The Second Quantum Revolution and Sissa's Computer

Philippe Chomaz

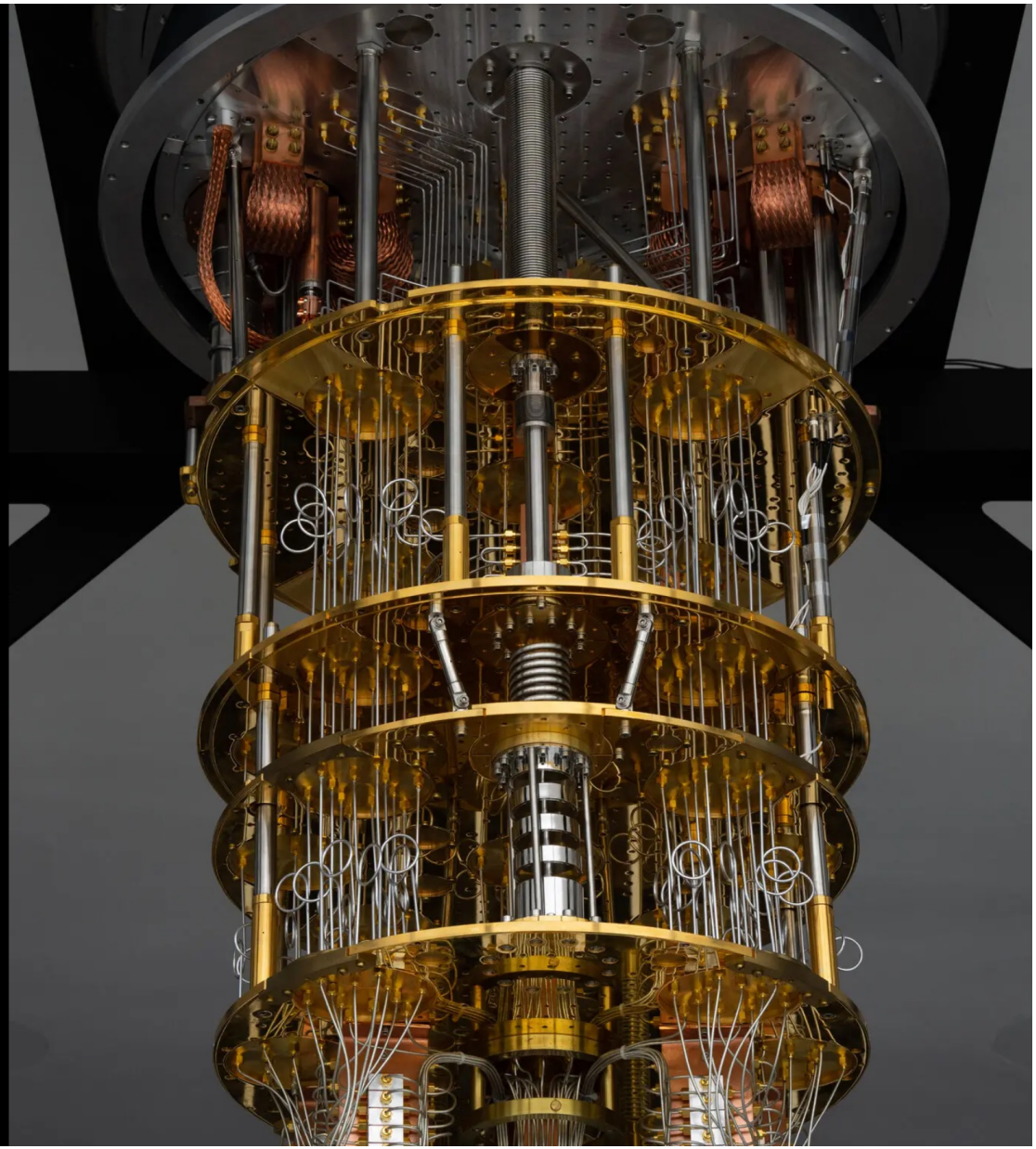
Executive Scientific Director of the Fundamental Research Department at CEA-France

Today Quantum Dominates Headlines

The New York Times

Quantum Computing Advance Begins New Era, IBM Says

A quantum computer came up with better answers to a physics problem than a conventional supercomputer.



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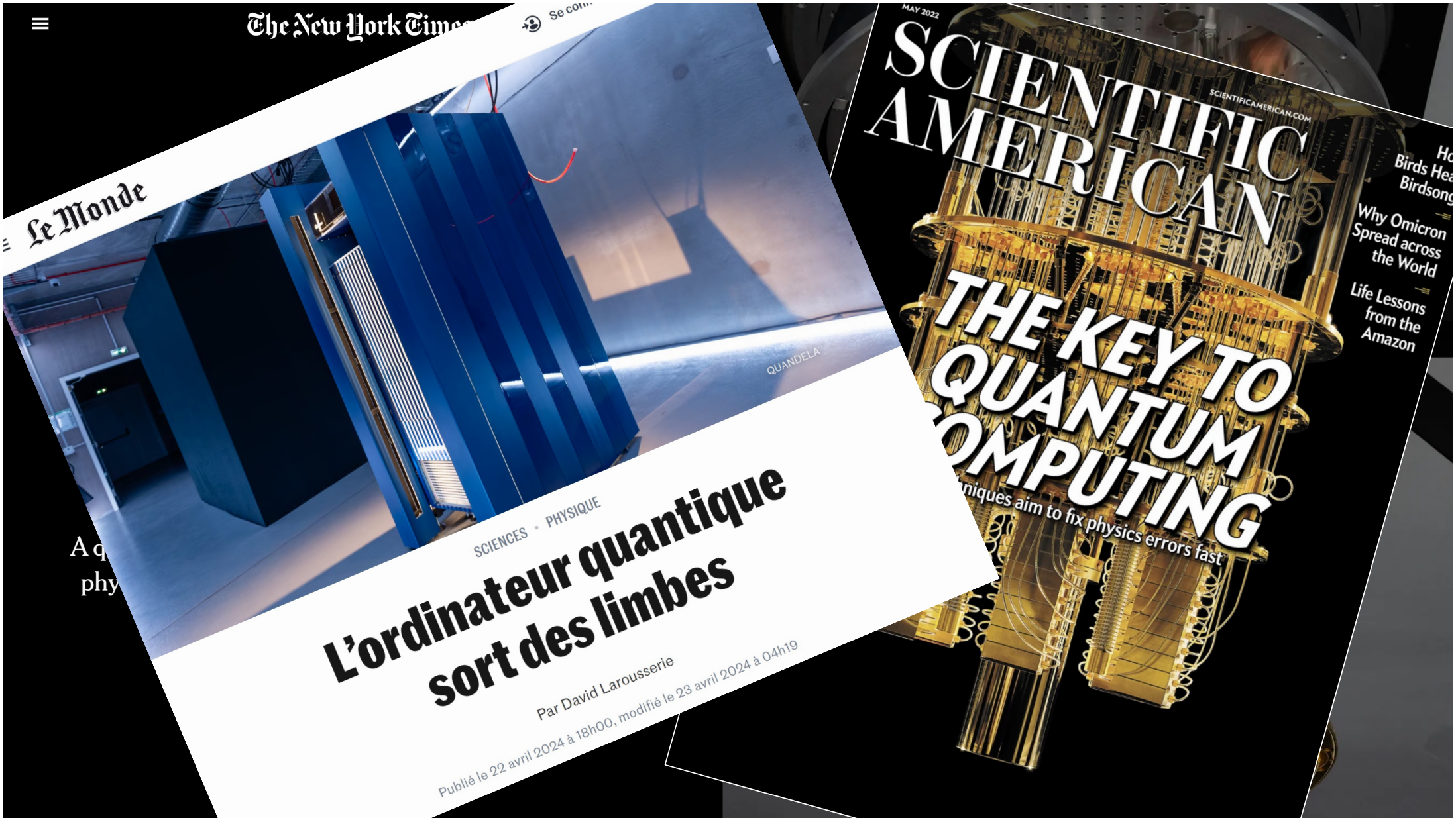
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Par David Larousserie
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THE KEY TO QUANTUM COMPUTING
niques aim to fix physics errors fast
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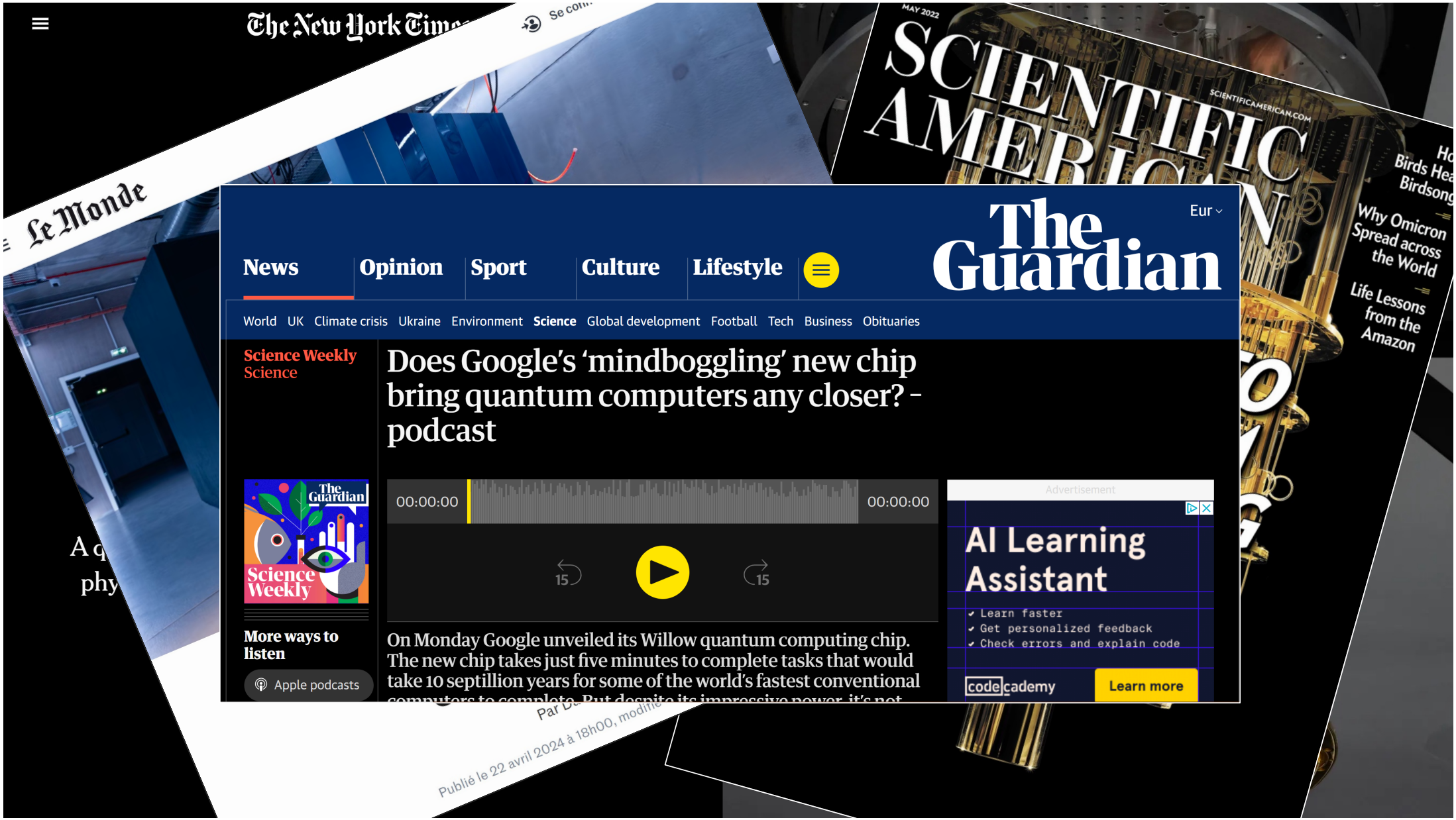
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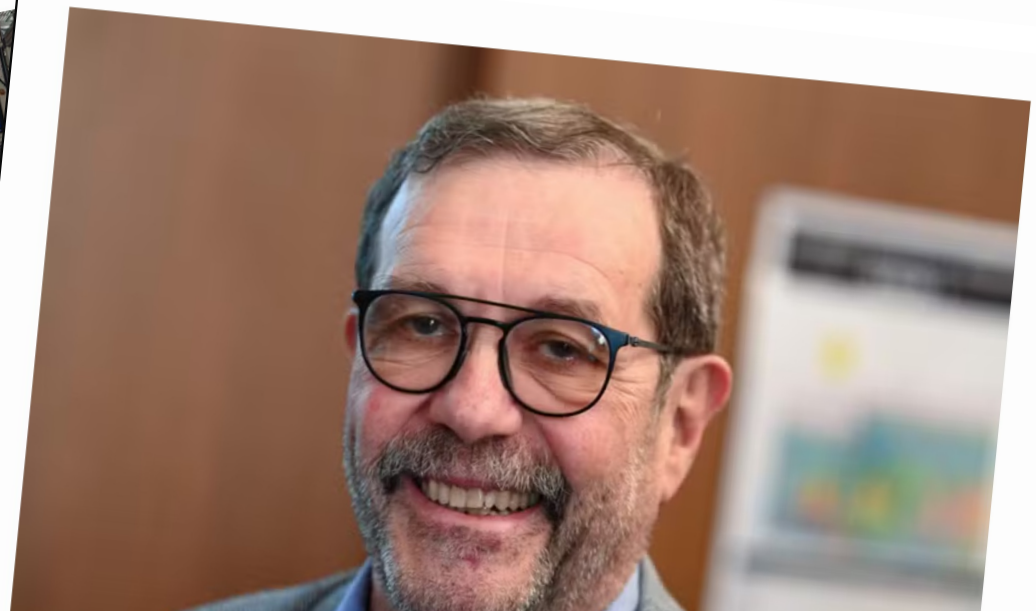
SCIENCES · PHYSIQUE

Le Nobel de physique récompense le Français Alain Aspect, pionnier de la « seconde révolution quantique »

Le chercheur est distingué avec l'Américain John Clauser et l'Autrichien Anton Zeilinger pour la mise en évidence de l'intrication de particules, ouvrant la voie à des applications en information quantique.



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The incredible chance to witness a major scientific and technological revolution

The second quantum revolution

1.

What is the first quantum revolution? When was that?

and by the way what means “quantum”?

Quantum is a Latin word meaning “elementary quantity”

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Used by physicists in the early 20th century

When they discovered the revolutionary laws explaining matter, atoms, electrons, light, and their interactions, …

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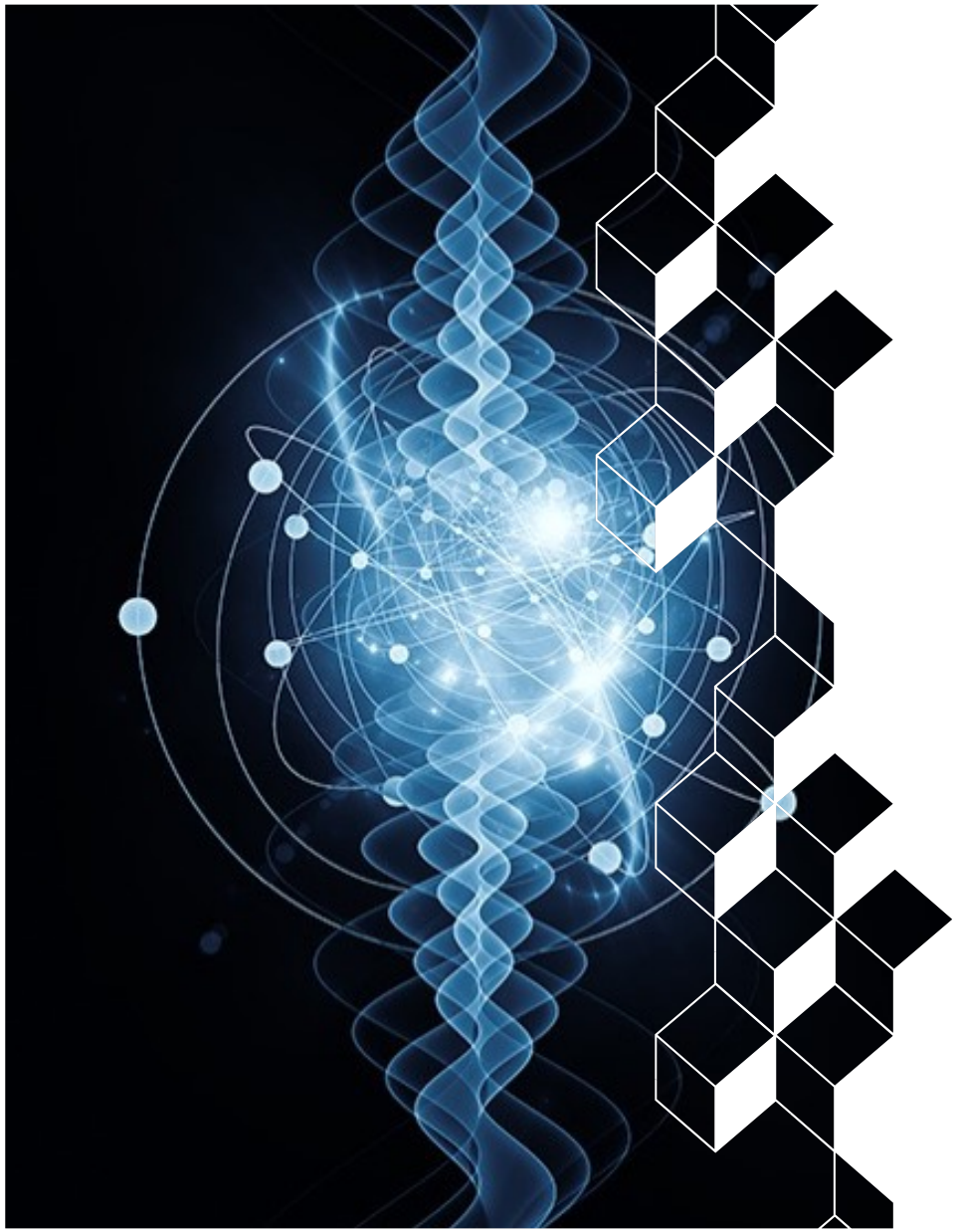
When they discovered the revolutionary laws explaining matter, atoms, electrons, light, and their interactions, …

Because in these laws quantities like energy and objects like light are quantized into elementary grains, called quanta.



