Left side

TEST

Right side

From imaginary experiments to quantum information

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Public lecture

Williams College, March 2024

Supported by DLS APS

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NIST

With special thanks to:

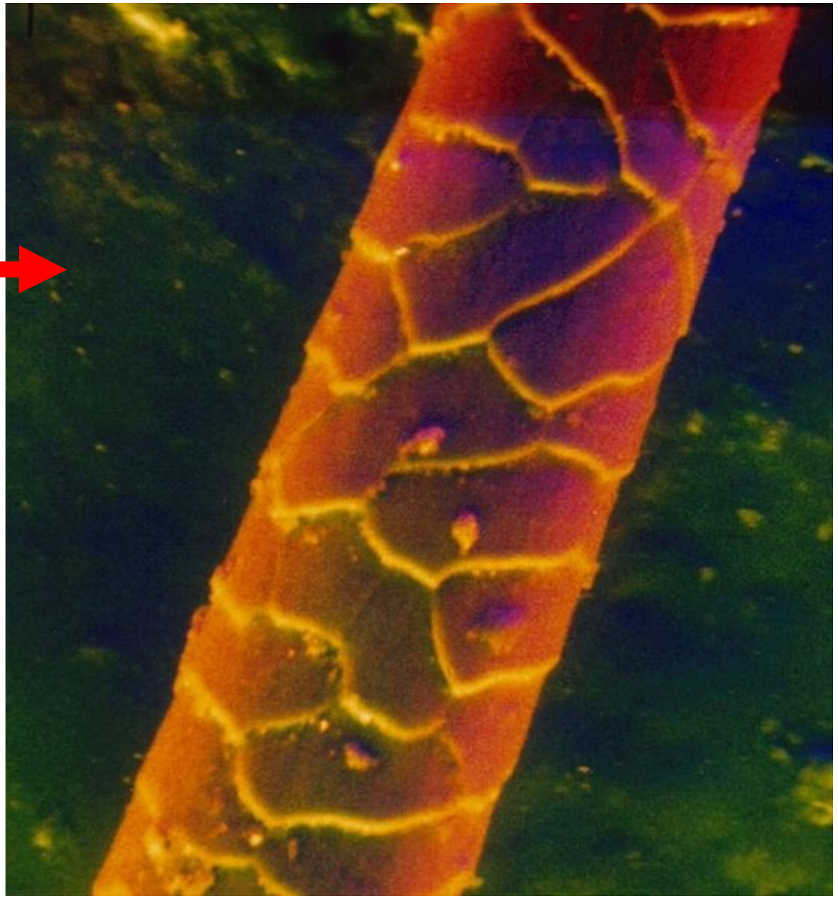
William D. Phillips
Howard J. Carmichael
Pablo Barberis Blostein

