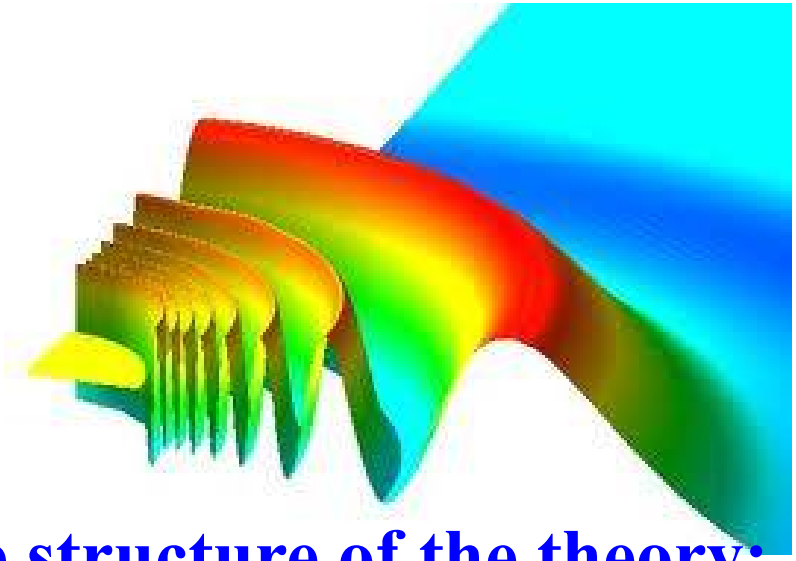
***There are the "objective properties"*, the “elements of physical reality” ?**

A. Einstein

What is the wave function ?

The **wave function** is a physical state of the quantum system.

Ψ



Mathematics dominates the structure of the theory:

["Wave function" | Ψ> tool to describe its essence or reality?]

$$|\,fotone\ in\ A\rangle + |\,fotone\ in\ B\rangle$$

The wave function

EPISTEMOLOGY

'Discussion on knowledge

or

ONTOLOGY

'Discussion on essence'

Quantum Mechanics:

"Lo scopo della nostra descrizione della natura non è il cercare l'essenza reale dei fenomeni ma soltanto l'indagare con la massima profondità possibile le relazioni tra i molteplici aspetti della nostra esperienza."

"The purpose of our description of nature is not the search for the real essence of phenomena but only to investigate the maximum possible depth relations between the manifold aspects of our experience."

Niels Bohr (1934)

FAPP interpretation (For All Practical Purposes)

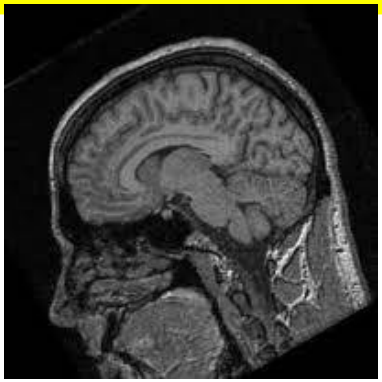
Per tutti i fini pratici

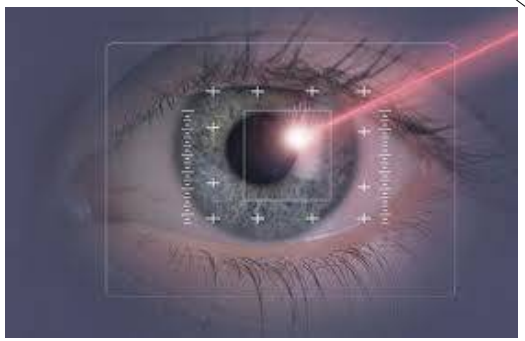
1960- Theodore Harold Maiman

Laser

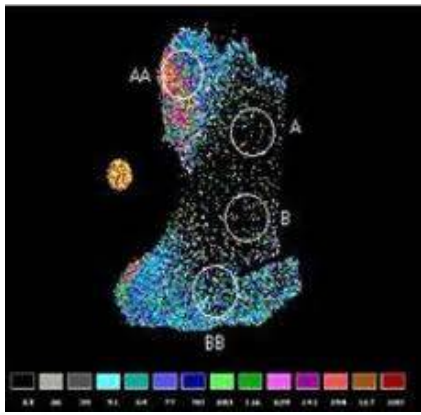
1946- Felix Bloch e Edward Purcell

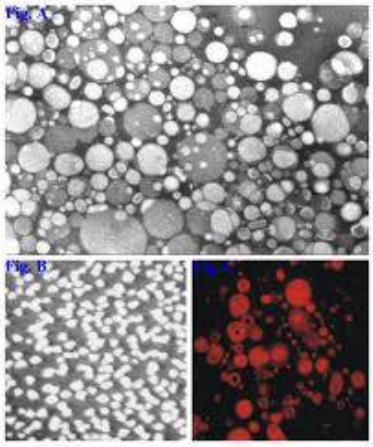
Nuclear Magnetic Resonance





Quantum Mechanics





1931- Ernst Ruska

Electronic microscope

Quantum Information

Information Theory + Quantum Mechanics:

It exploits the laws of quantum mechanics to communicate, manipulate and process information

Fundamental physics

Non-locality

Micro-macroscopic transition

Applied physics

Criptography

Computation

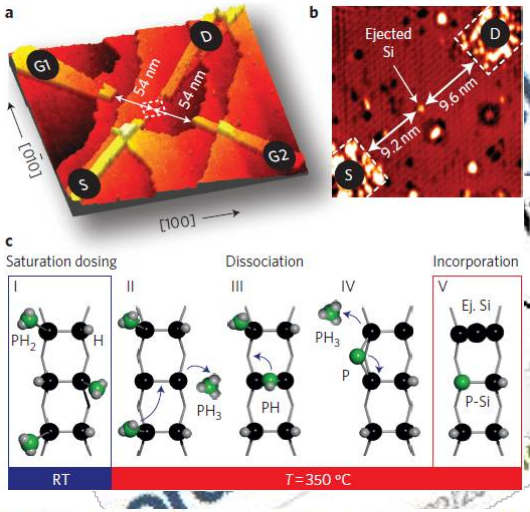
Metrology

NANOELECTRONICS

Transistors arrive at the atomic limit

A single-atom transistor has been made by positioning between metallic electrodes, also made of phosphorus, on a silicon surface.

Gabriel P. Lansbergen



tamaño de un
tesala del

EL MUNDO.es
Líder mundial en español | Lunes 20/02/2012. Actualizado 10:57h.