A short story of the first Quantum Revolution

At the end of the 19th century, physics was beautiful and seemed complete!

Everything was understood!...


Newtonian mechanics
and gravity


Electromagnetism

Thermodynamics

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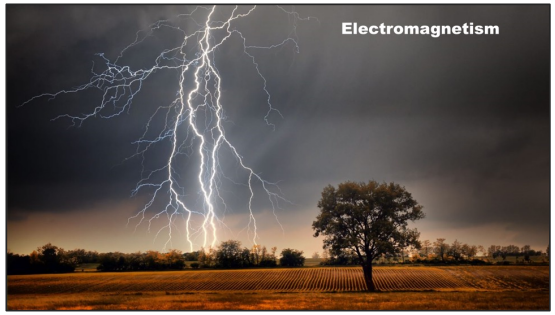

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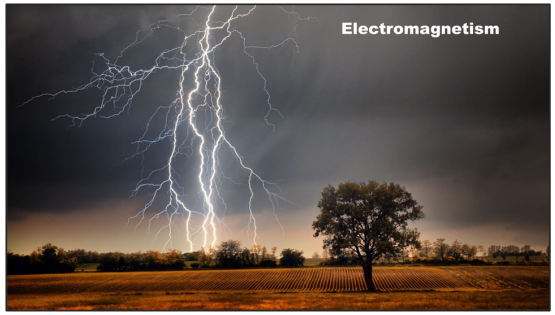

Or almost...

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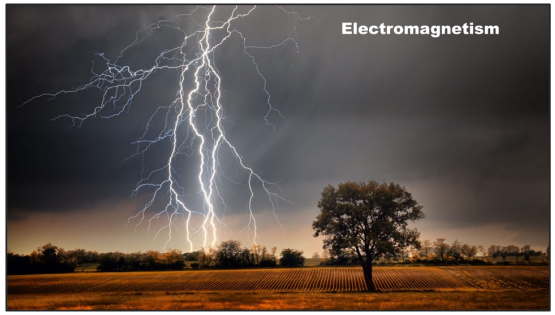
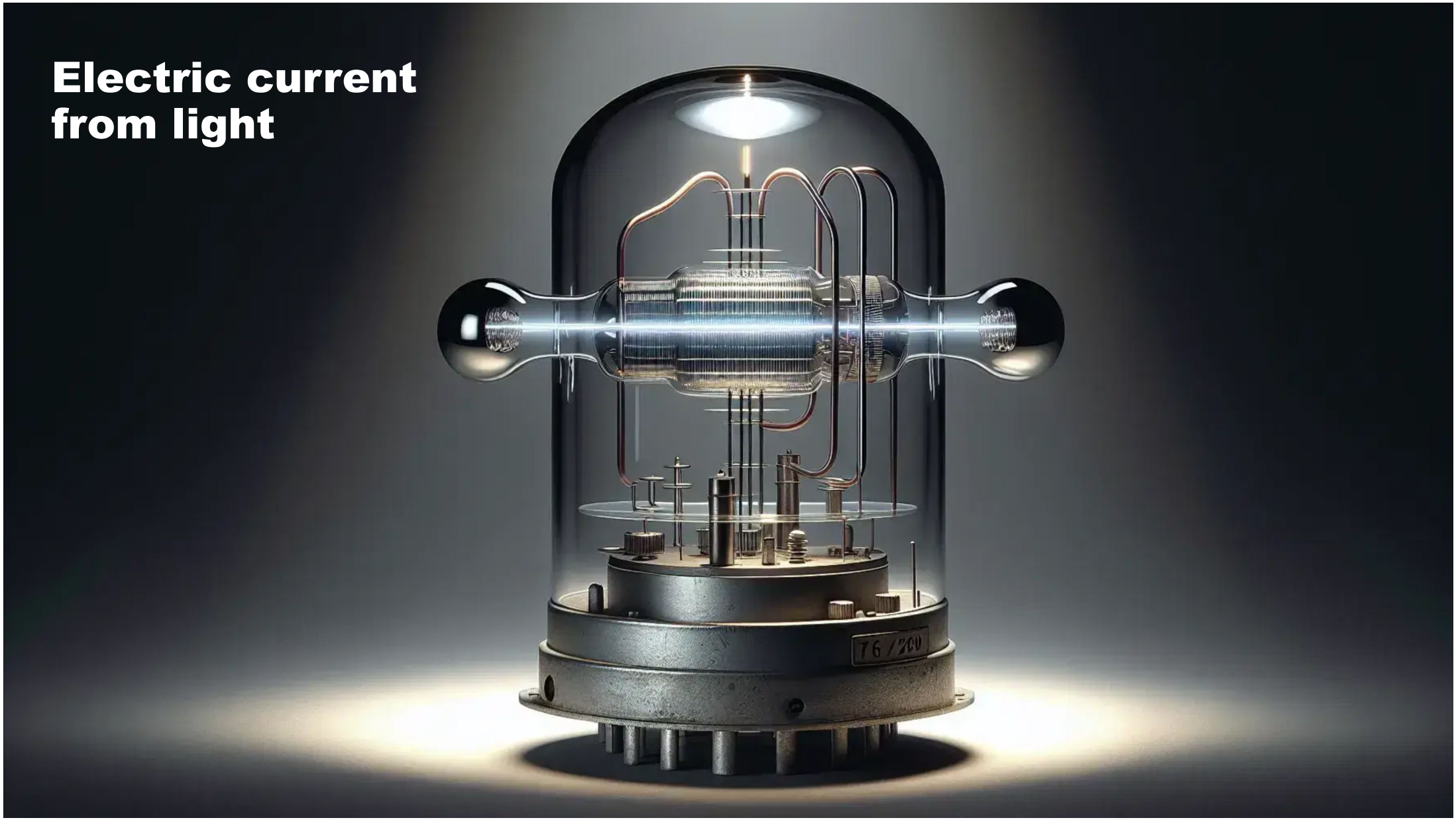


Or almost...

Only, minor issues between light and matter

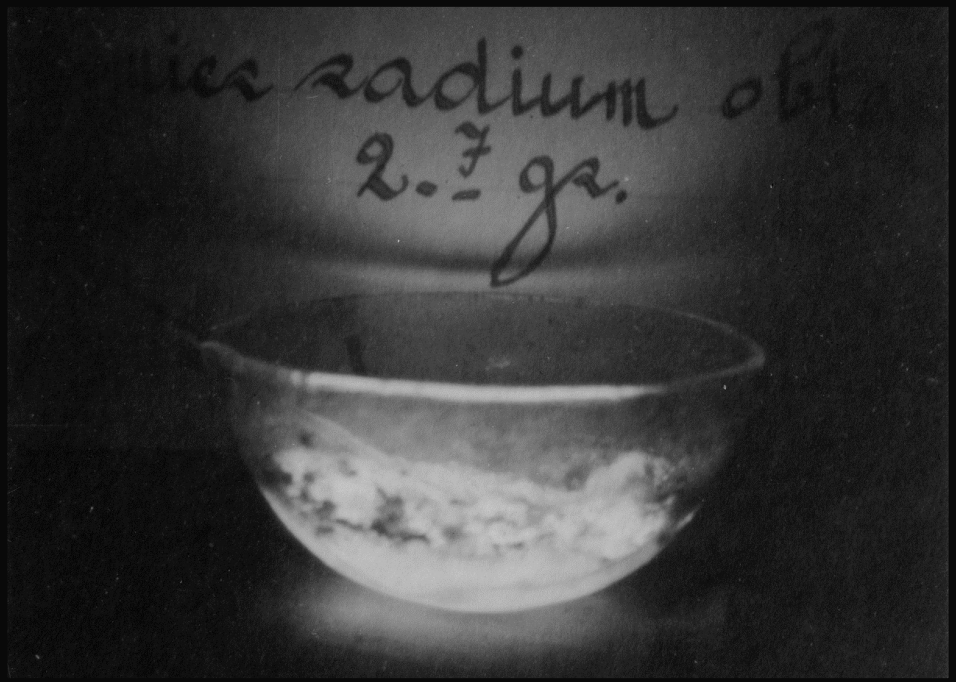
Light from hot bodies

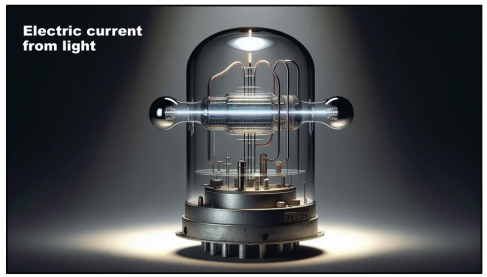
Electric current from light

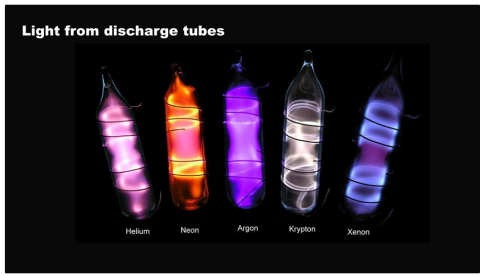


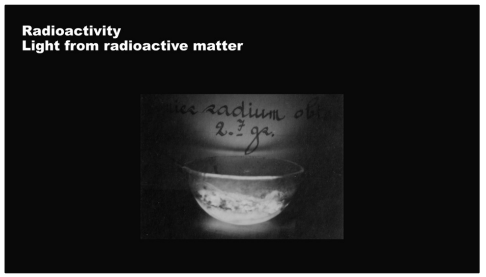
Light from discharge tubes

Radioactivity
Light from radioactive matter









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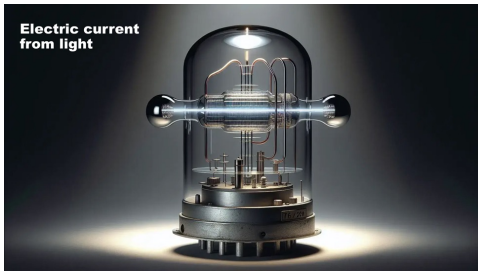
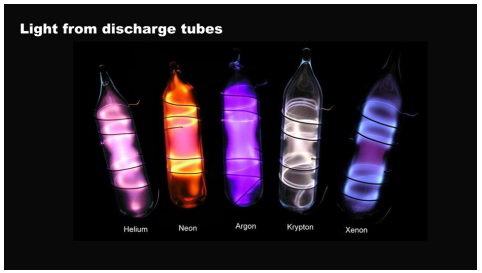
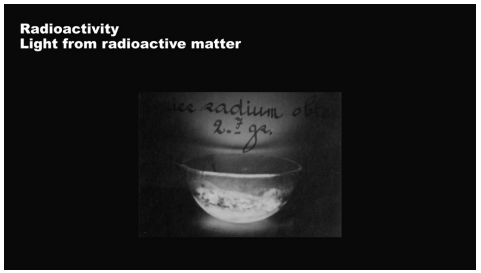
Except, minor issues between light and matter



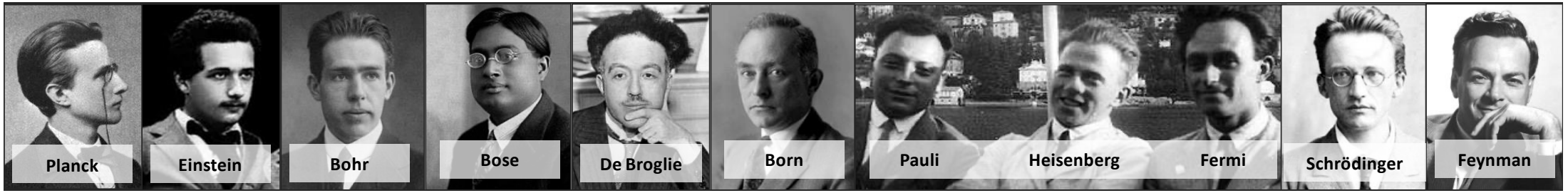


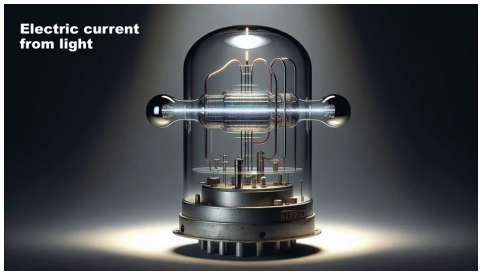


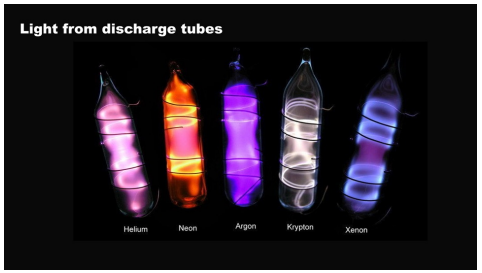
Except, minor issues between light and matter

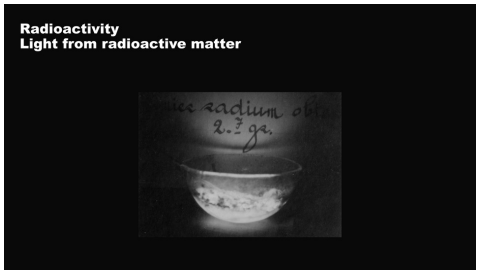
that led to the discovery of an entirely new physics

by the best physicist of the early 20th century









Light, ie electromagnetic wave, is quantized into elementary grains

Matter, ie particles, behave like waves

Except, minor issues between light and matter

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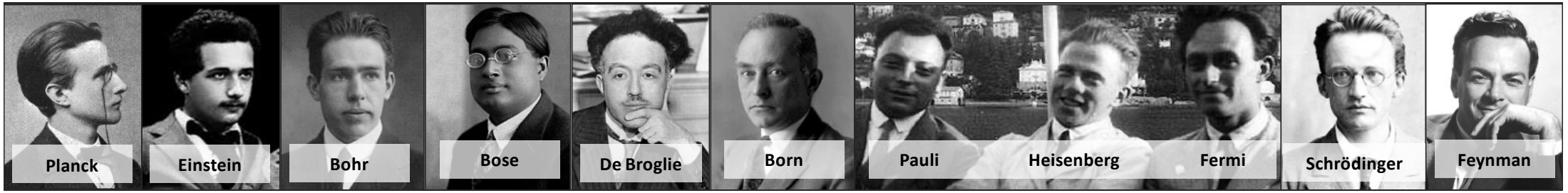
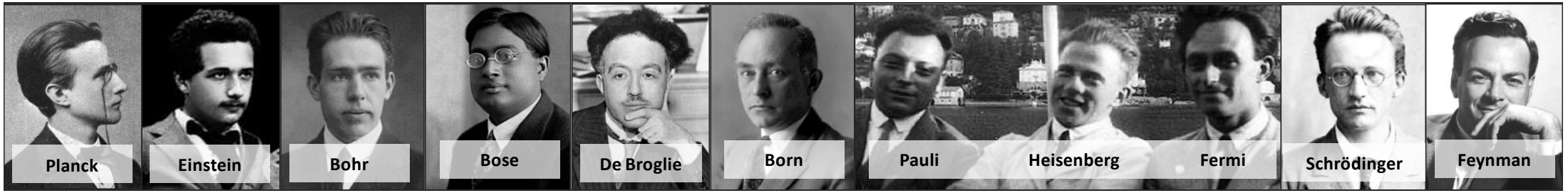
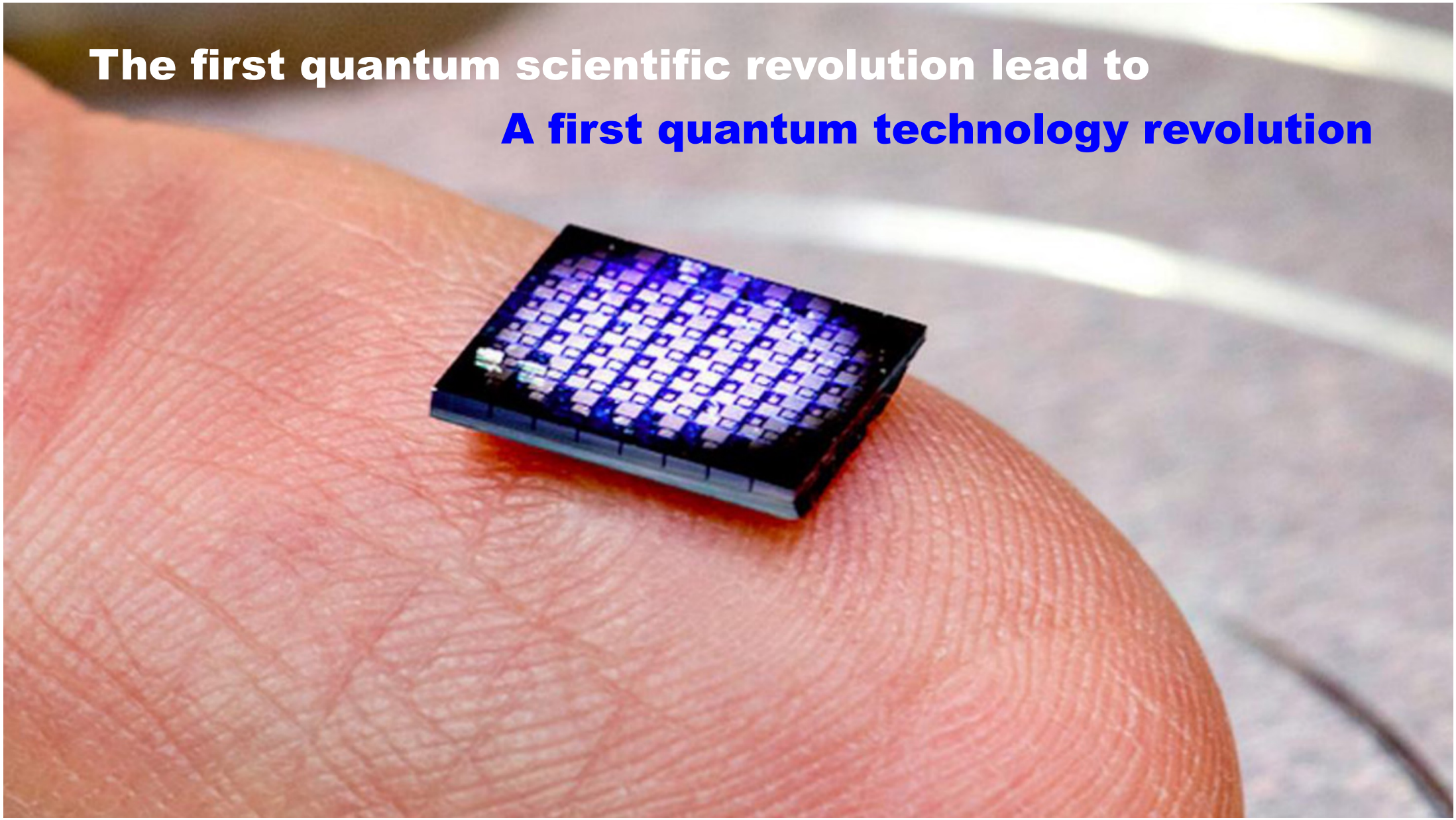


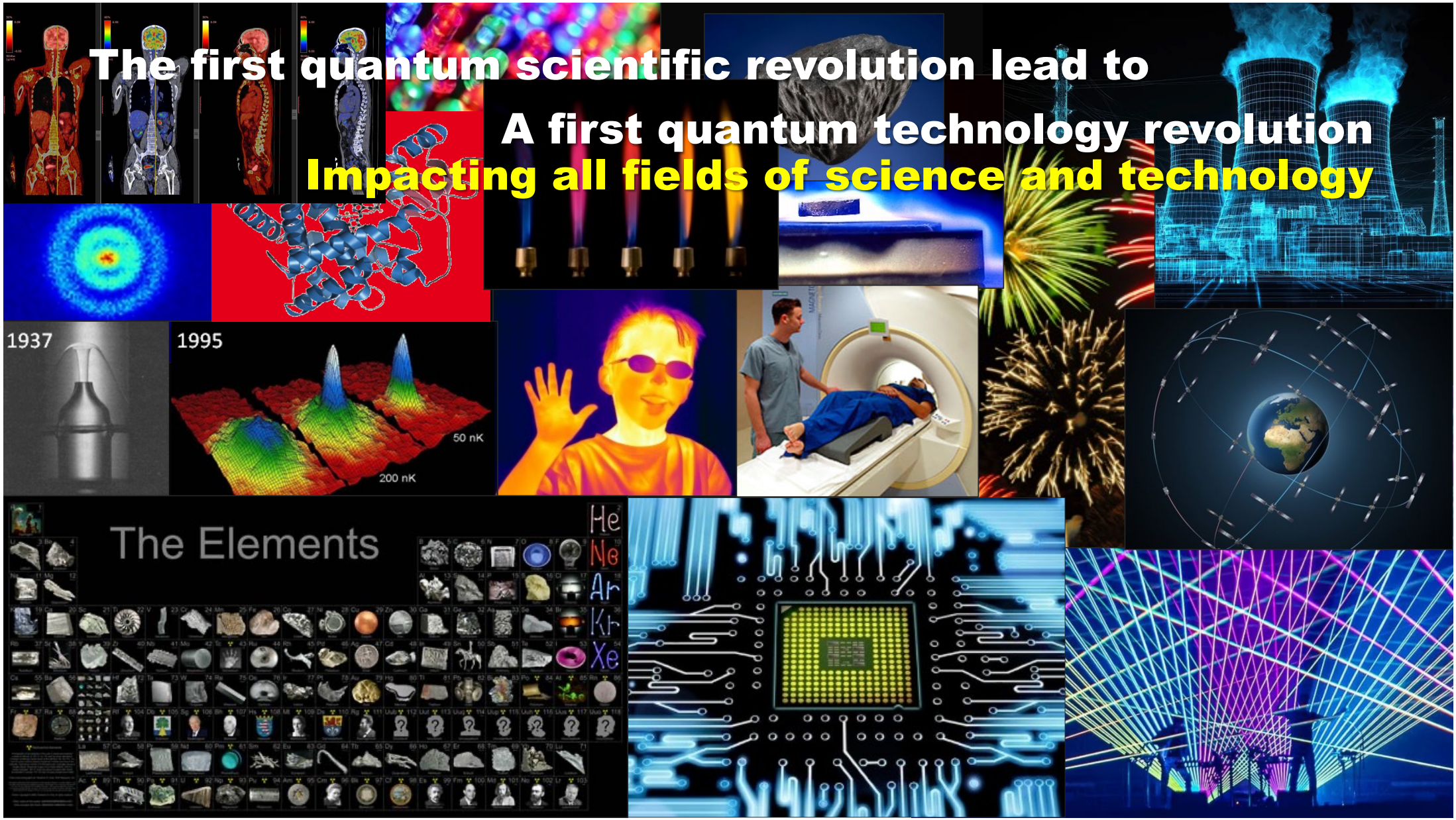
The first quantum scientific revolution

"Wave-particle duality“

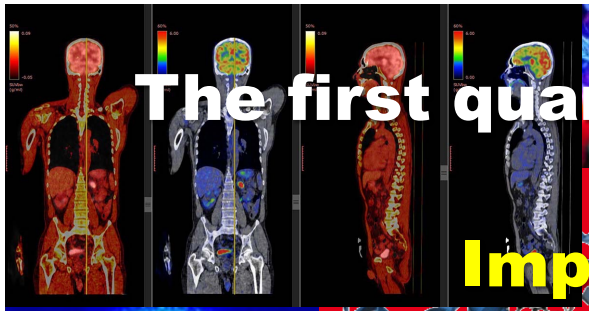
Matter, light, and their interactions
are made up of particles
described as superposition's of states
governed by wave mechanics

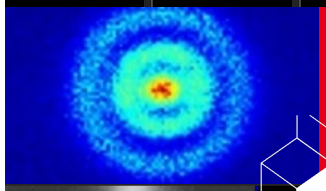


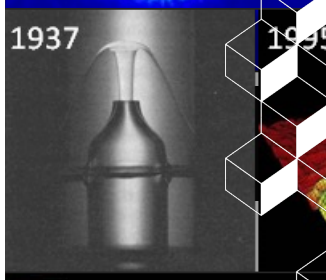

The first quantum scientific revolution lead to
A first quantum technology revolution


The first quantum scientific revolution lead to
A first quantum technology revolution
Impacting all fields of science and technology
1937
1995
50 nK
200 nK
The Elements
He
Ne
Ar
Kr
Xe

The first quantum scientific revolution lead to
The first quantum technologies revolution
Impacting all fields of science and technology







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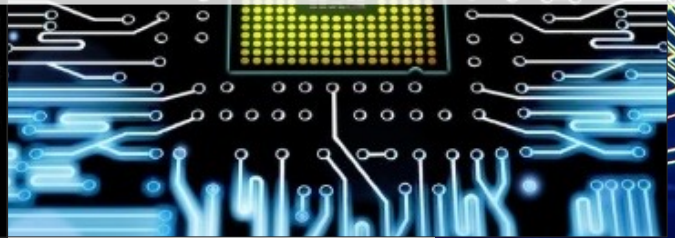
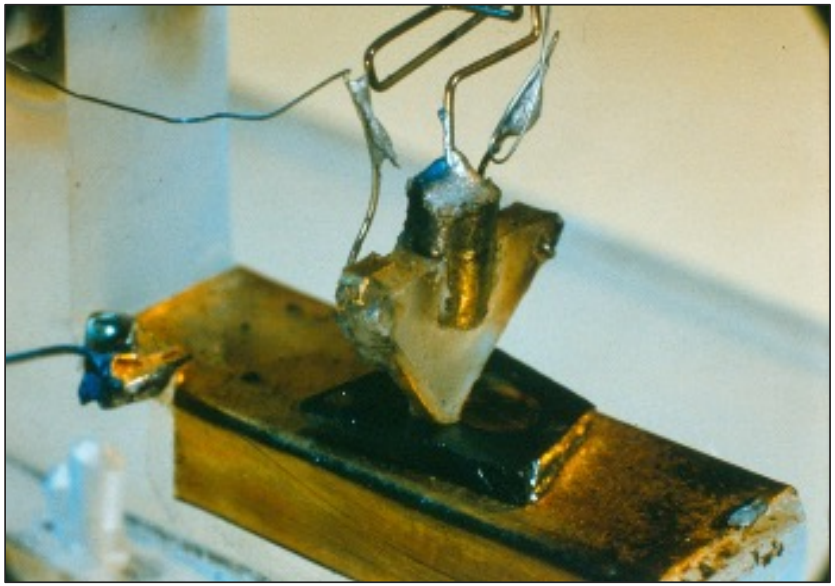


Quantum revolution of information treatment



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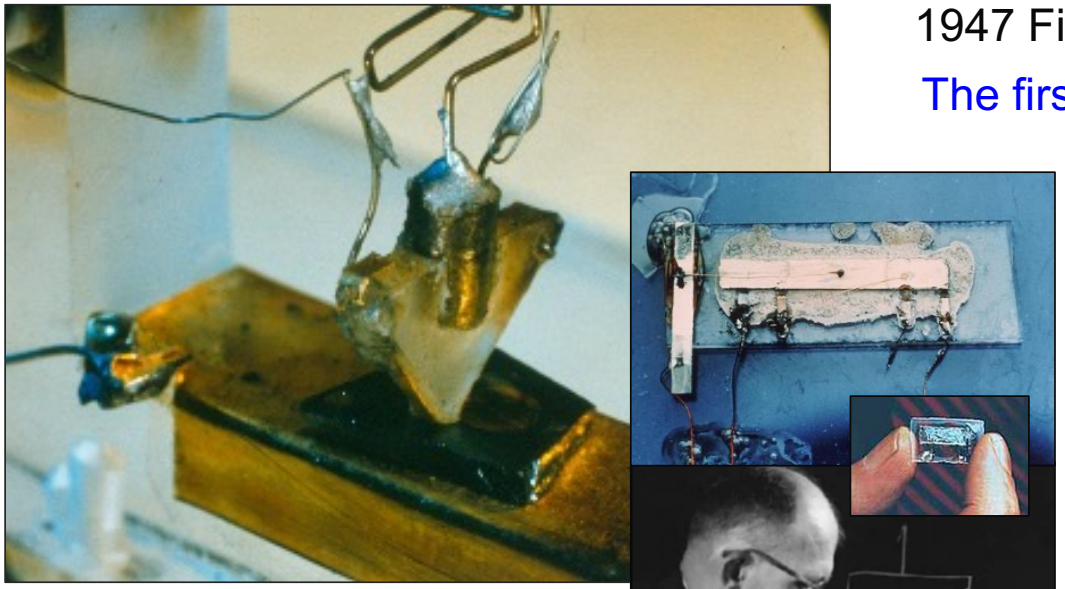
The first quantum switch controlling electrical signals

Quantum revolution of information treatment



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1959, First integrated circuit
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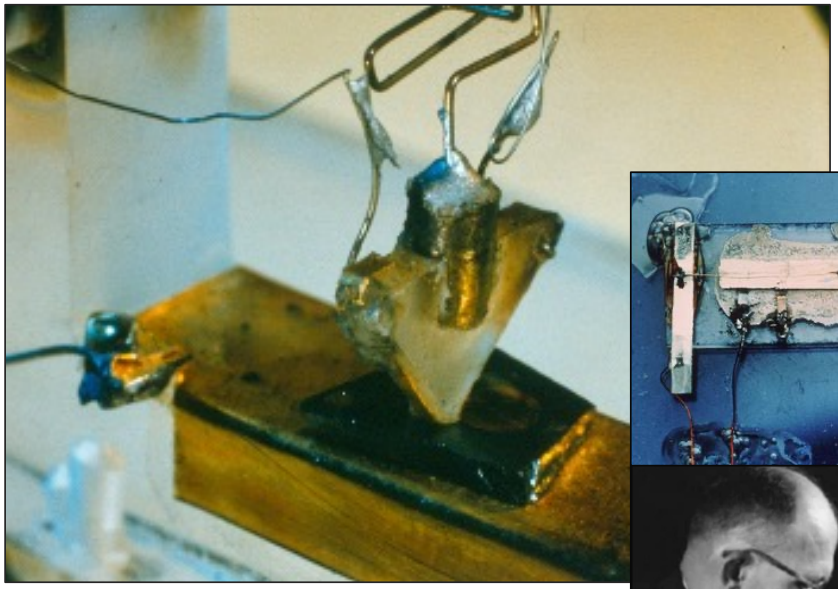

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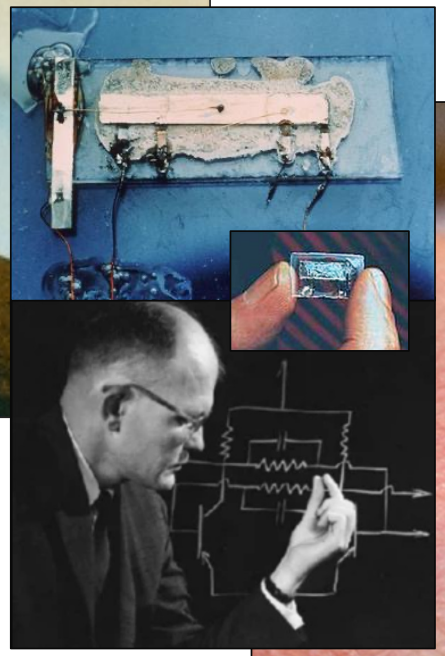

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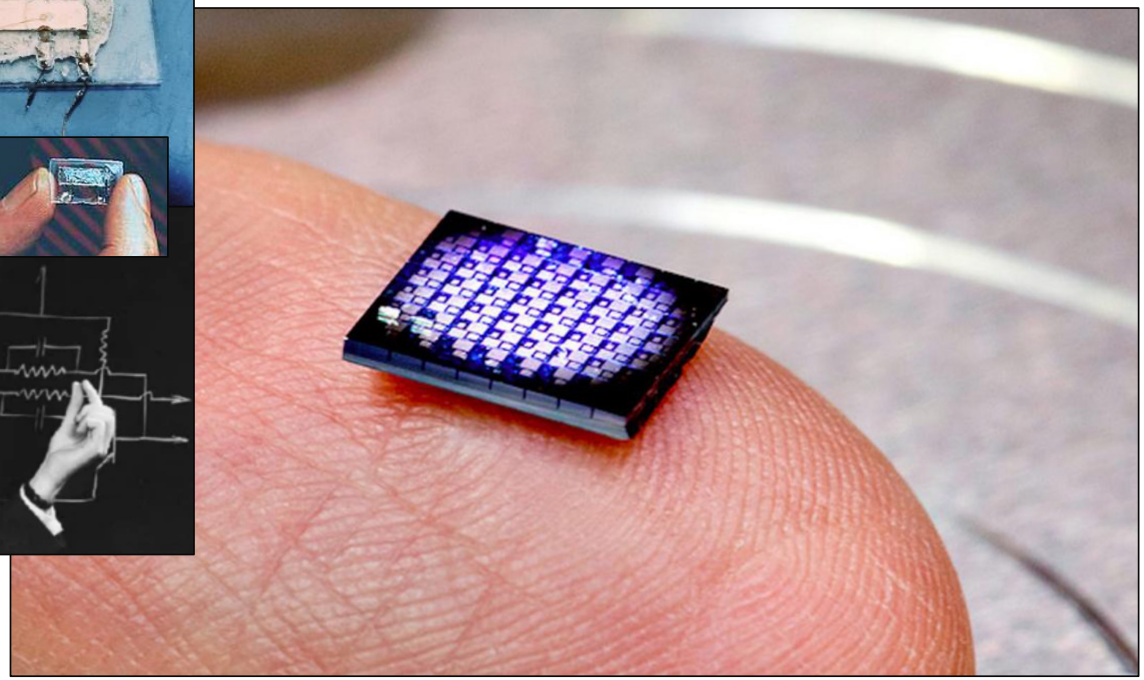
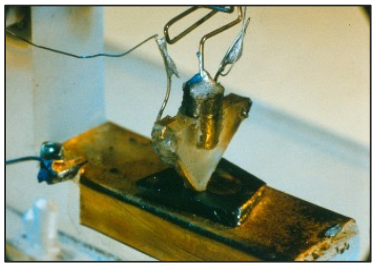


2021 First 2 nm chip with 50 billion transistors @IBM

Quantum revolution of information treatment

Transistors as quantum switch controlling electrical signals



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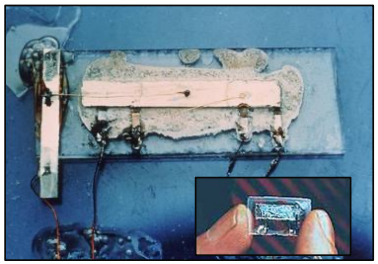

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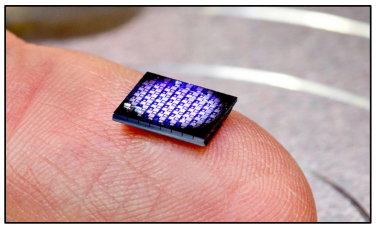