The New York Times

U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS

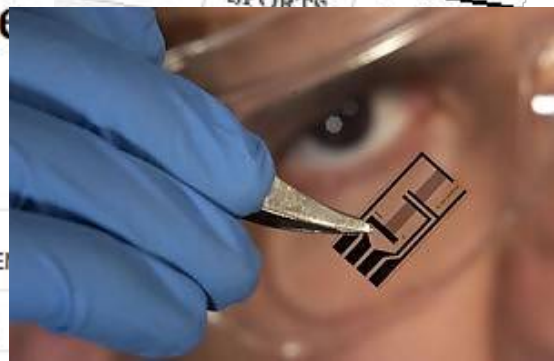
Science

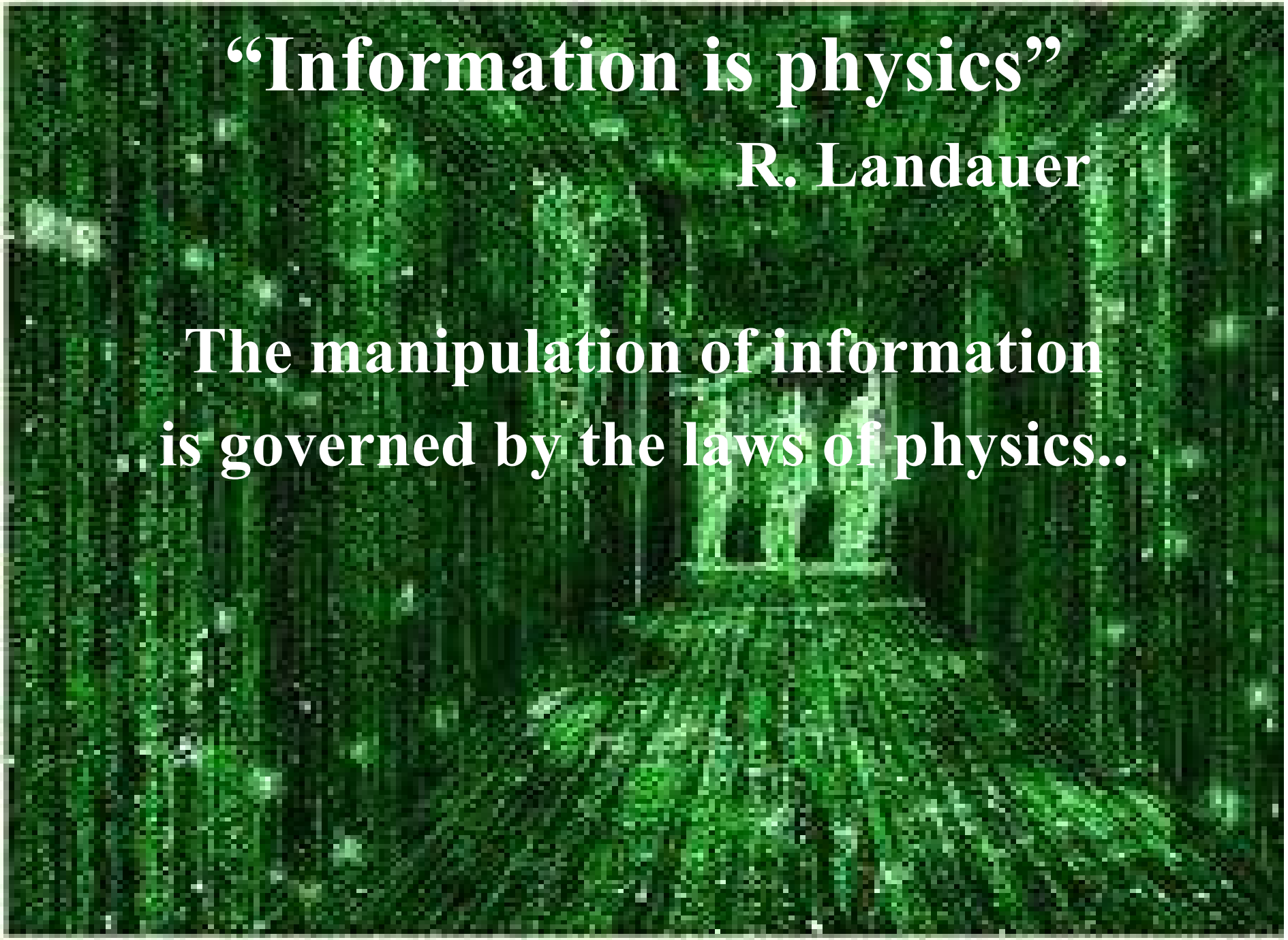
Physicists Create a Working Transistor From a Single Atom

By JOHN MARKOFF
Published: February 19, 2012

Australian and American physicists have built a working transistor from a single phosphorus atom embedded in a silicon crystal.

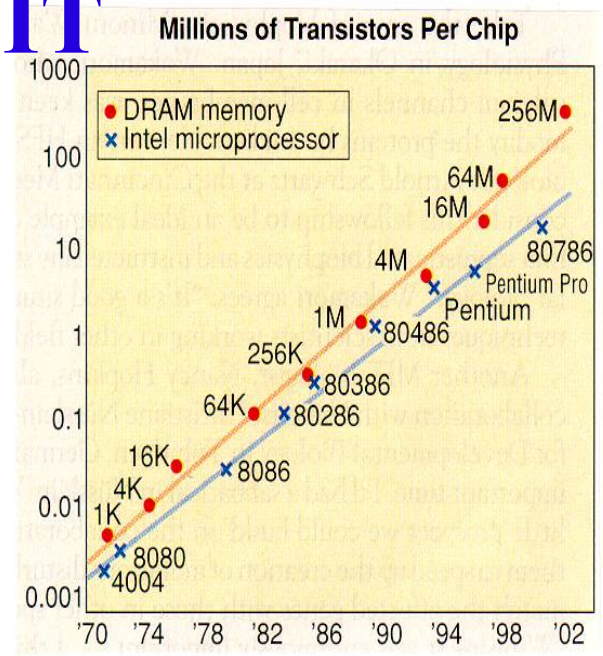
RECOMMEND
TWITTER



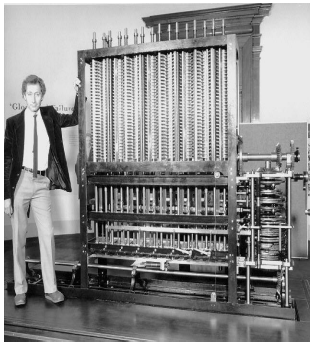

“Information is physics”
R. Landauer
The manipulation of information
is governed by the laws of physics..