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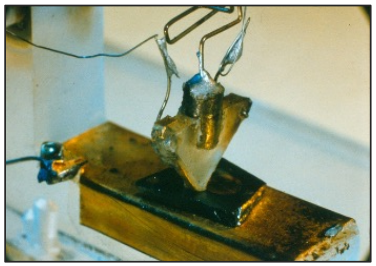

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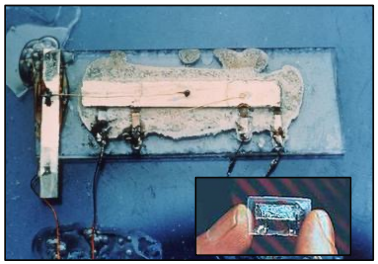

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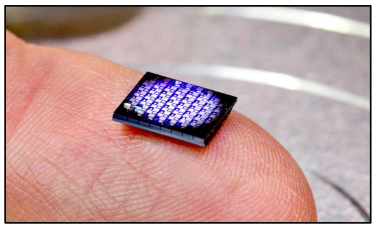

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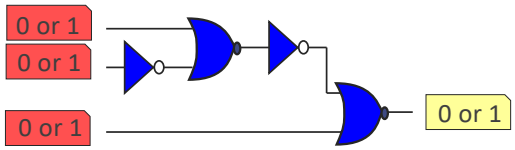
Classical computers

Elementary information:

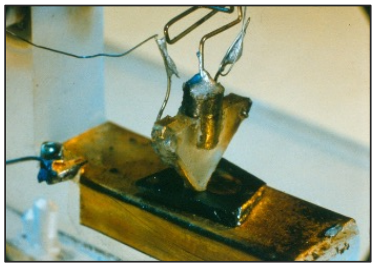
Bit: 0 or 1

Processed with logic gates (transistors)



NOT and a single 2 bit gate (as **XOR**) are enough :
Universal set

Quantum revolution of information treatment



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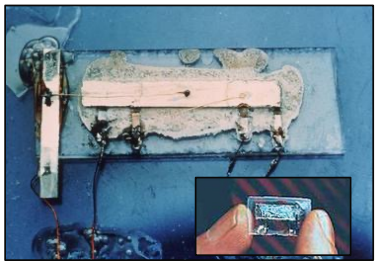
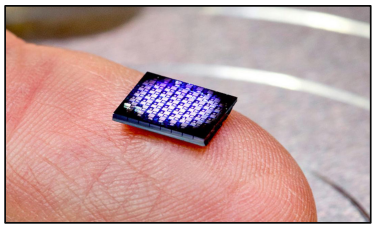


1959, First chip
@Texas Instruments



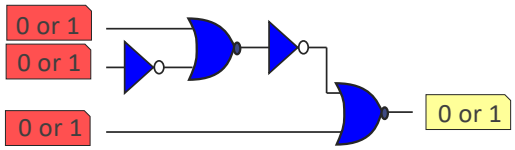
2021 First 2 nm chip with
50 billion transistors @IBM

Classical computers

Elementary information:

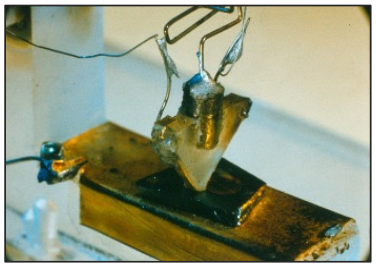
Bit: 0 or 1

Processed with logic gates (transistors)

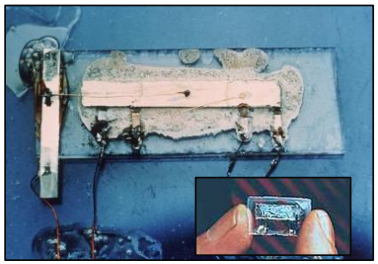


NOT and a single 2 bit gate (as **XOR**) are enough :
Universal set

Quantum revolution of information treatment



1947 First transistor
@Bell-Lab



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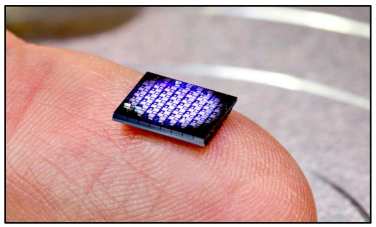

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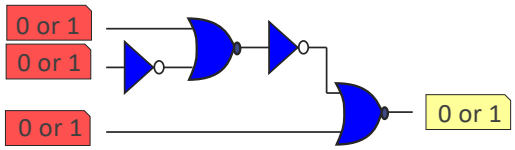
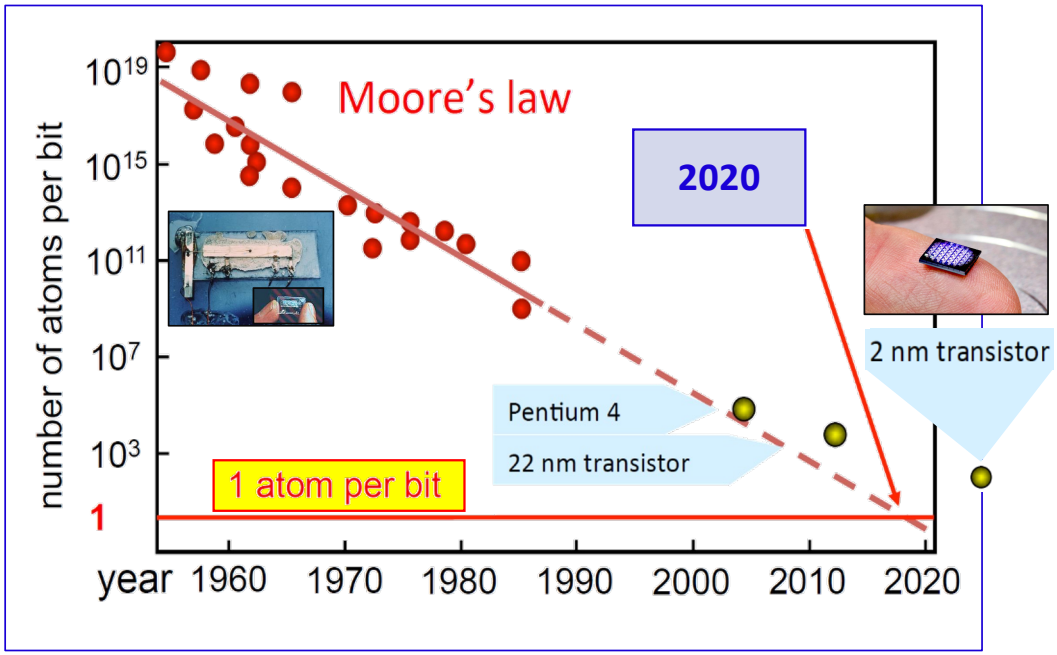


NOT and a single 2 bit gate (as **XOR**) are enough :
Universal set

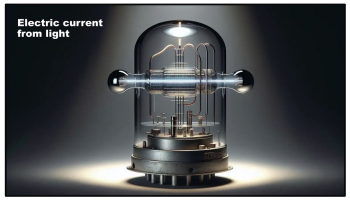
Are reaching the limit of one atom per bit

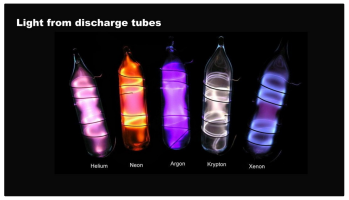


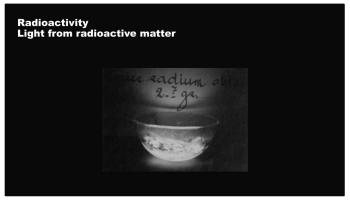
Take home message

Quantum revolution 1.0

A century ago, minor issues between light and matter



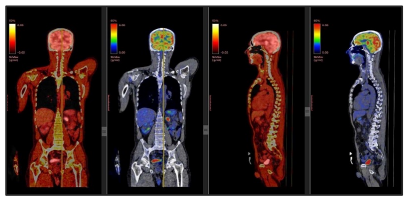


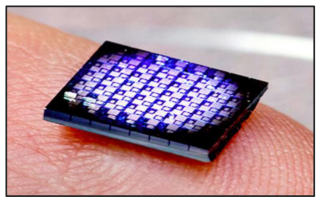


Forced the best physicist to invent quantum mechanic

matter and light are particles described as superposition's of states governed by wave dynamics

Which has revolutionize science and technology



But reaching now the limits of miniaturization

Is it the end of the quantum revolution?

2.

Is it the end of the quantum revolution?

No!

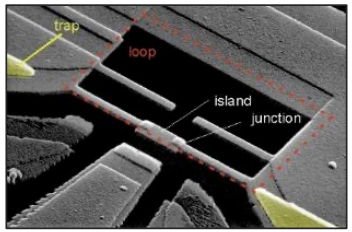
A second quantum revolution is about to reshape our world!

What makes a second revolution possible ?

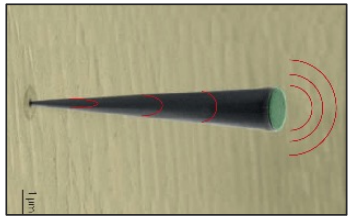
The same reason why the first one is ending

The same reason why the first one is ending

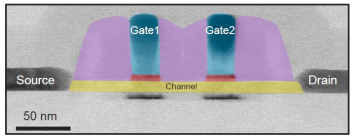
Technology reaching the limit of individual quantum object / degree of freedom

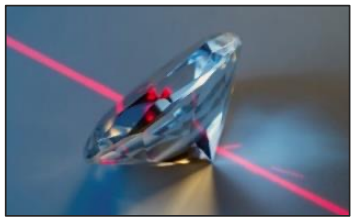


- **Individual electron pair / individual quantum of superconductor current**
  - In quantronium - transmon

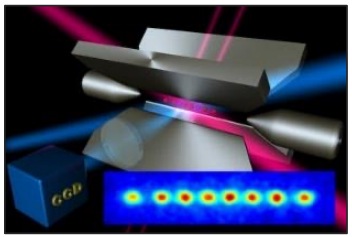


- **Individual photon**
  - Detection
  - Emission

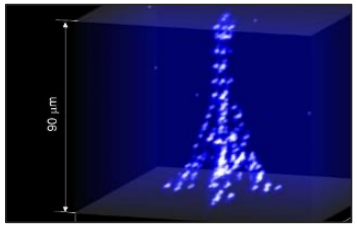




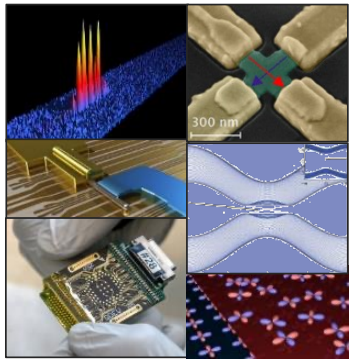
- **Individual spin**
  - Electrons or holes in semiconductors (AsGa, Si, Ge, …)
  - Individual NV centers NV in diamond (Nitrogen vacancy)



- **Individual ions**
  - In traps



- **Individual atoms or Molécules**
  - In laser trapping and cooling systems



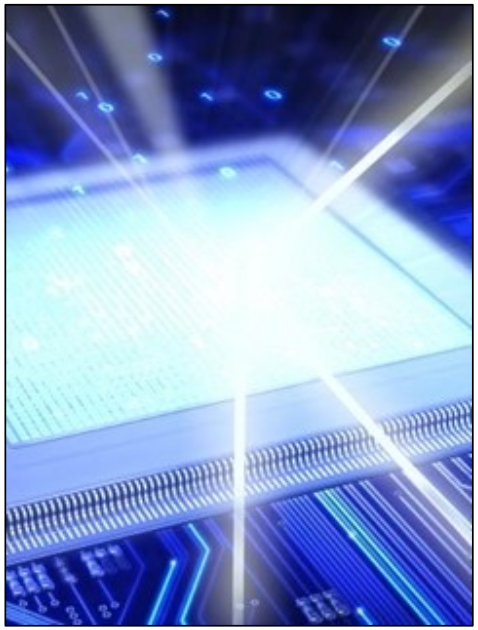
- **Individual novel quantum degree of freedom in new quantum materials**

  Flying qubits, levitons, pseudospin, Skyrmions, spin-orbit coupling, 2D systems, topological materials, Majorana fermions, anti/multi-ferroelectric materials…

From quantum 1.0 to quantum 2.0

- **Quantique 1.0: Reaching its end**
  Manipulating macroscopic quantum systems
  ie with many quantum “objects”/ degrees of freedom

- **Quantique 2.0: Opens a new world**
  Mastering individual quantum “objects”
  ie individual quantum degrees of freedom

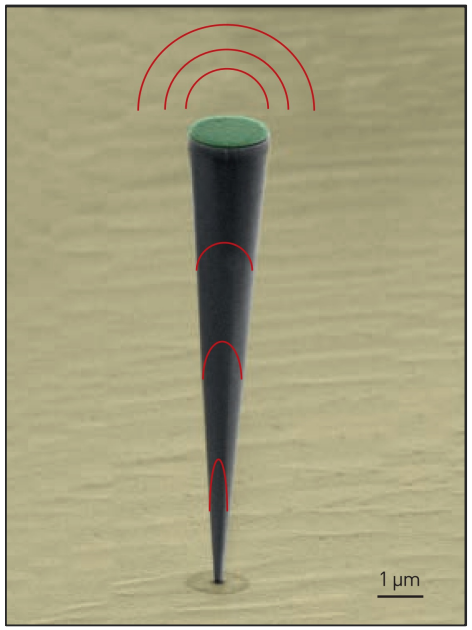


Germanium laser

- **Same quantum degrees of freedom**
  but
  going from a **macroscopic ensemble**
  to **individual states**

- **Huge paradigm shift**
  for the accessible space of possibilities
  => access to the **huge** space of quantum states
  (Hilbert/Fock space)

  => access the "strangest" quantum phenomena
  - **Superposition**
  - **Non-locality**
  - **Entanglement**



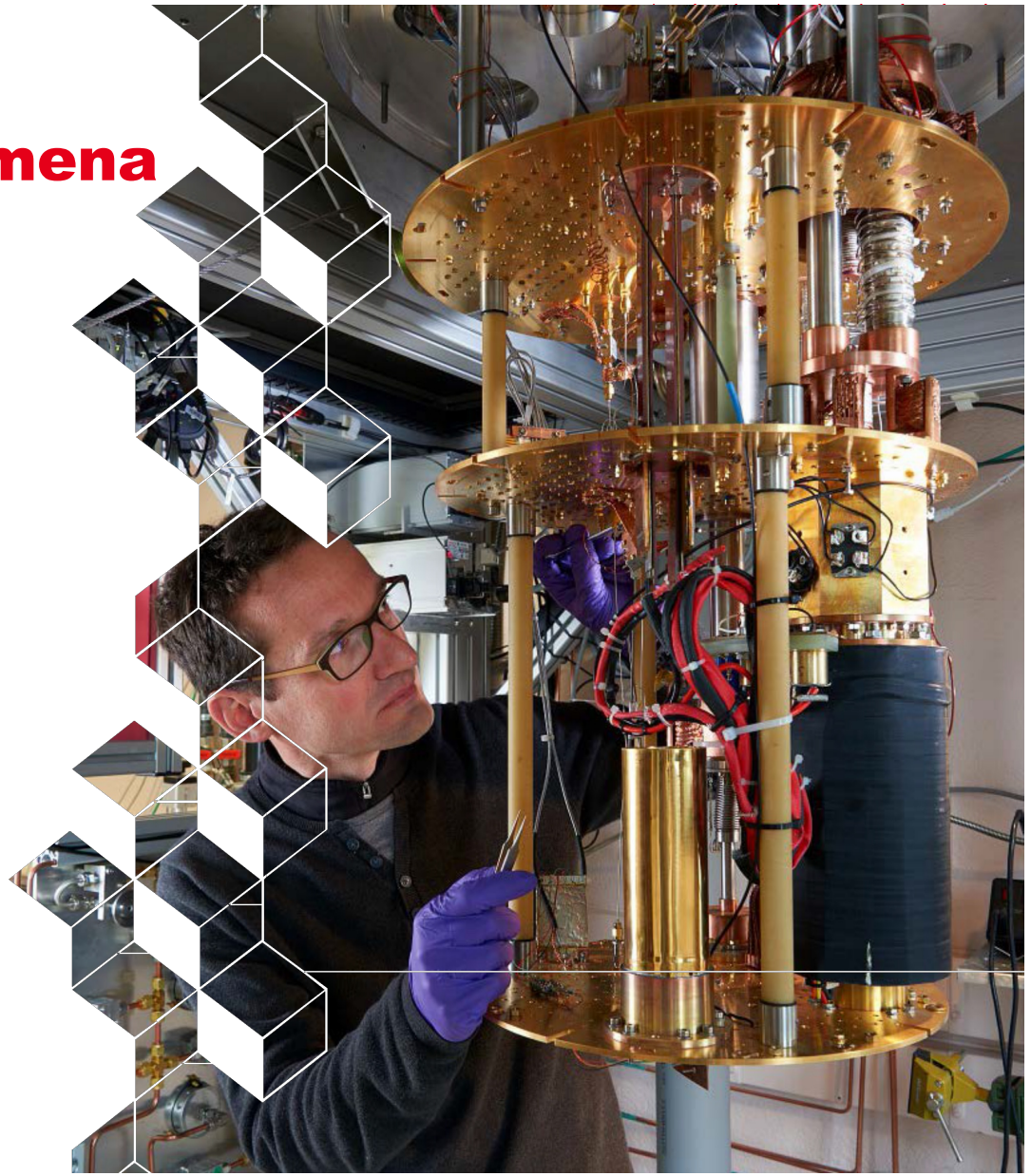
Single photon source

Accessing "strangest" quantum phenomena

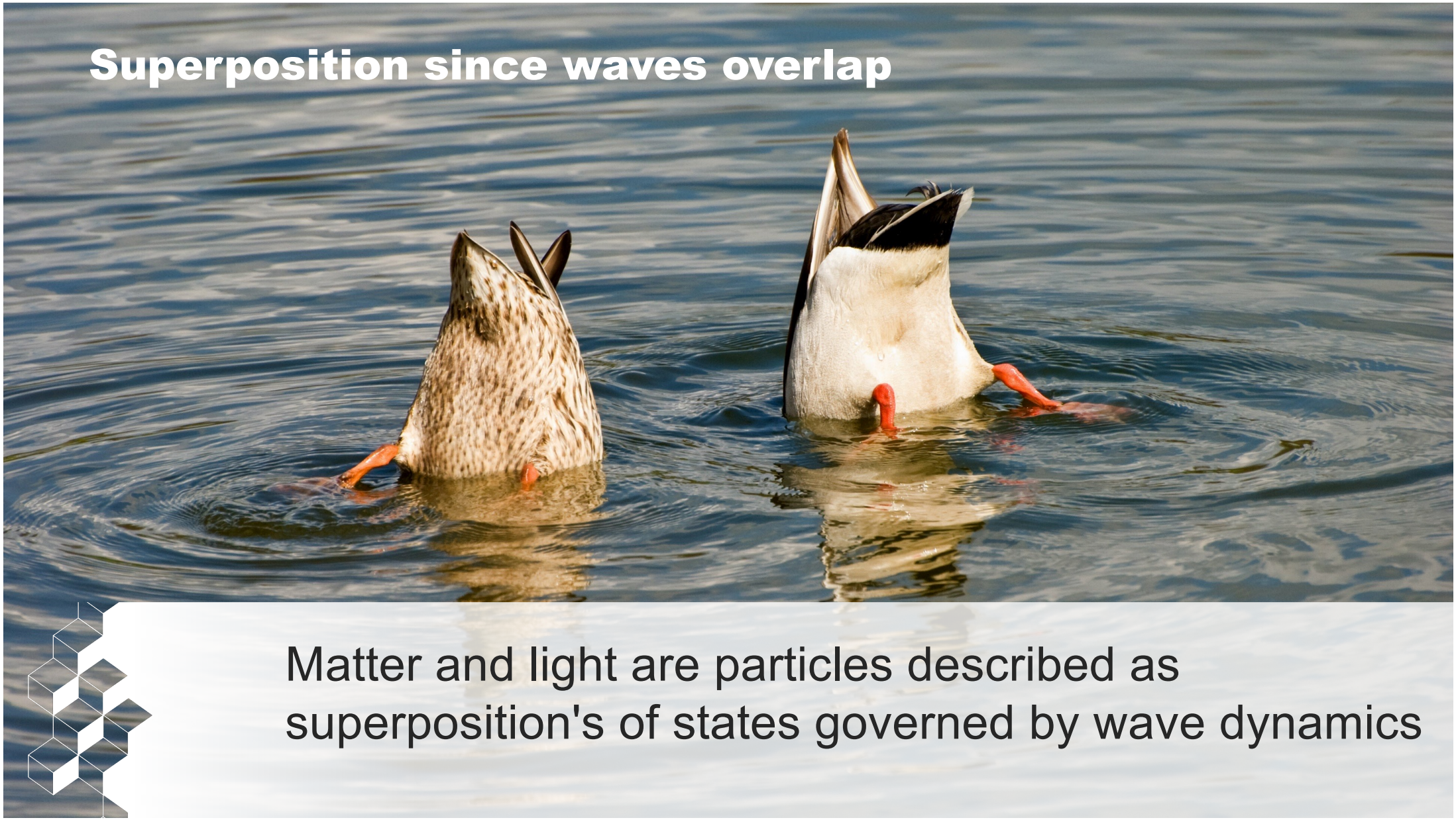
What means Superposition?

Non-locality?

Entanglement?

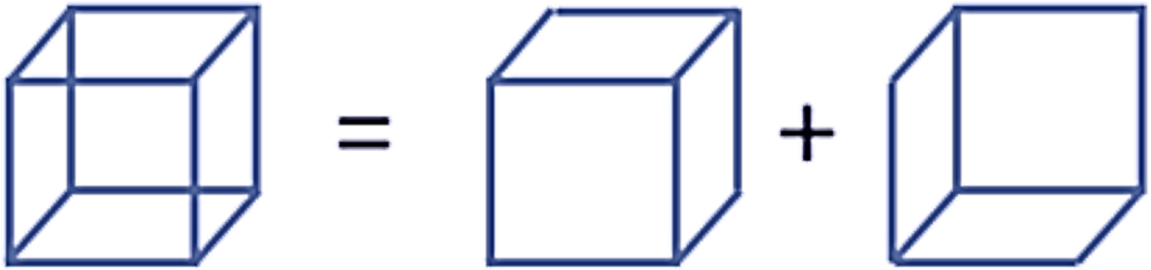



Superposition

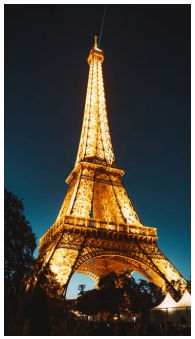


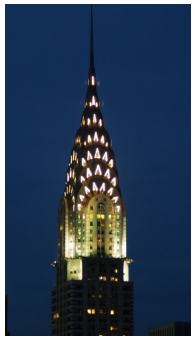
Matter and light are particles described as superposition's of states governed by wave dynamics

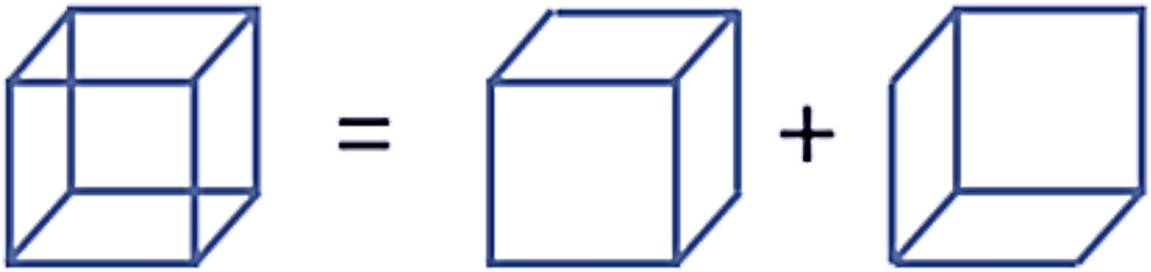
Superposition since waves overlap



Non-locality since waves are extended



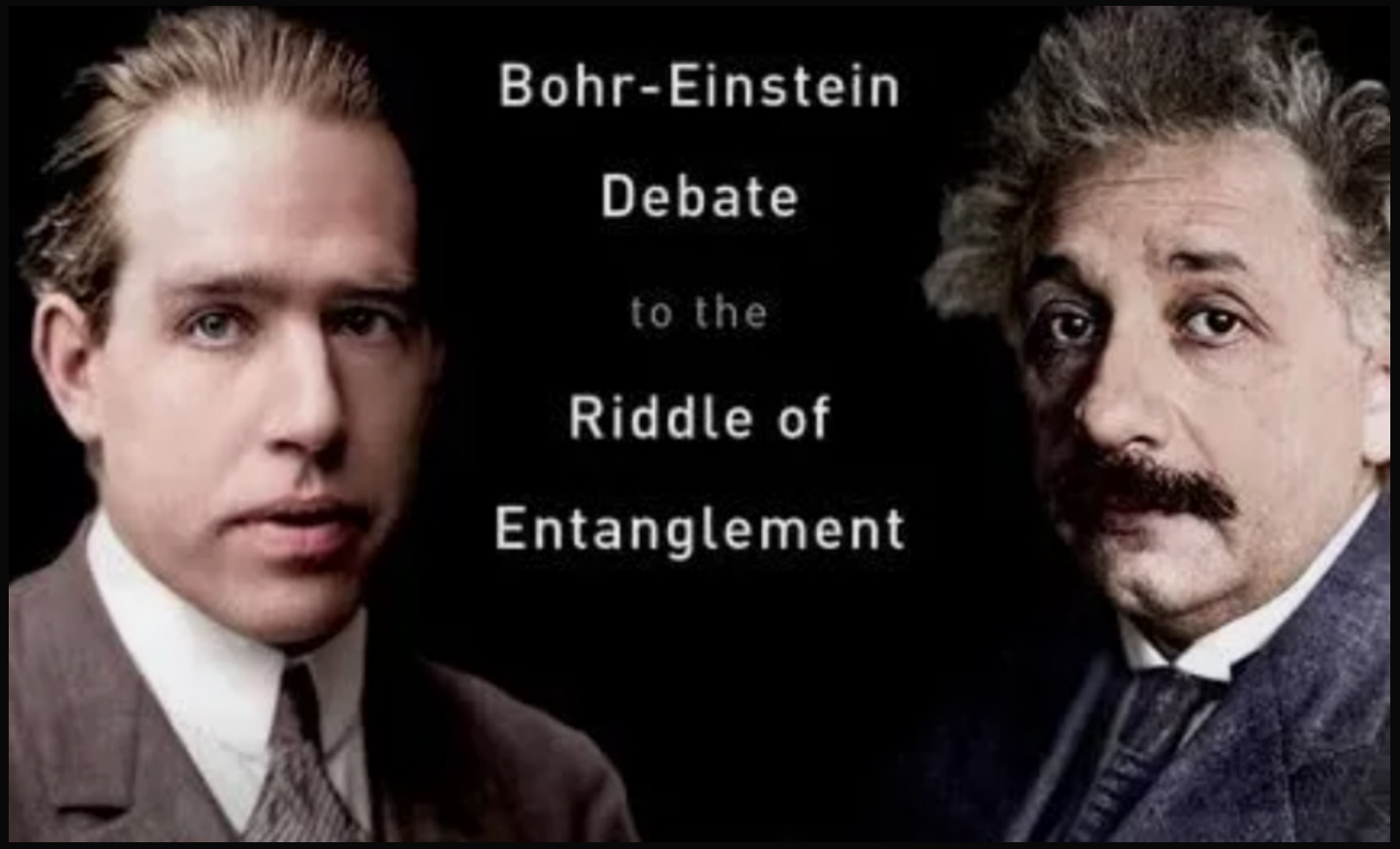




Entanglement

Entanglement

Entanglement



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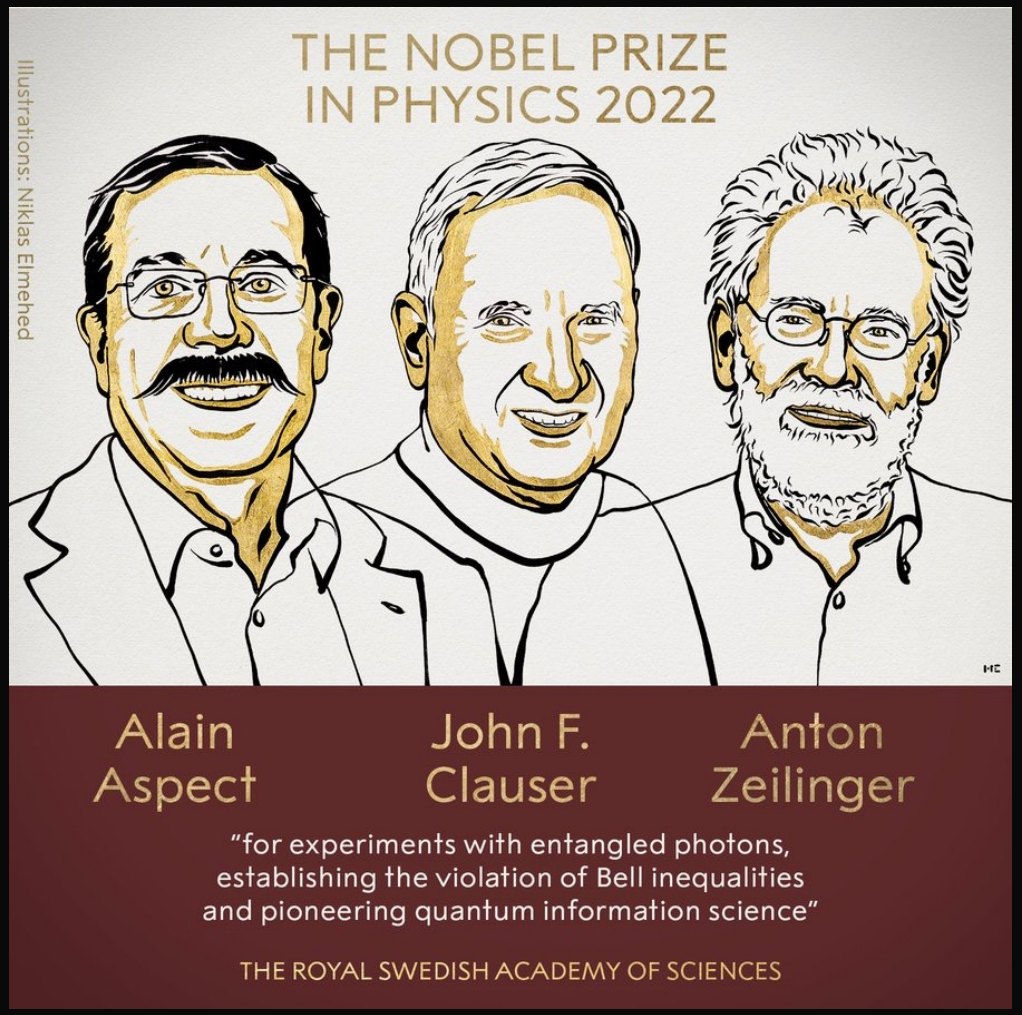

Entanglement


Entanglement

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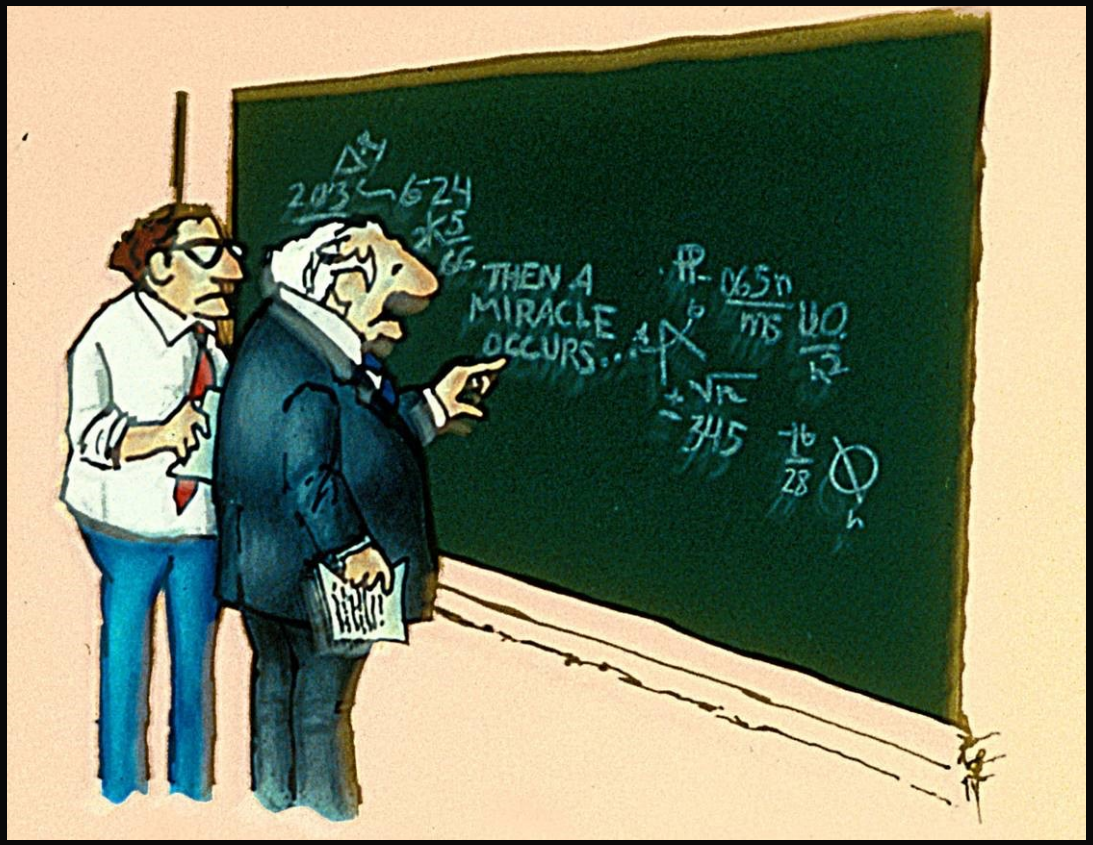
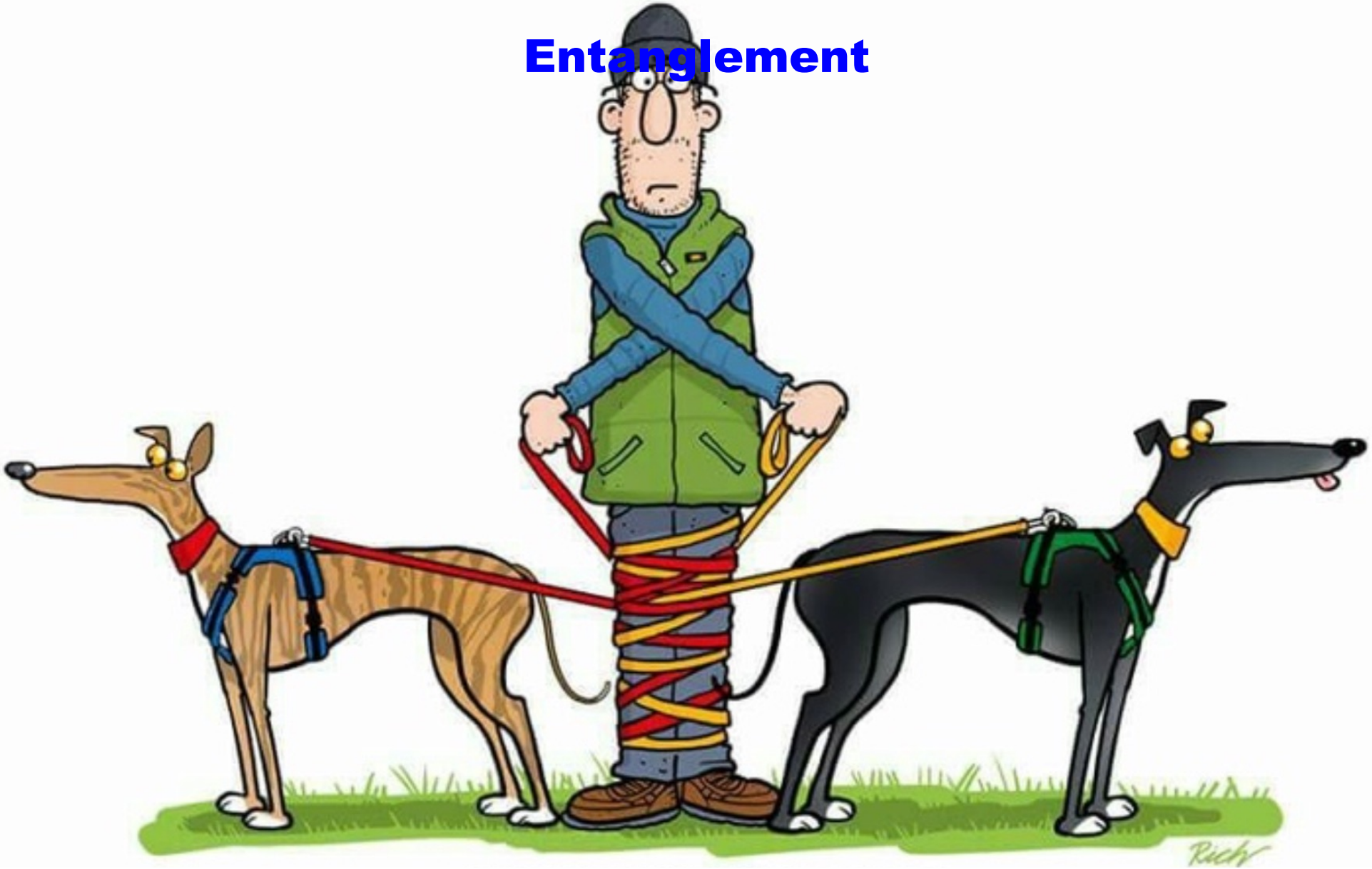