Evolution of Information Technology

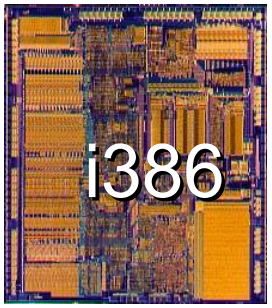
BIT



1879

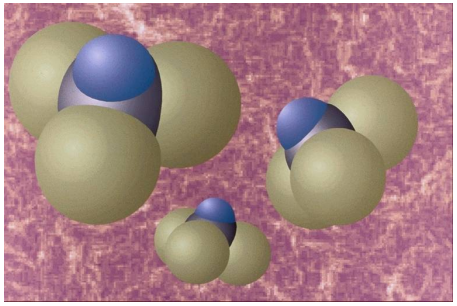


1986



1 micron

2020



1 nanometro

BIT: **Dichotomic variable**

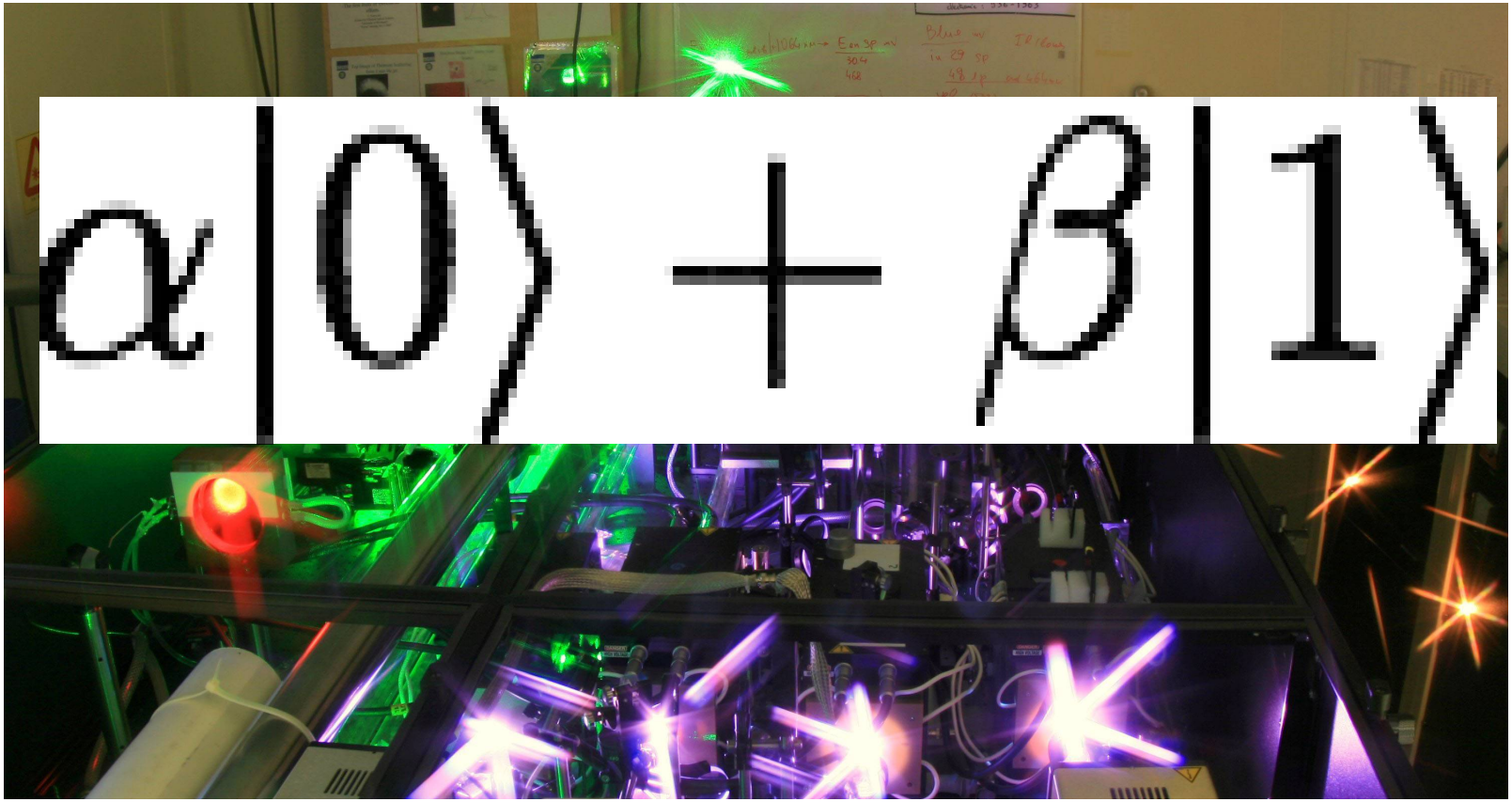
0 *o* 1

QUBIT (Quantum Bit)

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

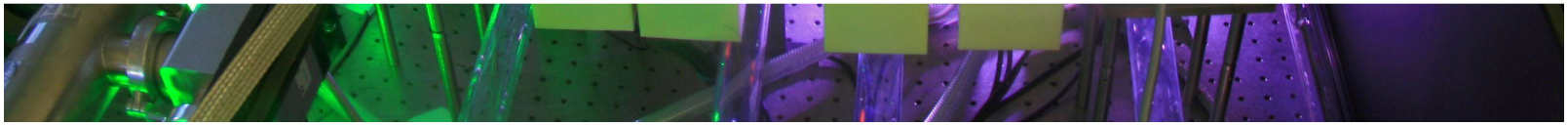
QUANTUM INFORMATION

QUBIT (Quantum Bit)

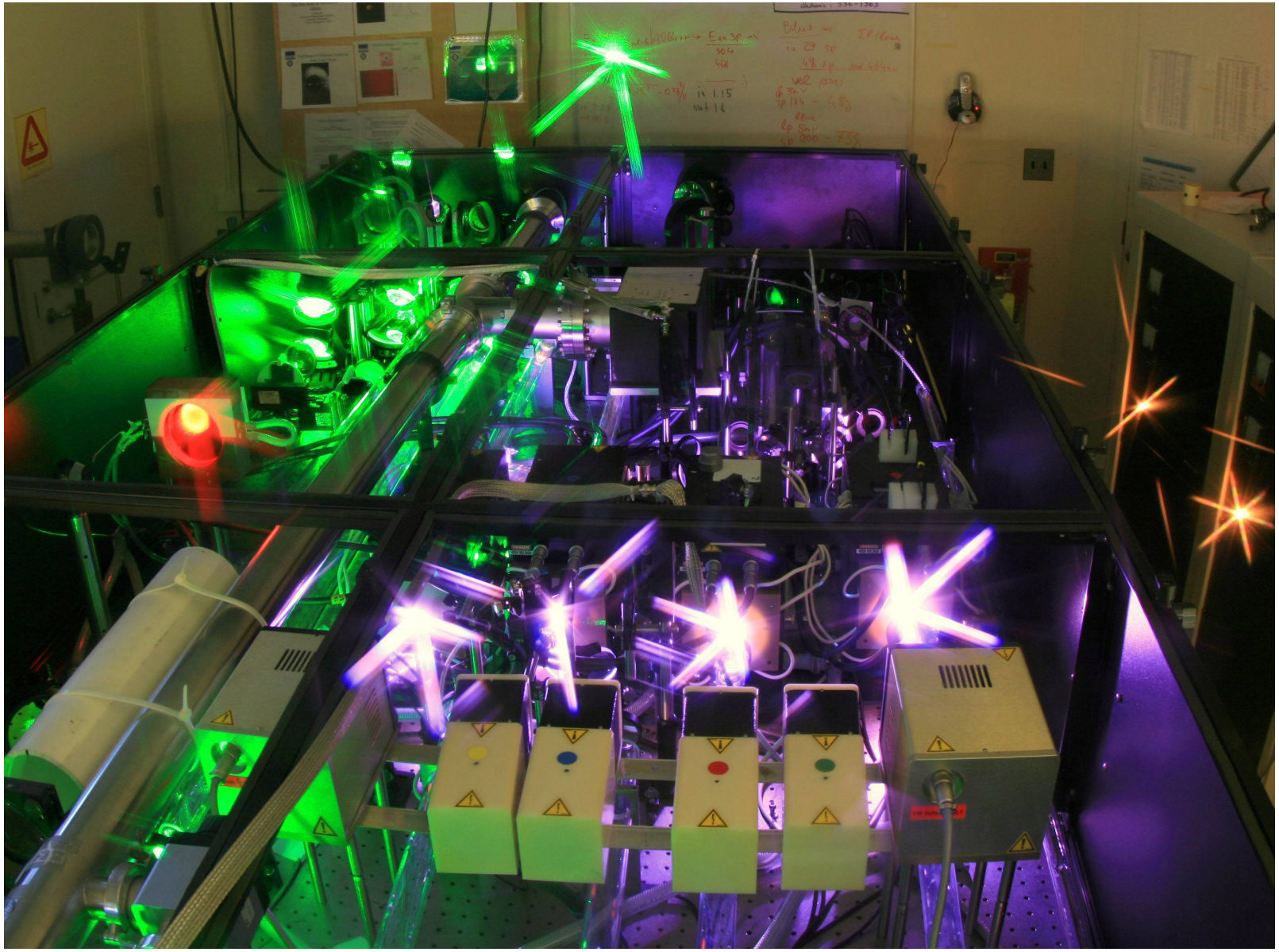


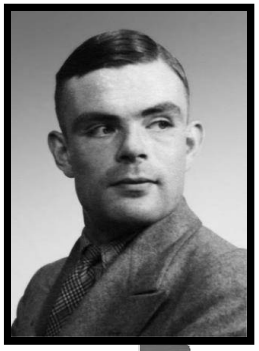
GOAL:

TO EXPLOIT QUANTUM PARALLELISM



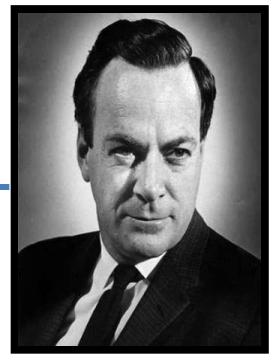
QUBIT (Quantum Bit)

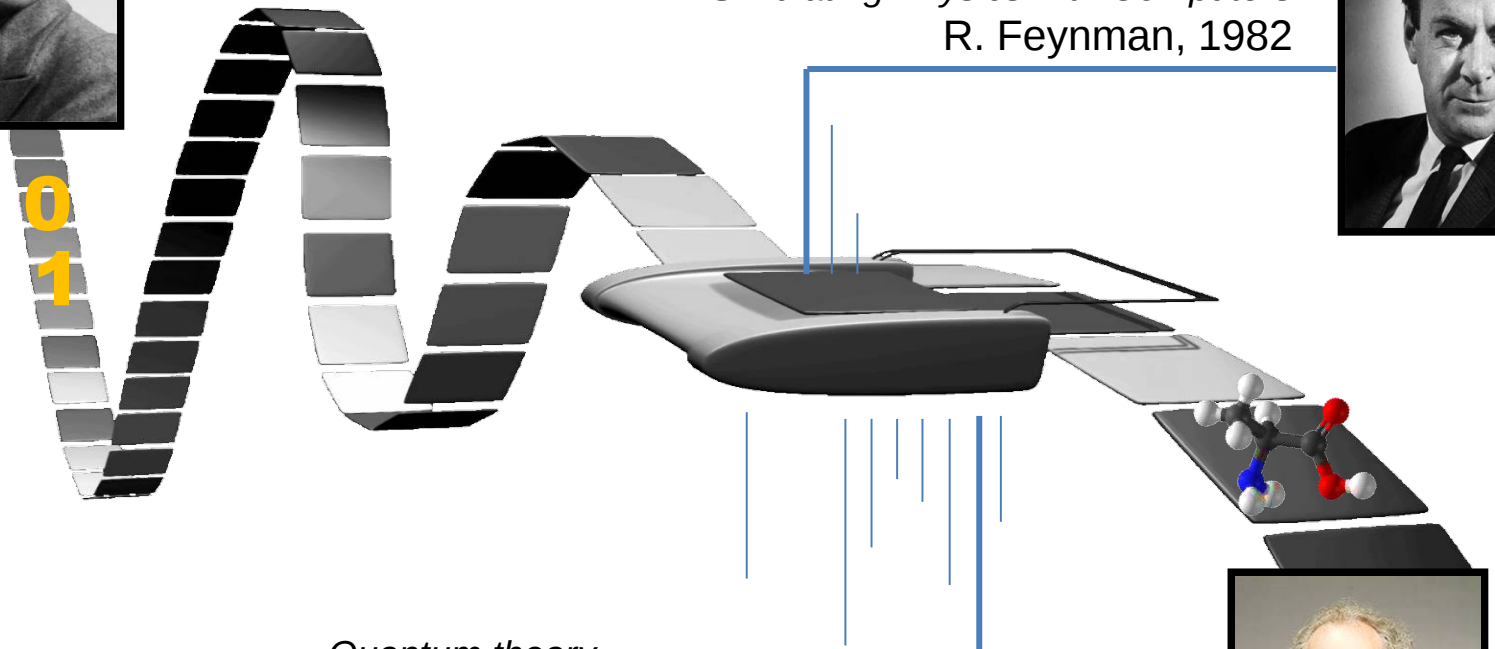




On computable numbers, with an application to the Entscheidungsproblem
A. Turing, 1936

Simulating Physics with Computers
R. Feynman, 1982

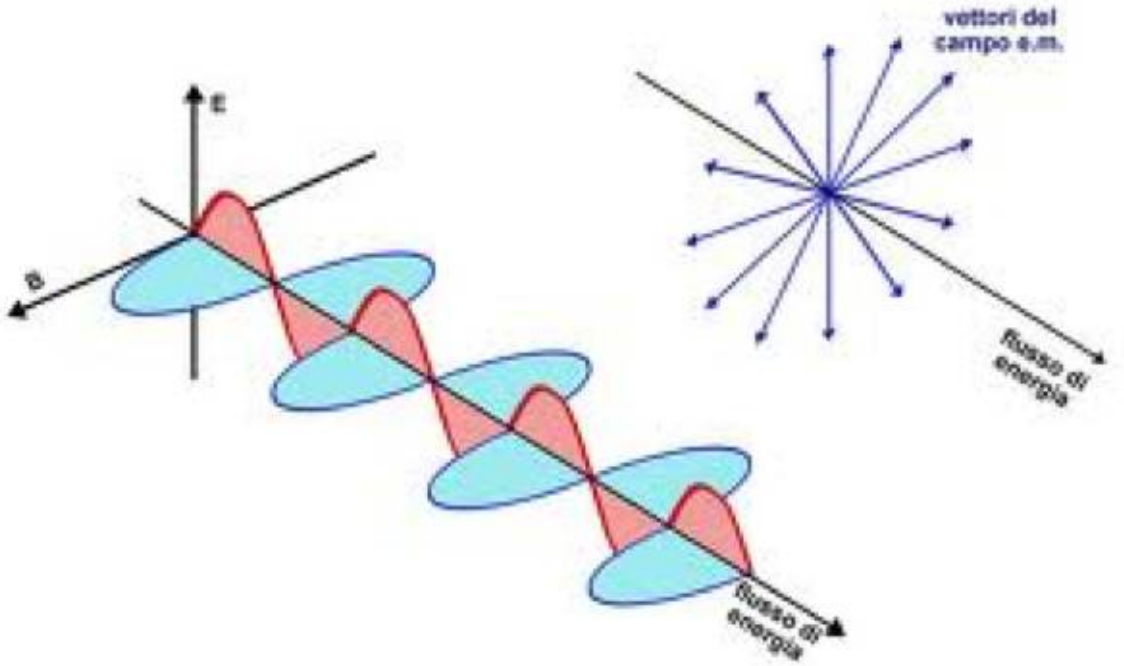




Quantum theory, the Church-Turing principle and the universal quantum computer
D. Deutsch, 1984