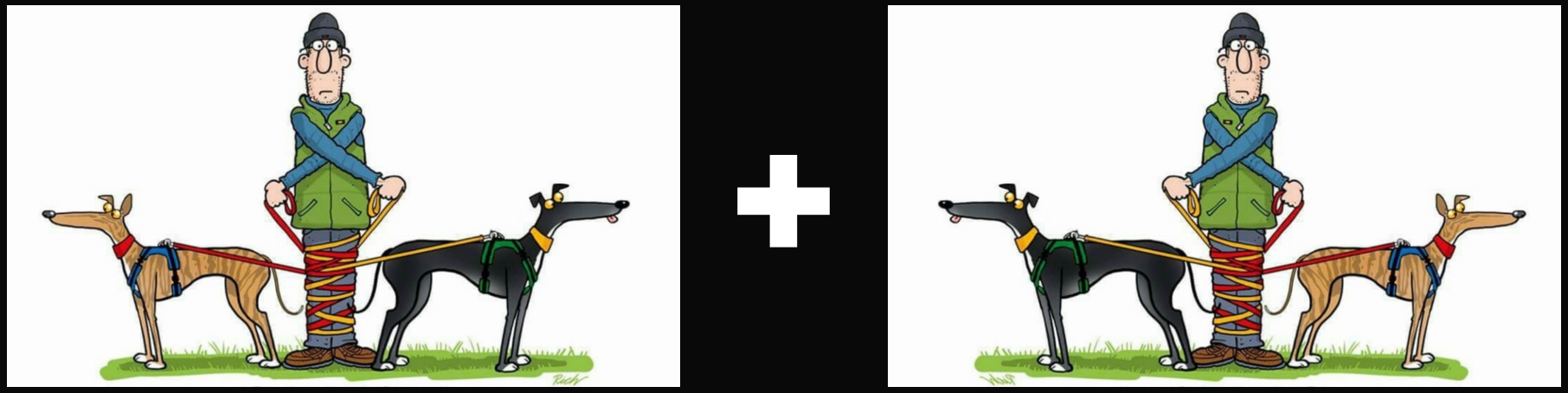
Entanglement



Entanglement

+

Entanglement



Superposition

2 or more quantum objects/degrees of freedom

Entanglement

Superposition
2 or more quantum objects

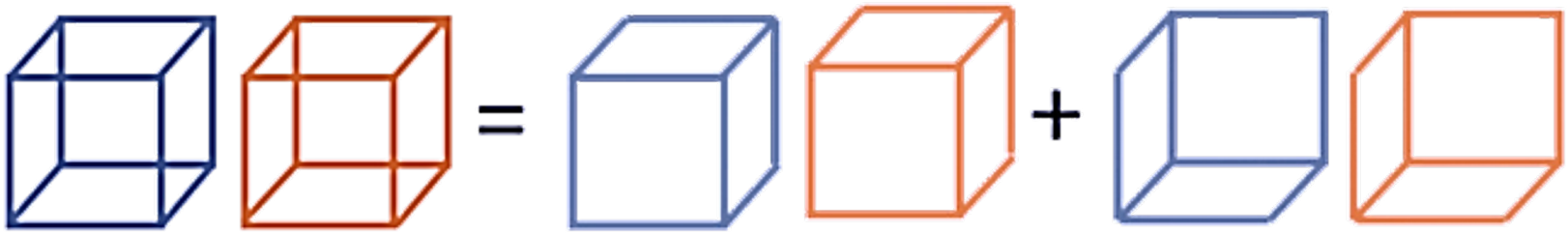
EINSTEIN ATTACKS

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

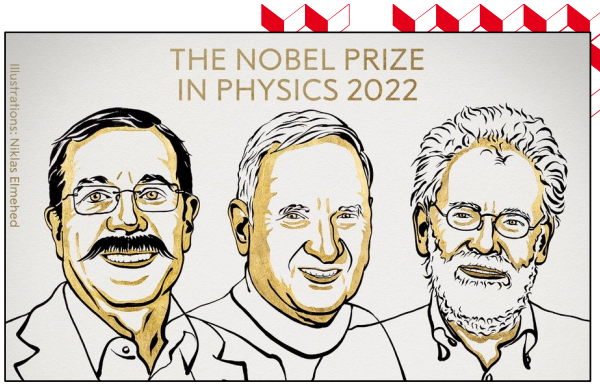
A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

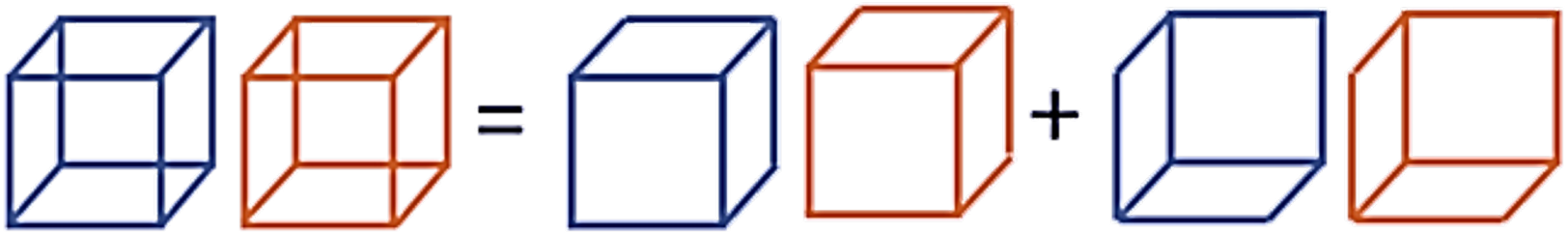


Coupled quantum objects cannot be considered separately => they are intertwined: entangled

Entanglement



Superposition
2 or more quantum objects



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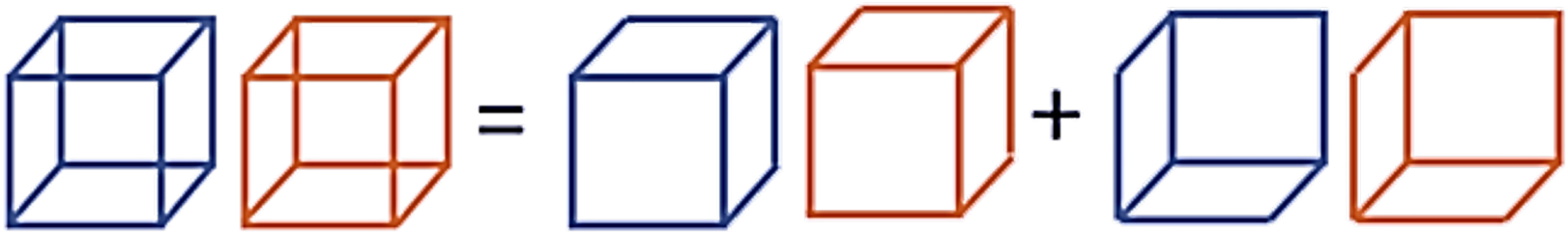
Entanglement

Superposition
2 or more quantum objects



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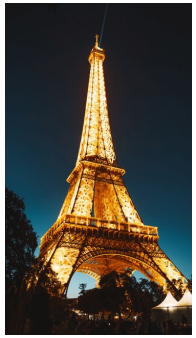
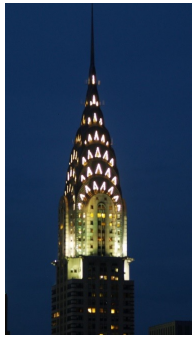


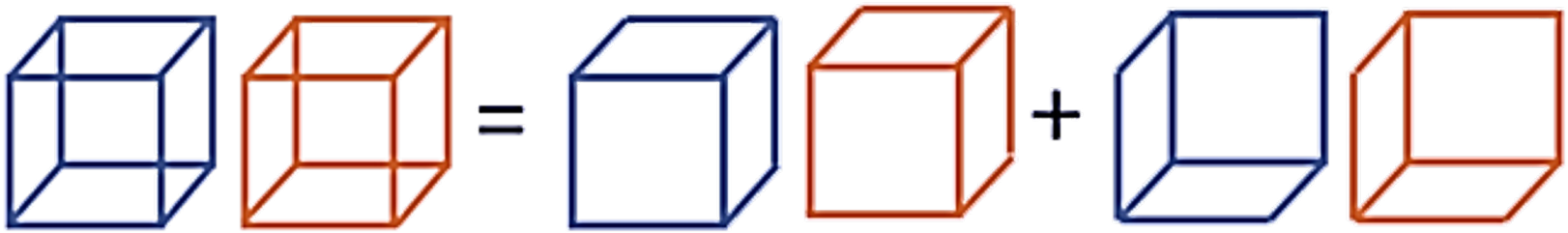


Non locality

If the blue in Paris is observed pointing left, then the red in New York points left
Conversely,
If the blue in Paris is observed pointing right, the red in New York points right

Entanglement and computing

Superposition
2 or more quantum objects

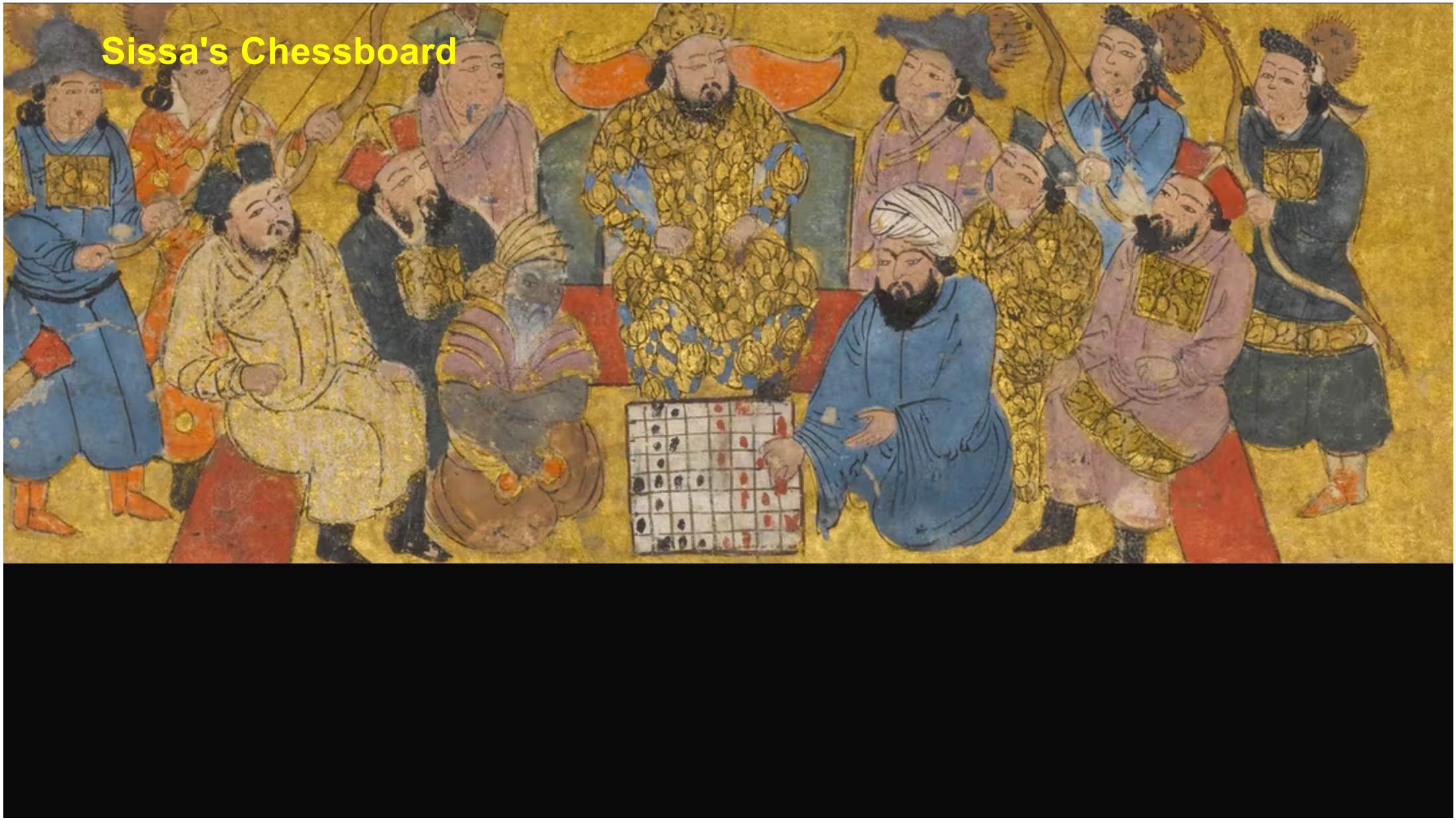


Coupled quantum objects cannot be considered separately => they are intertwined: entangled

Entanglement and the exponential groth of the space of states

N quantum objects with 2 states each (N quantum bits / Qubits) => 2^N possible entangled states

⇒ Access to the enormous space with 2^N dimensions for entangled states
⇒ Evolutions of 2^N solutions "simultaneously"


Sissa's Chessboard

Sissa's Chessboard

The Grand Vizier Sissa ben Dahir presents his new game, chess, to the Indian king Shirham and requests his reward: "Just 1 grain of wheat on the first square, 2 on the second, 4 on the third, 8 on the fourth, … and so on, doubling the number of grains on each square up to the sixty-fourth."

The king agreed, not realizing that it would require a cube 10 km wide and 10 km high to contain the 2^{63} grains of wheat for the sixty-fourth square... and 1,000 years of global wheat production to fill it!

Sissa's Chessboard

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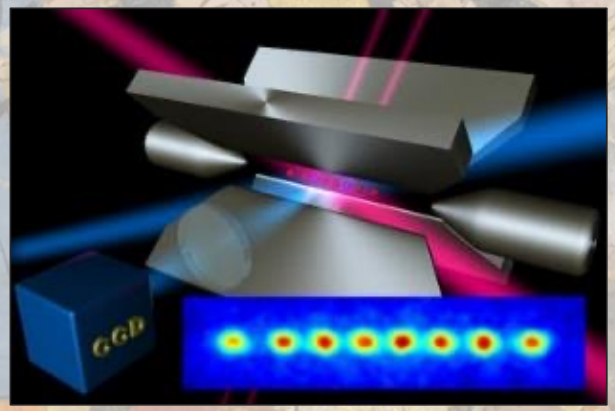
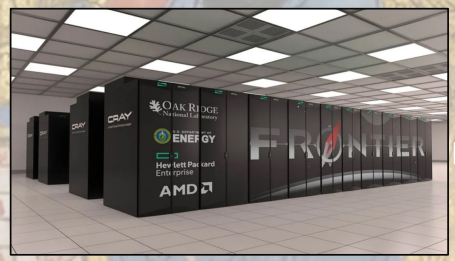
The king agreed, not realizing that it would require a cube 10 km wide and 10 km high to contain the 2^{63} grains of wheat for the 64^{th} square... and 1,000 years of global wheat production to fill it!