Algorithms for quantum computation: Discrete log and factoring
P. W. Shor, 1994

Light Polarizzazion



Qubit → **Single photon polarization**

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

$$\alpha|H\rangle + \beta|V\rangle$$

H: horizontal

V: vertical

Light Polarization

Polarizzazione: direzione di oscillazione del campo elettromagnetico

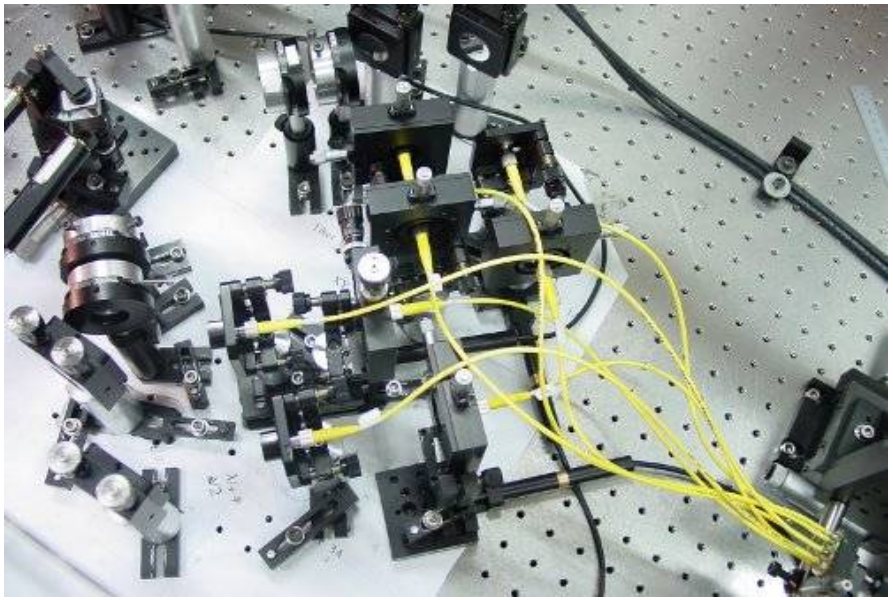
Polarizzazione orizzontale $|H\rangle$

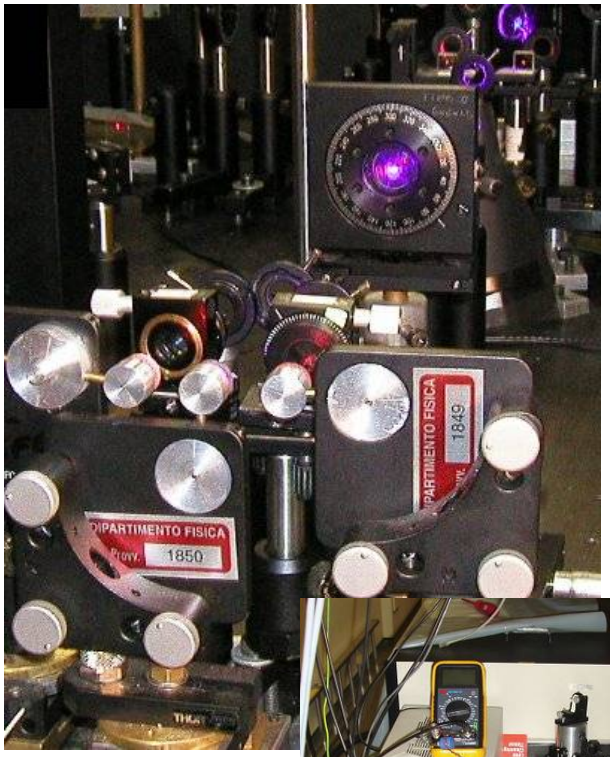
Polarizzazione verticale $|V\rangle$

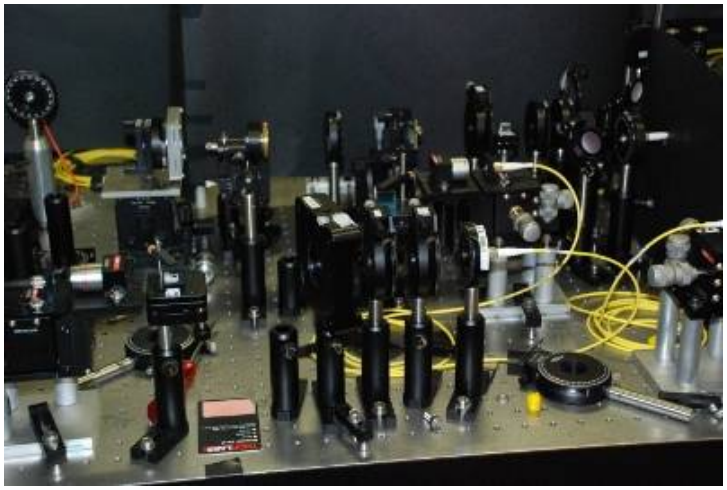
Polarizzazione a + 45° $|H\rangle + |V\rangle$

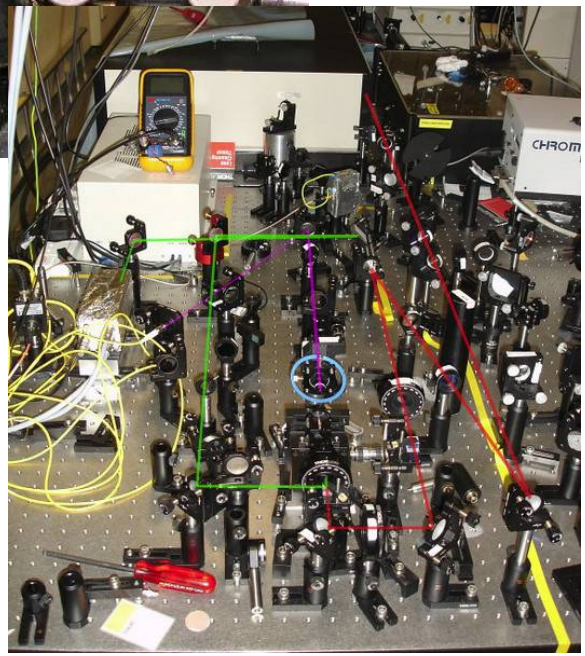
Polarizzazione a - 45° $|H\rangle - |V\rangle$

Non-locality in laboratory...





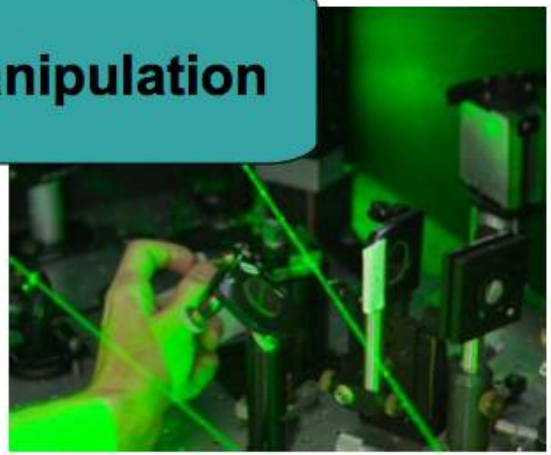


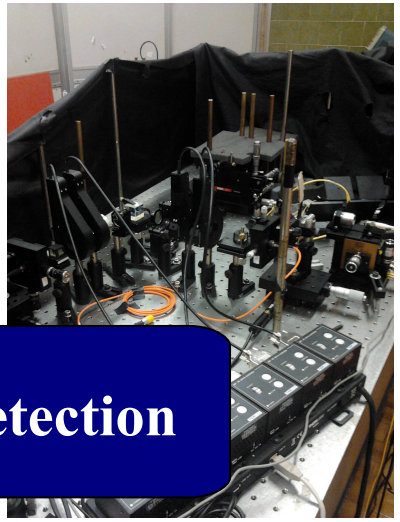


Integrated quantum photonics

Preparation

Manipulation



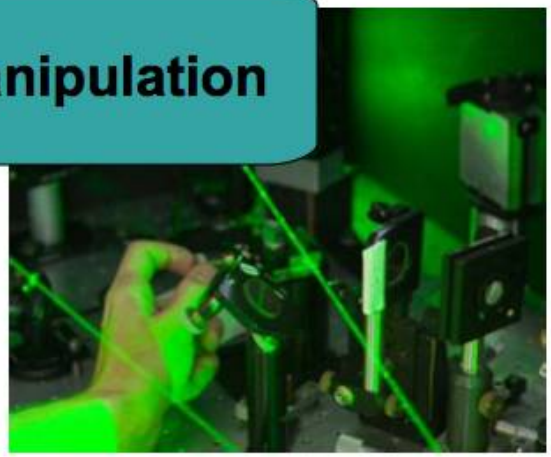


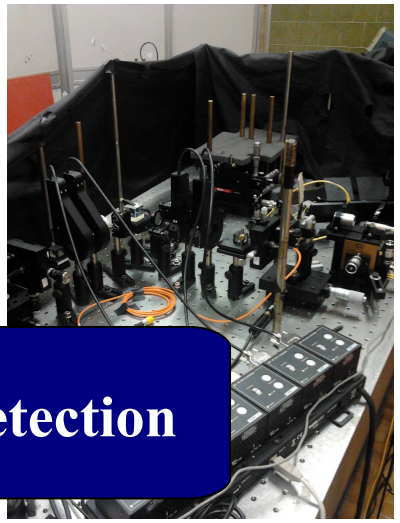
Detection

Integrated quantum photonics

Preparation

Manipulation

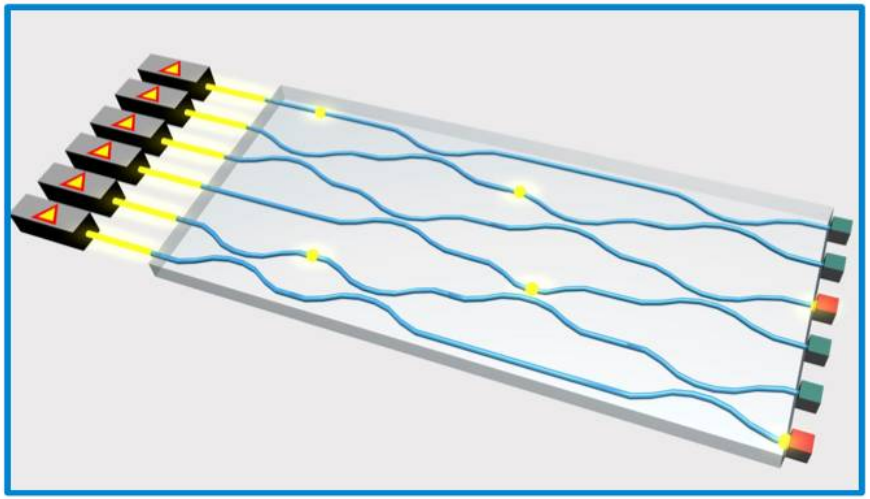




Detection

- Single photon sources
- Manipulation
- Single photon detectors

ON THE SAME CHIP



Marie Curie Initial Training Network (ITN)

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UNIVERSITÀ DI ROMA

Consiglio Nazionale delle Ricerche

universität wien

TOSHIBA
Leading Innovation

PICQUE project:
« Photonic Integrated Compound Quantum Encoding

UNIVERSITY OF OXFORD

University of BRISTOL

UNIVERSITÄT PADERBORN
Die Universität der Informationsgesellschaft

CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

TU/e Technische Universiteit Eindhoven University of Technology
Where innovation starts