Sissa's Computer

Adding a single quantum object/qubit doubles the size of the space of entangled states

To manipulate this space on classical computers we must double their size

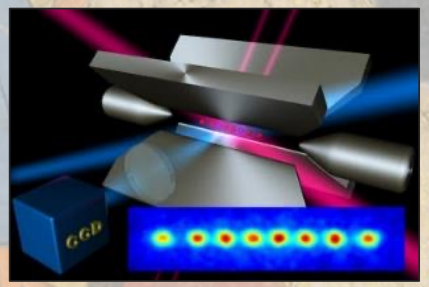


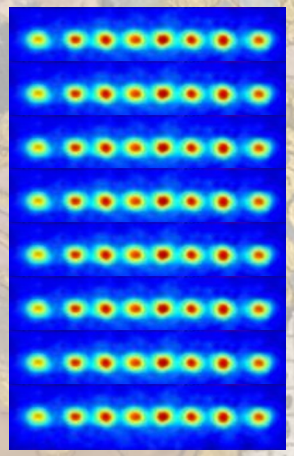


Sissa's Computer

Adding 64 quantum object/qubit multiplies by 2^{64} the size of the space of entangled states

To manipulate this space on classical computers we must multiply by 2^{64} their size





2.0 quantum revolution disrupting information and communication society

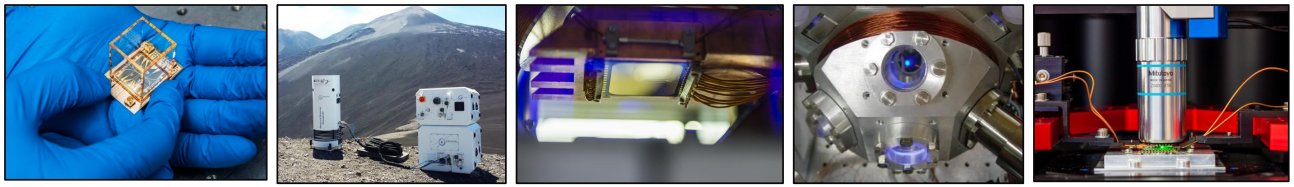
Mastering individual quantum objects: ultimate sensitivity

Entangling distant quantum objects: unbreakable communications

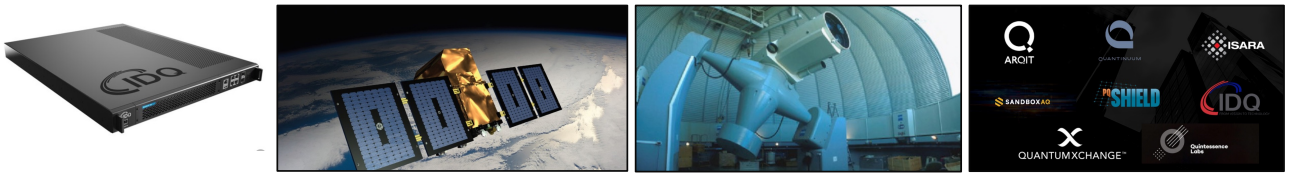
Massive entanglement: unprecedented computational power

2.0 quantum revolution disrupting information and communication society

Mastering individual quantum objects: ultimate sensitivity



Entangling distant quantum objects: unbreakable communications



Massive entanglement: unprecedented computational power

QUANTUM Sensing metrology

QUANTUM Communication

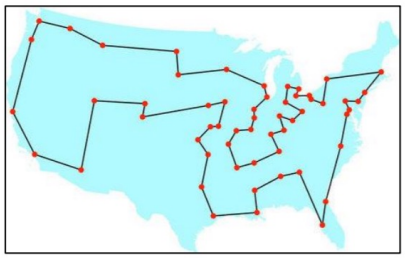
QUANTUM Computing

QUANTUM Simulation

Quantum computing: Disruptive potential

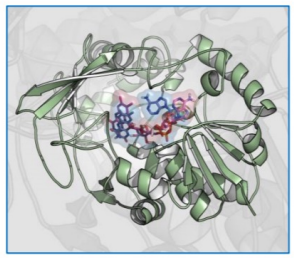
Changing the World

TIME
"Quantum Will Change Everything"

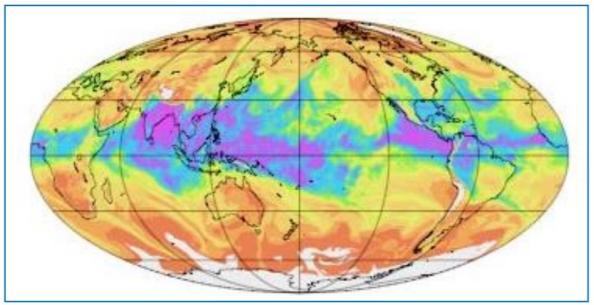


Travel and Logistics

Image Processing



Pharmacology



Improved Forecasting

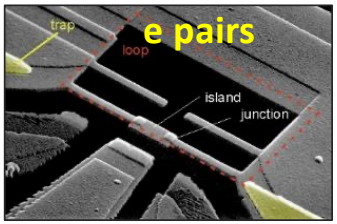
Improved Stock ROI

Cryptography

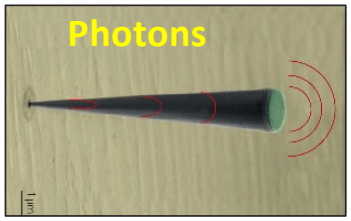
Take home message

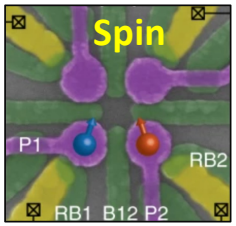
Quantum revolution 2.0

Technology mastering **individual quantum object** / degree of freedom

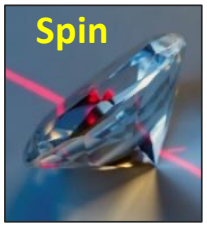


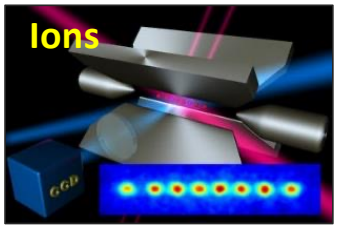
e pairs

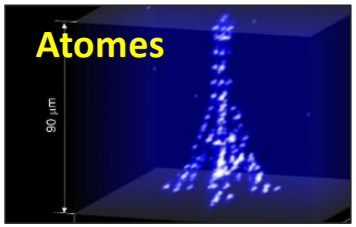

Photons



Spin


Spin

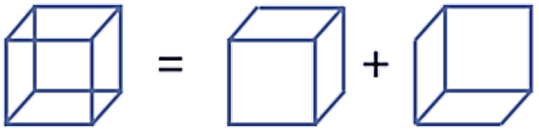

Ions

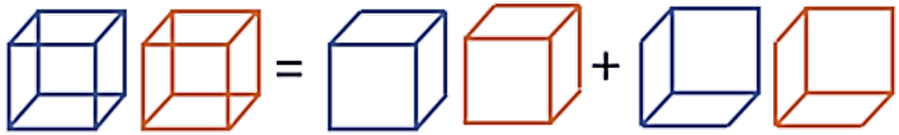


Atomes

Is giving access to powerful quantum phenomena

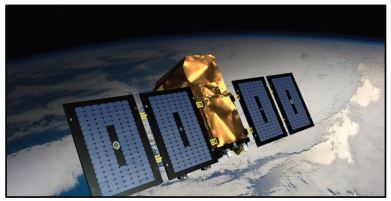
Superposition of quantum states, **Non-locality** of quantum states, **Entanglement** of quantum states

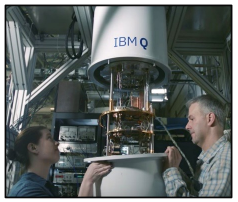




With a huge disruption potential

ultimate **sensitivity,** unbreakable **communications,** unprecedented **computational power**





Is it the end of the story?

3.

Is it the end of the story?

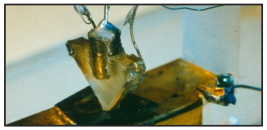
No!

This only the beginning and success is not guaranteed!

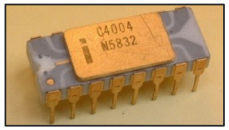
Quantique 2.0: Major difficulties

Fabrication challenges:

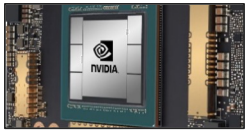
- Even more difficult then the 1st quantum revolution



1947, 1st Transistor

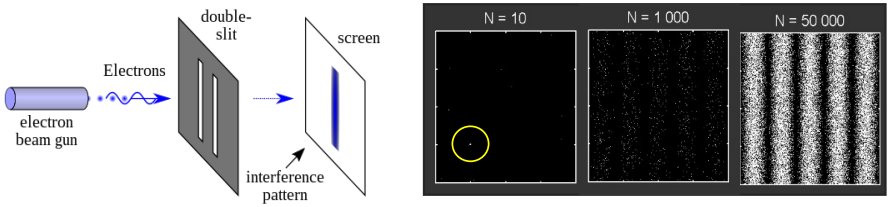


1971, 2 300 transistors.

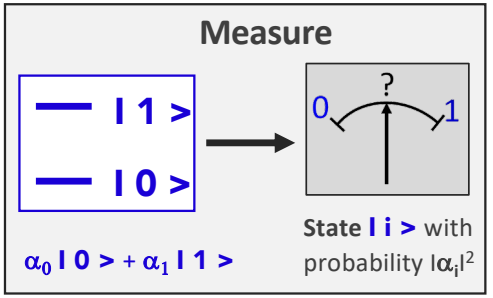


2020, 54 milliard transistors

Quantum is probabilistic: the measure destroys the superposition

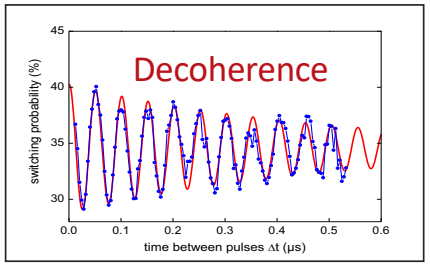


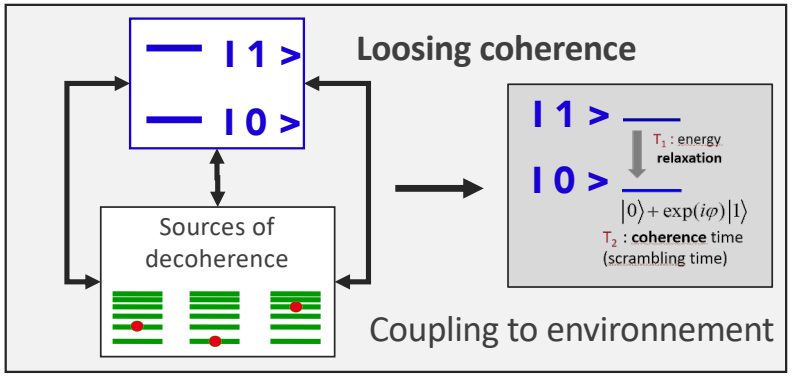
Example. Electron waves and probabilistic measure on screen



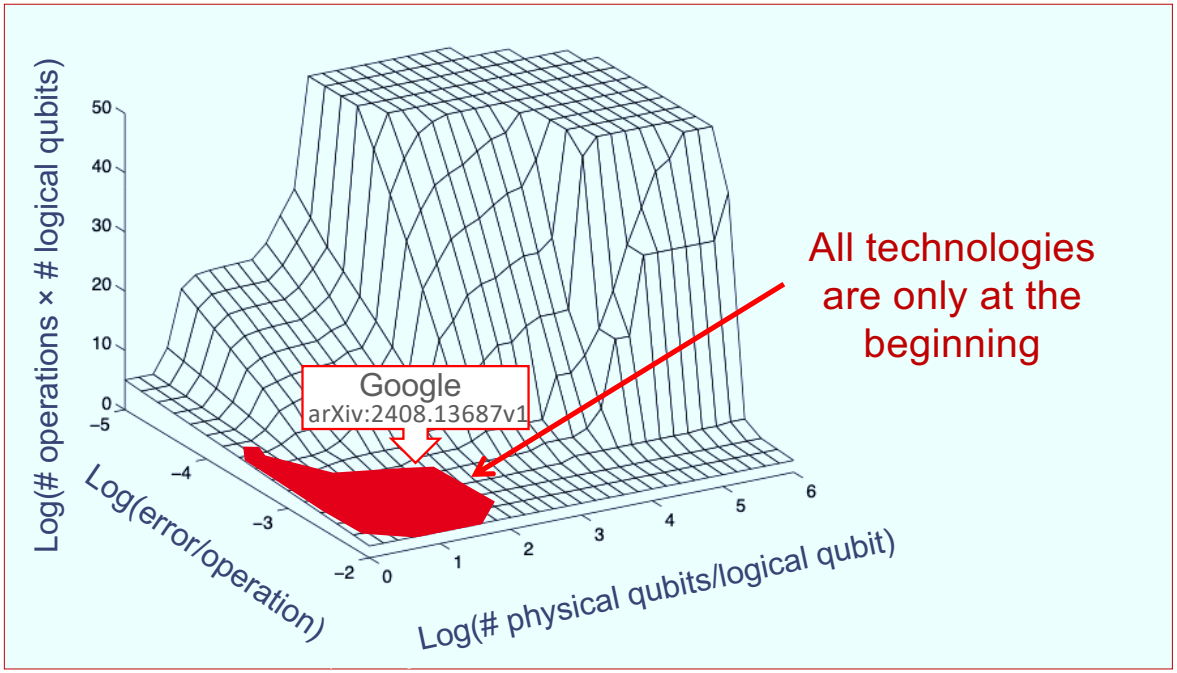
Coupling to environment is destroying coherence: Superposition & entanglement

- **Error correction codes needed**
  => thousands of physical qubits to protect a single logical qubit
- **Or new robust qubits**
  protected from decoherence

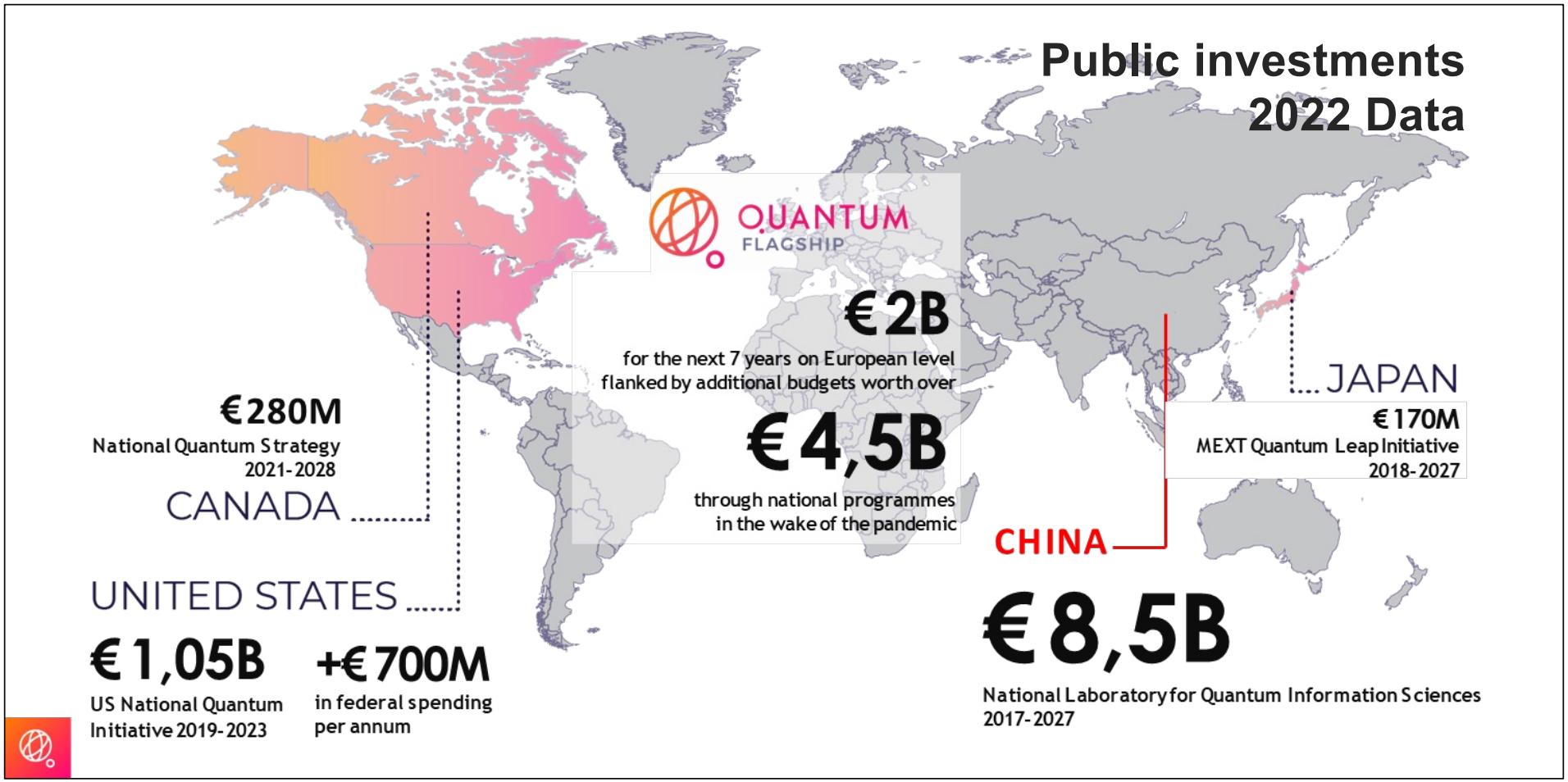




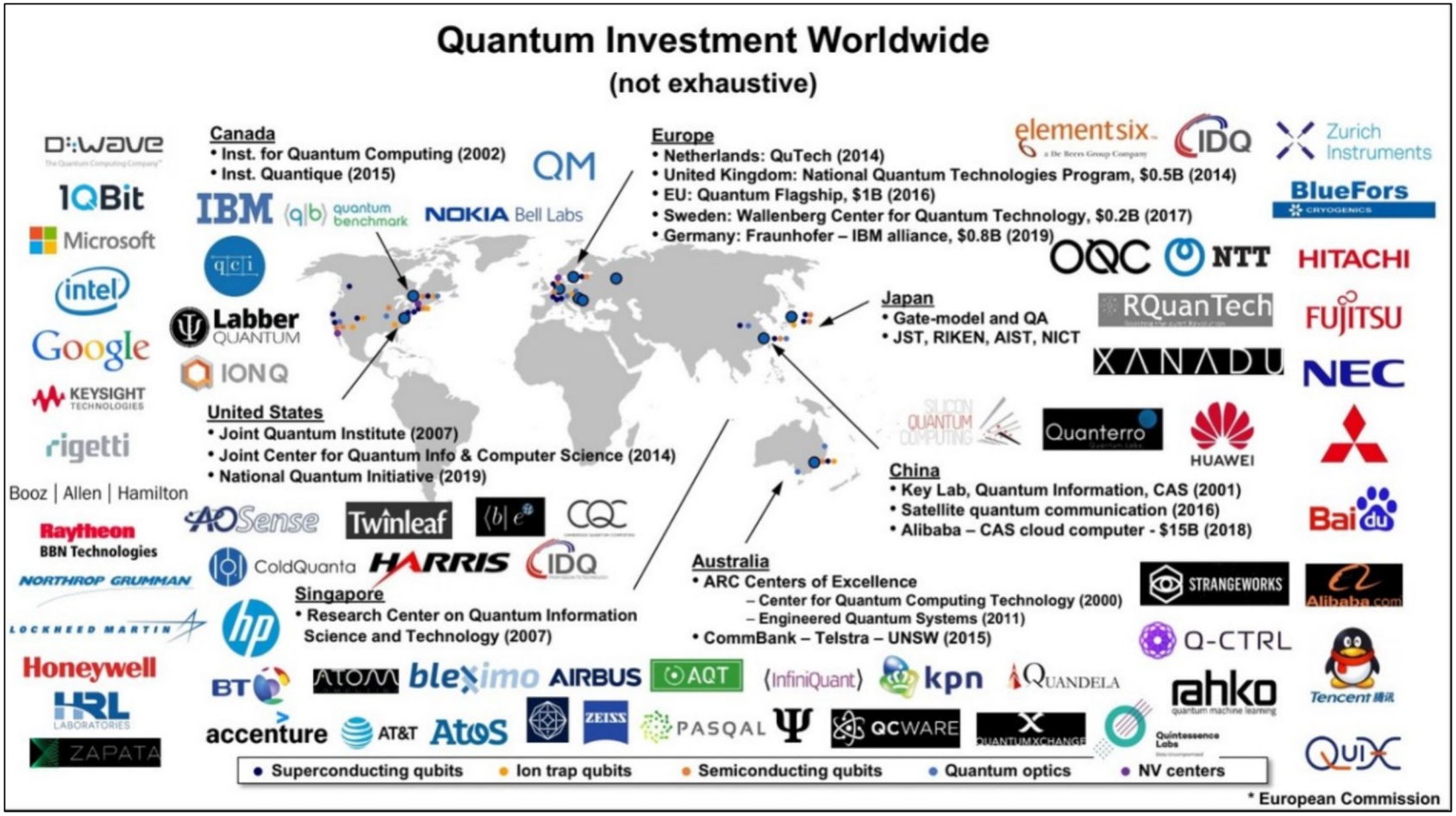
Reduction of quantum errors needed before any applications of quantum computing



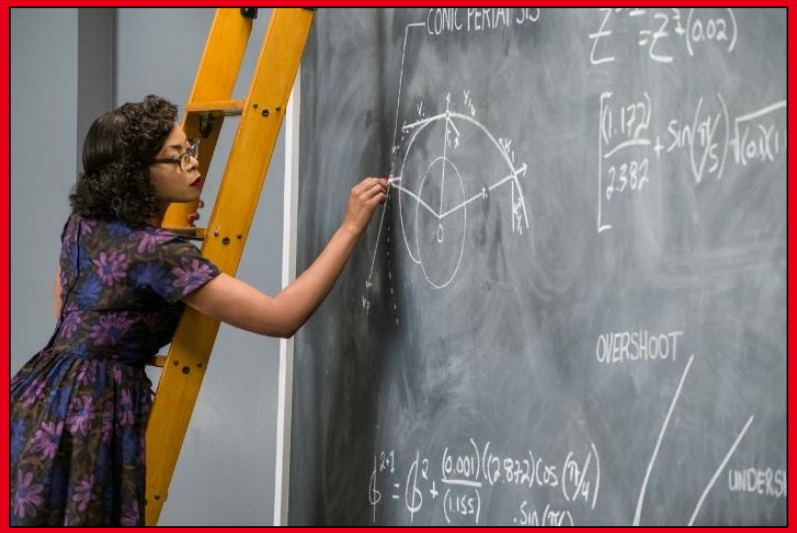
2022 International competition and collaboration



2022 International competition and collaboration



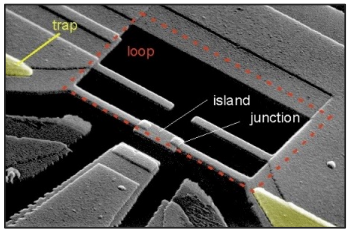
Conclusion: a revolution to come



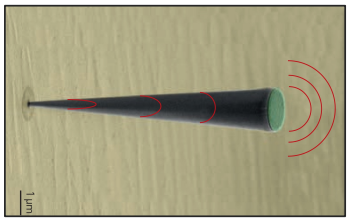
4. Back-up

Many possible technologies/degrees of freedom

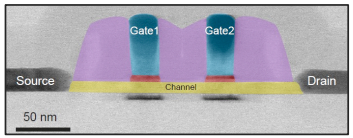
Quantum “objects”/degrees of freedom

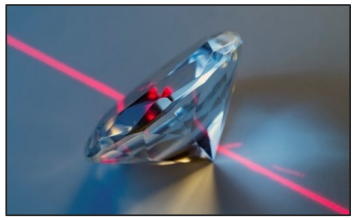


- **Electrons pairs / superconducting curent**
  - Quantronium - transmon

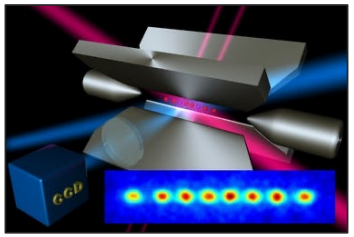


- **Photons**

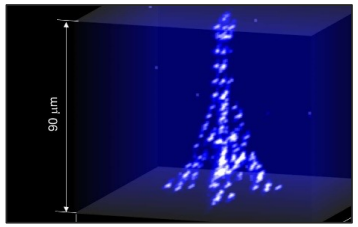




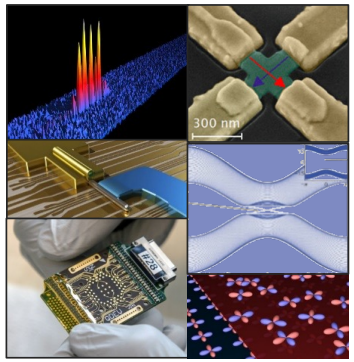
- **Spin**
  - Electrons or holes in semiconductors (AsGa, Si, Ge, …)
  - NV centers in diamond (Nitrogen vacancy)



- **Ions**



- **Atoms**
- **Molecules**



- **New quantum degrees of freedom / quantum materials**

  Flying qubits, surface states, leviton, pseudospin, Skyrmions, spin-orbite, 2D systems, topological materials, Majorana fermions, anti/multi-ferroïc …

Different quantum computing strategies

▶ **Quantum annealing**

$|\psi\rangle \Rightarrow |\psi_0\rangle$

Looking for ground states

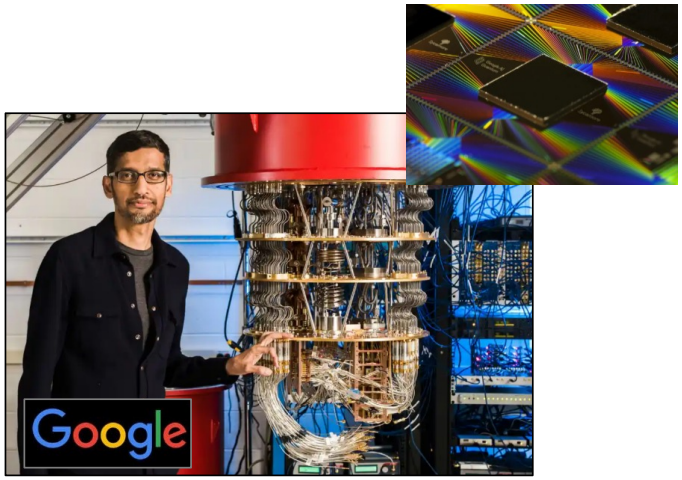
- adiabatic optimization
- exploring many paths
- using tunnel effects

▶ **Quantum simulation**

$|\psi(t)\rangle = \hat{U}(0,t) \; |\psi(0)\rangle$

Quantum evolution

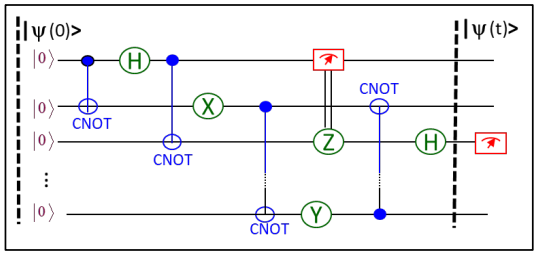
- analogue computing



▶ **Quantum digital computing**

$|\psi(N\Delta t)\rangle = \hat{U}_N(\Delta t) \ldots \hat{U}_1(\Delta t)|\psi(0)\rangle$

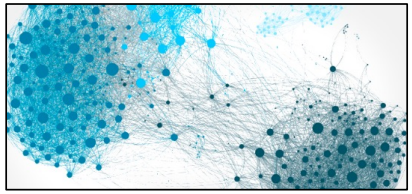
Gate based evolution



Main classes of quantum algorithms

- **Search**

  based on Deutsch-Jozsa, Simon and Grover's algorithms
  - Polynomial acceleration



Exploring graphs and data bases

- **Quantum Fourier transforms (QFT)**

  such as Shor's algorithm for factorization (&Bitcoin)
  - Exponential acceleration

Cryptography

- **Optimization**

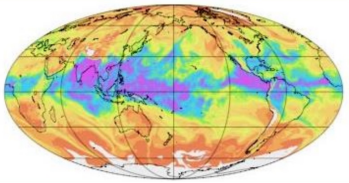
  searching equilibrium point of a complex system
  such as neural network and optimal path (PCA)
  - Exponential acceleration

Image processing

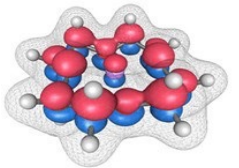
Market evolution

- **Quantum simulation and variational approach**

  Quantum many body problems
  Resolution of linear differential equations (HHL)
  - Exponential acceleration



Weather broadcast



Molecules

Computing in the 2^N dimensions' space of quantum states
(Hilbert/Fock)

Classical computers	Quantum computers
Classical bit: $\boxed{i} = \boxed{0}$ ou $\boxed{1}$	$\alpha \mid 0 > + \beta \mid 1 >$: QuBit, Quantum bit
(2 possibilities)	(R^3 possibilities, 3D)
Classical register: $\boxed{X} = \boxed{i_1}\boxed{i_2}\boxed{\ldots}\boxed{i_N}$	$\mid X > = \Sigma \alpha_{i_1,i_2,\ldots,\, i_N} \mid i_1,i_2,\ldots,\, i_N >$: Quantum register
(2^N possibilities)	(C $^{2^N}$ possibilities, 2^N D)
Classical computing: $\boxed{X} \rightarrow \boxed{Y} = \boxed{T}\boxed{X}$	$\mid X > \rightarrow \mid X > = \Sigma \alpha_{i_1,i_2,\ldots,\, i_N} \hat{U} \mid i_1,i_2,\ldots,\, i_N >$
	: Quantum Computing

(Turing machine) ← **completely different computing paradigm** → **(Unitary transformation + measuring, statistical projection)**

<u>Evolution of 2^N states simultaneously</u>
⇒ Computing power and memory beating all classical computers as soon as N ~ 50 qubits
(since 2^N soon larger then any classical memory)

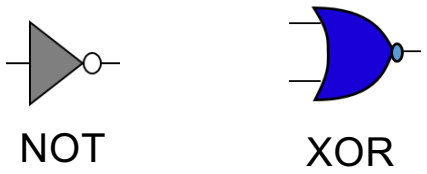
cea

Similar “gate” vocabulary but very different paradigms: Turing versus Unitary

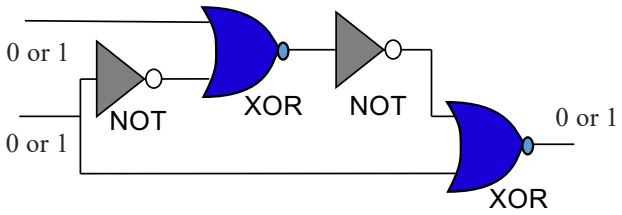
Classical computers

Logic gates in classical computing

Single bit Double bit



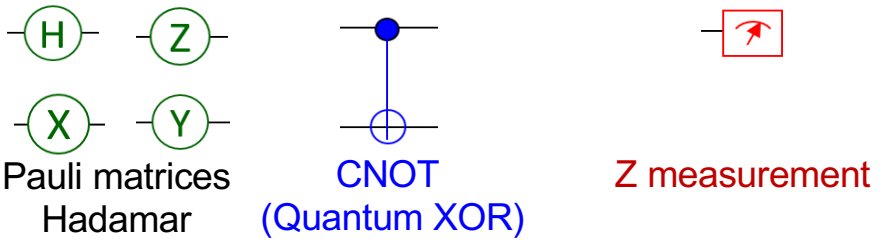
Algorithm: Turing machine



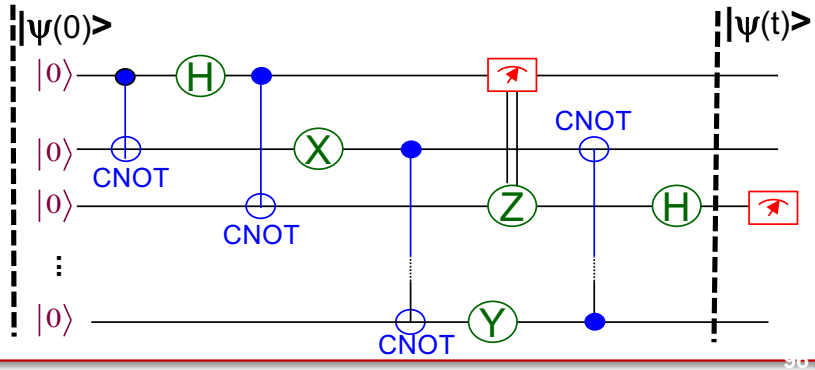
Quantum computers

Unitary gates and measurement in quantum

Single Qubit Double Qubit Measurement



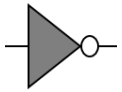
Algorithm: Unitary evolutions + projections



Similar “gate” vocabulary but very different paradigms: Turing versus Unitary

Logical gate in classical computing

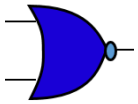
Single bit



NOT

0 ➔ 1
1 ➔ 0

Double bit



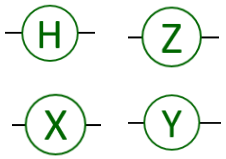
XOR

00 ➔ 0
01 ➔ 1
10 ➔ 1
11 ➔ 0

Function in the space ofbits {0,1}

Unitary gates and measurement in quantum computing

Single Qubit



Pauli matrices
Hadamar

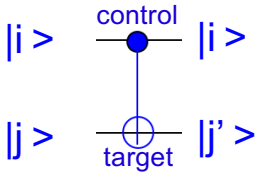
$|i> \rightarrow \hat{U}|i> = U_{0i}|0>+U_{1i}|1>$

Ex: Hadamard gate

$|0> \rightarrow \frac{|0> +|1>}{\sqrt{2}}$

$|1> \rightarrow \frac{|0> -|1>}{\sqrt{2}}$

Double Qubit



CNOT
(Quantum XOR)

$|i\,j> \rightarrow \hat{U}|i\,j> = U_{00ij}|00>+U_{01ij}|01>+U_{10ij}|10>+U_{11ij}|11>$

Ex CNOT:

|00> ➔ |00>
|01> ➔ |01>
|10> ➔ |11>
|11> ➔ |10>

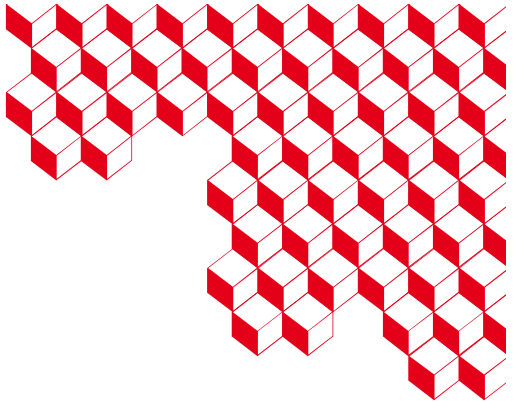
Qubit Measurment

Z measurement

$\alpha_0|0>+\alpha_1|1> \rightarrow$
either
$|0>$ with $p=|\alpha_0|^2$
or
$|1>$ with $p=|\alpha_1|^2$
when measuring
either 0 or 1.

Superposition **Entanglement** **Projection**

Unitary transformation **Probabilistic**



Merci pour votre attention