ADAPTICA

id Quantique

THALES

POLITECNICO MILANO

qutools

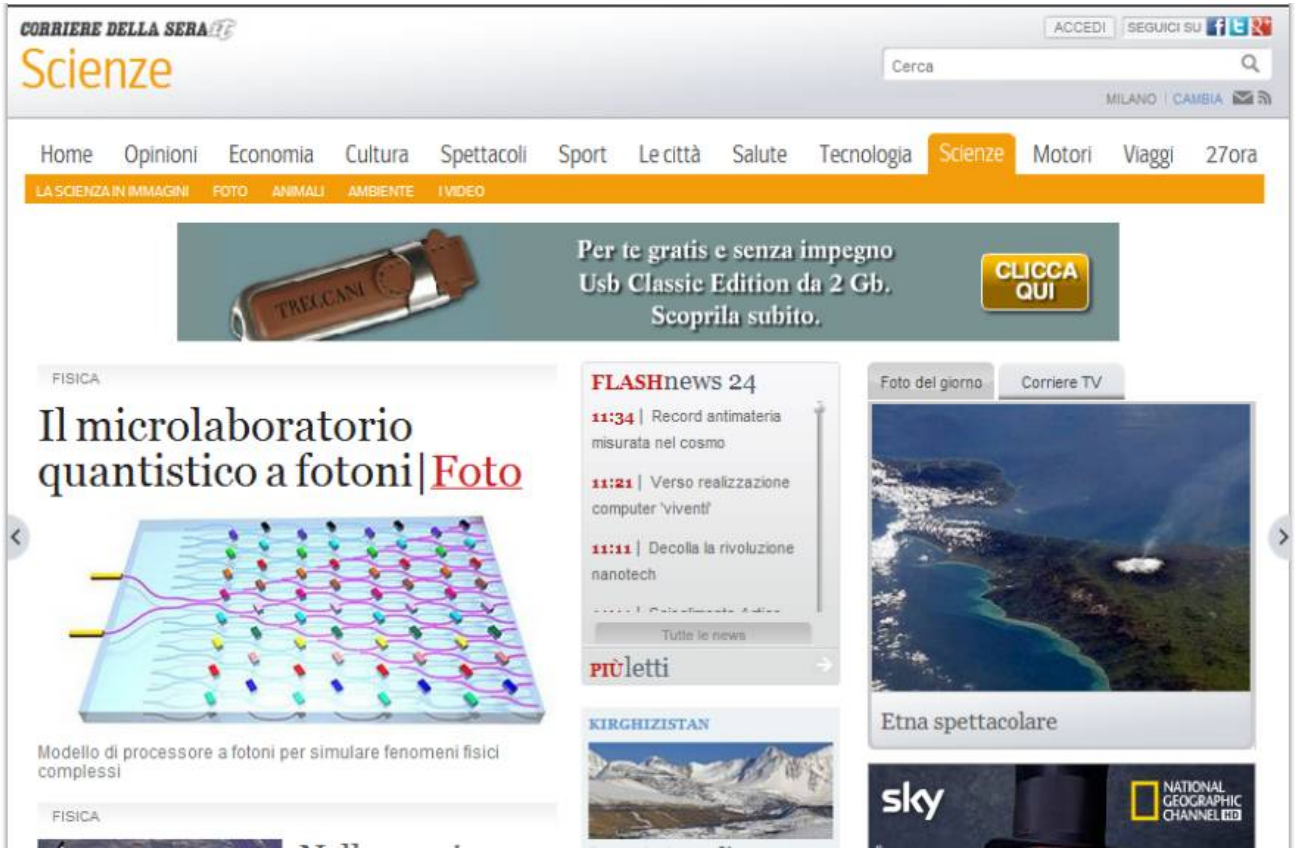
SINGLE QUANTUM

SISTEMI FORMATIVI CONFINDUSTRIA

ma per seguir virtute e canoscenza
SISSA

Towards the integrated quantum information

SAPIENZA
UNIVERSITÀ DI ROMA



INO-CNR
ISTITUTO NAZIONALE DI OTTICA

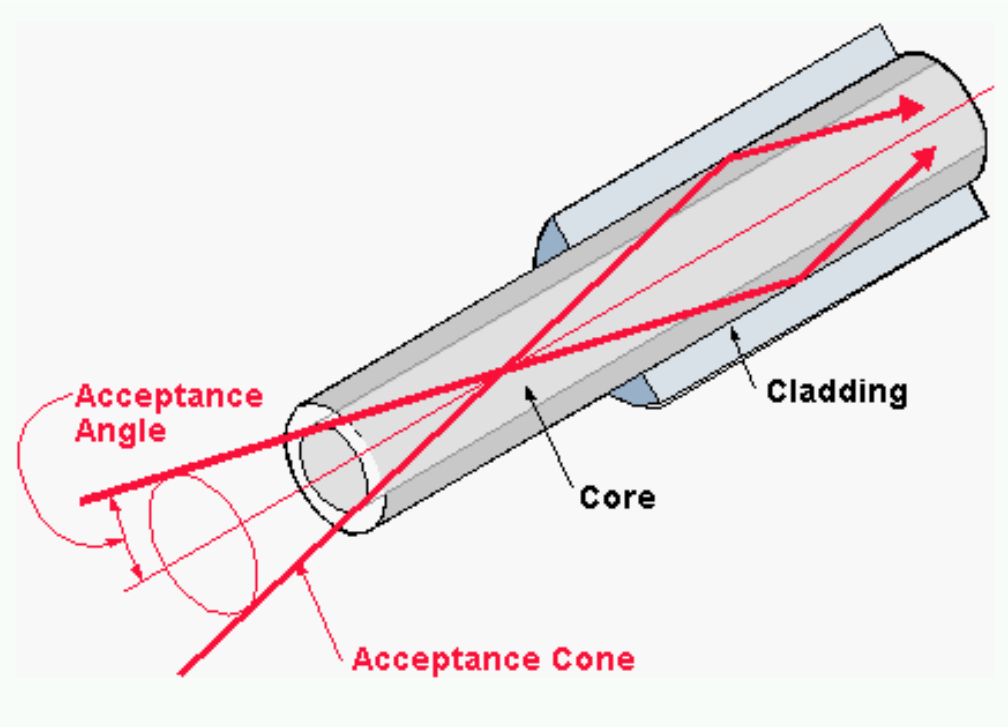
POLITECNICO MILANO

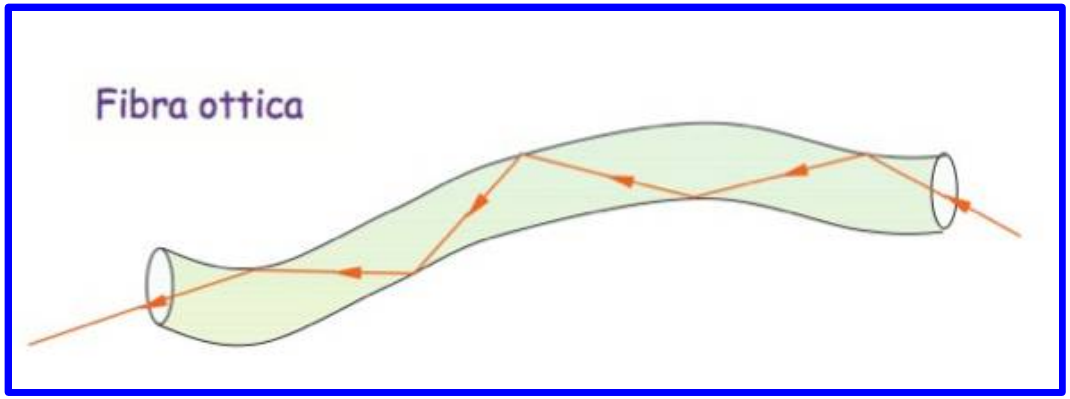
ifn

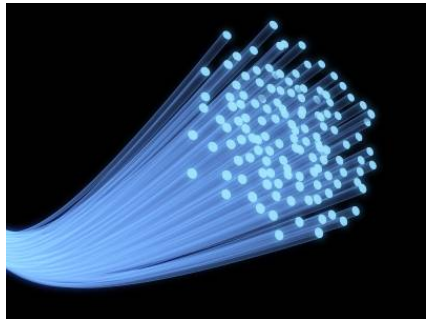
How to guide light inside the chip ?

Optical fibre:

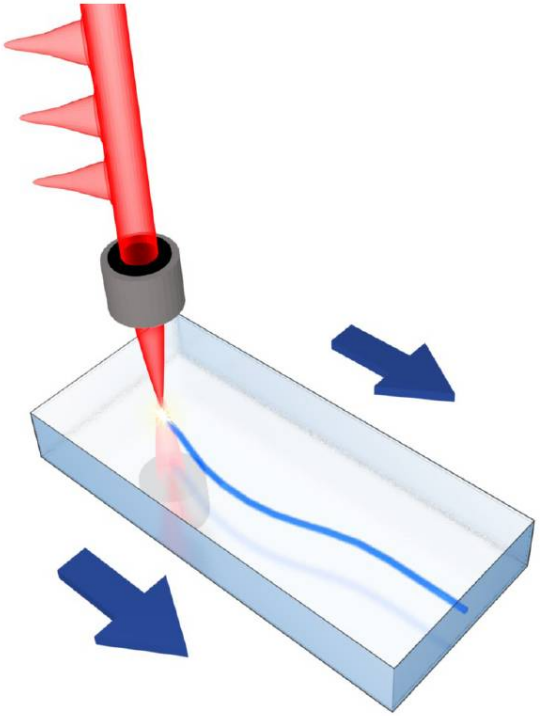
Guide the light

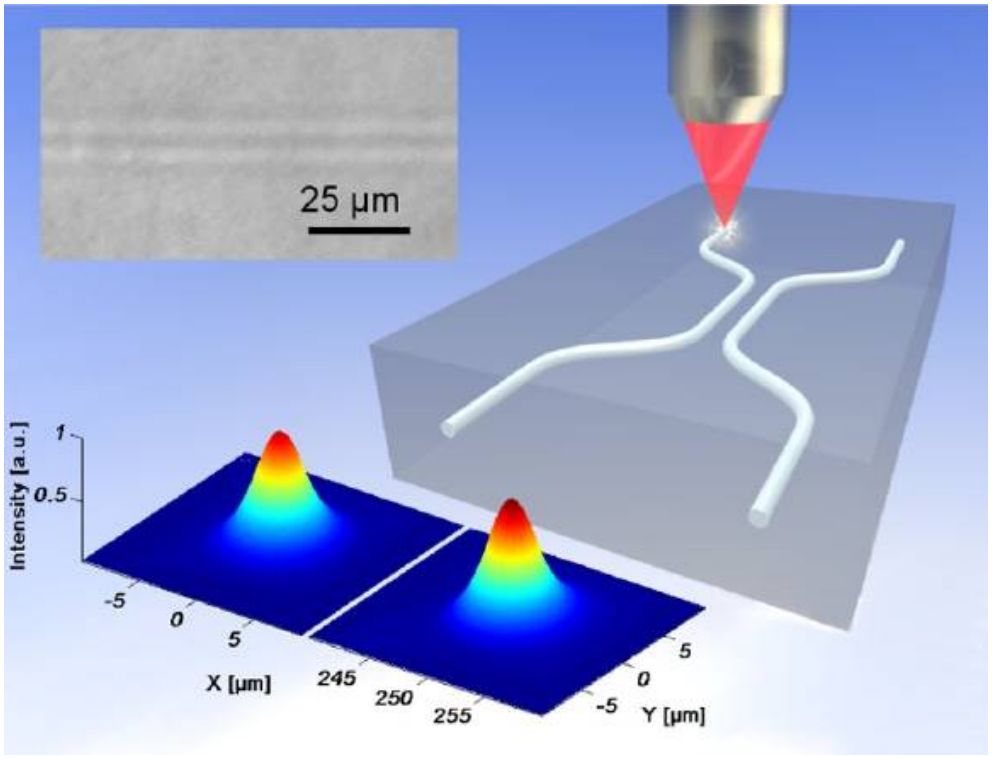


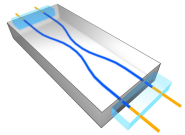




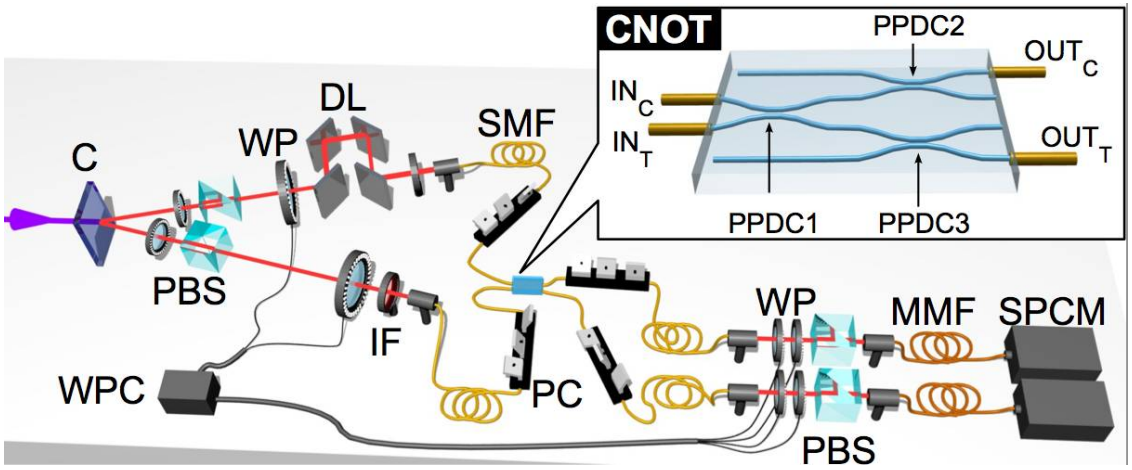
Laser written integrated circuit

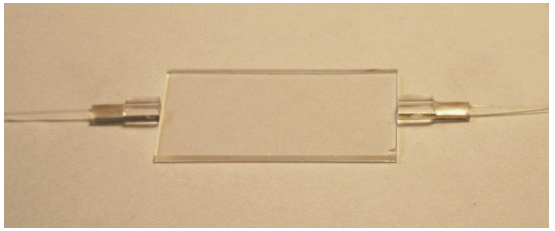






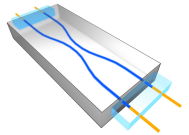
Logic gate on a chip





Input		Output	
Control C	Target T	Control C’	Target T’
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0

Fundamental for quantum computation



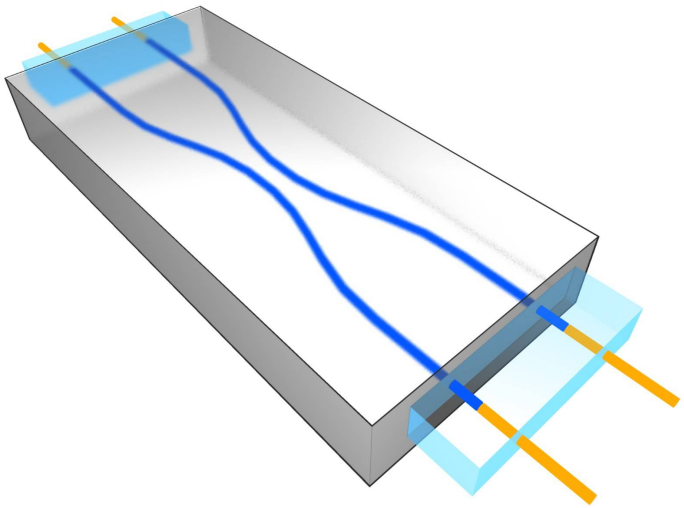
Towards quantum simulation...

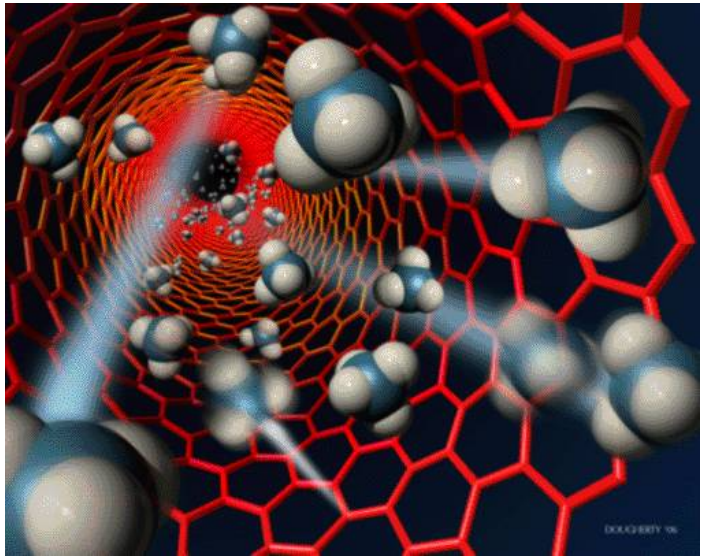
Richard Feynman:

« There is a plenty of room at the bottom»

Exploit a quantum hardware
to simulate a quantum system

Richard Feynman





Thanks for the attention!

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Enjoy life, enjoy quantum!

http://quantumoptics.phys.uniroma1.it