Work supported by
National Science Foundation

Travelling Lecturer of the Division of Laser Science, American Physical Society

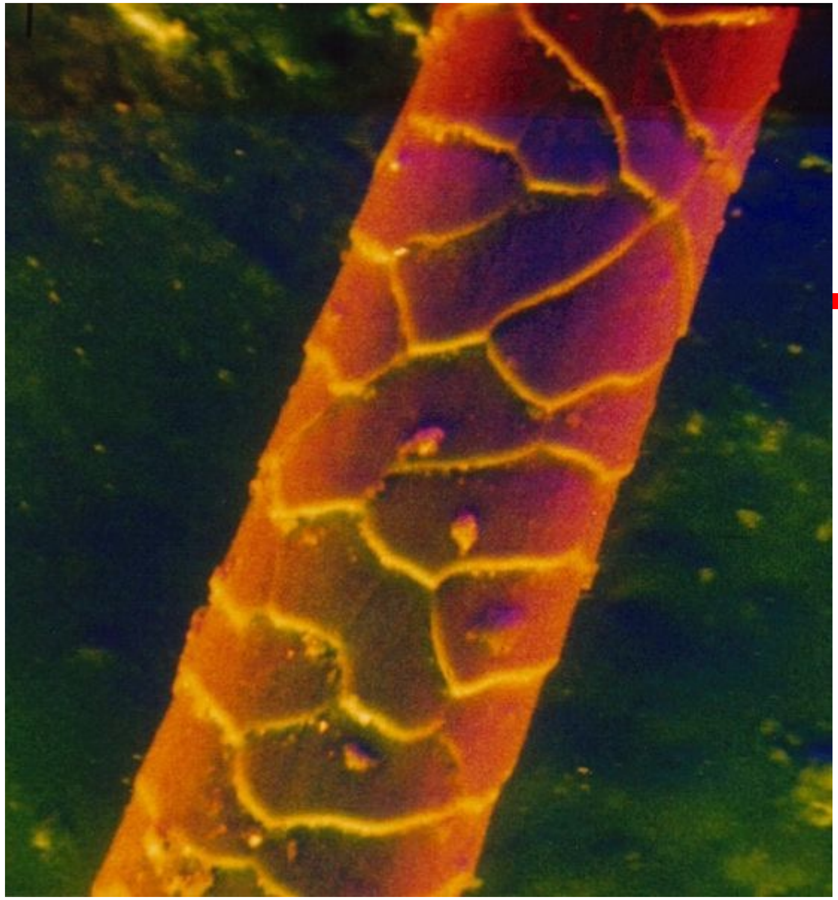
Everything is made of parts

10,000X

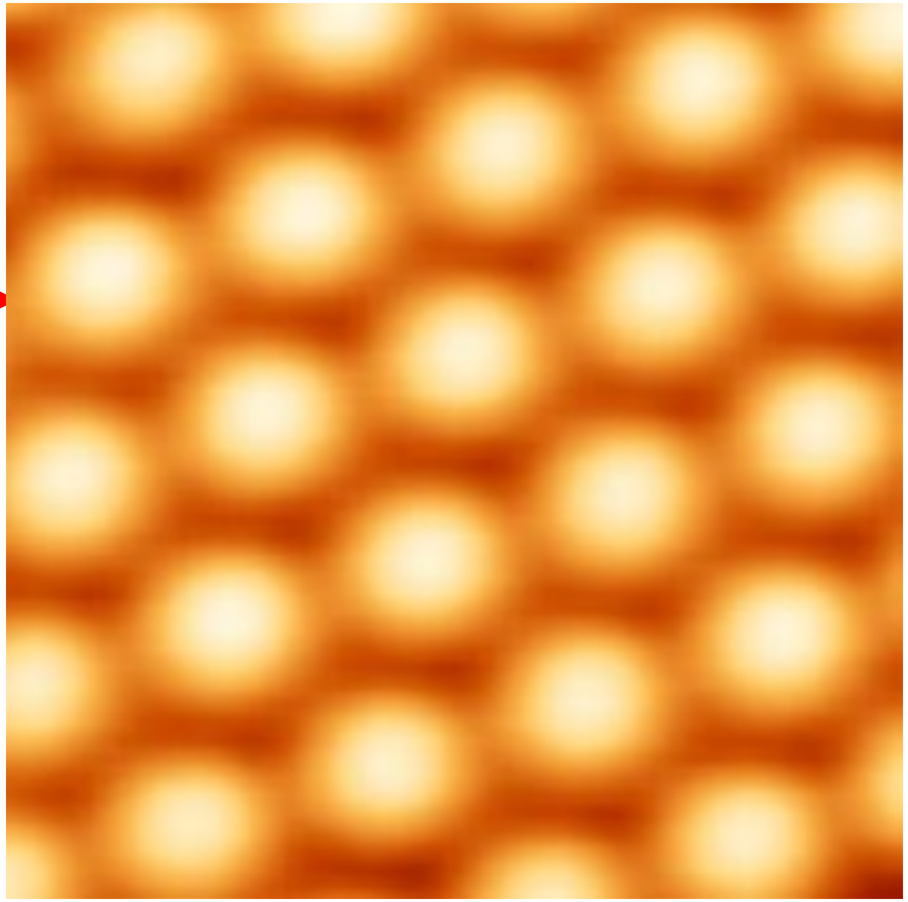


50 centimeters

50 micrometers



50,000X



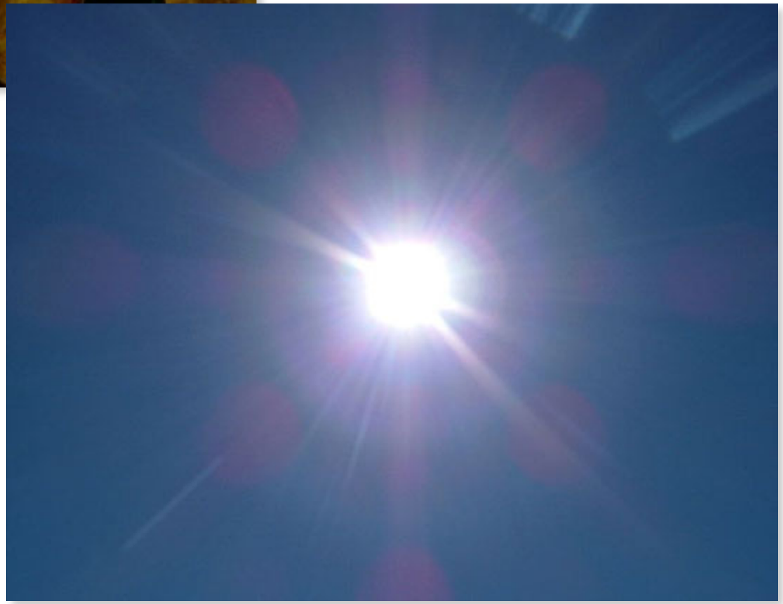
50 micrometers

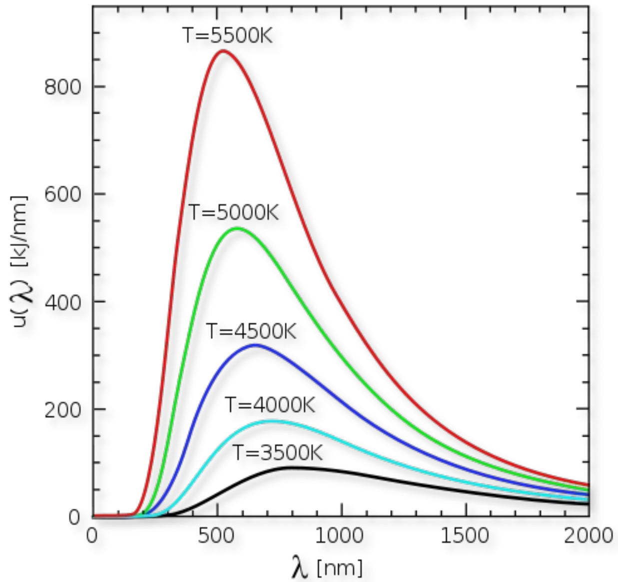
1 nanometer

Nature is discretized, it comes in quanta.
There are no half electrons!

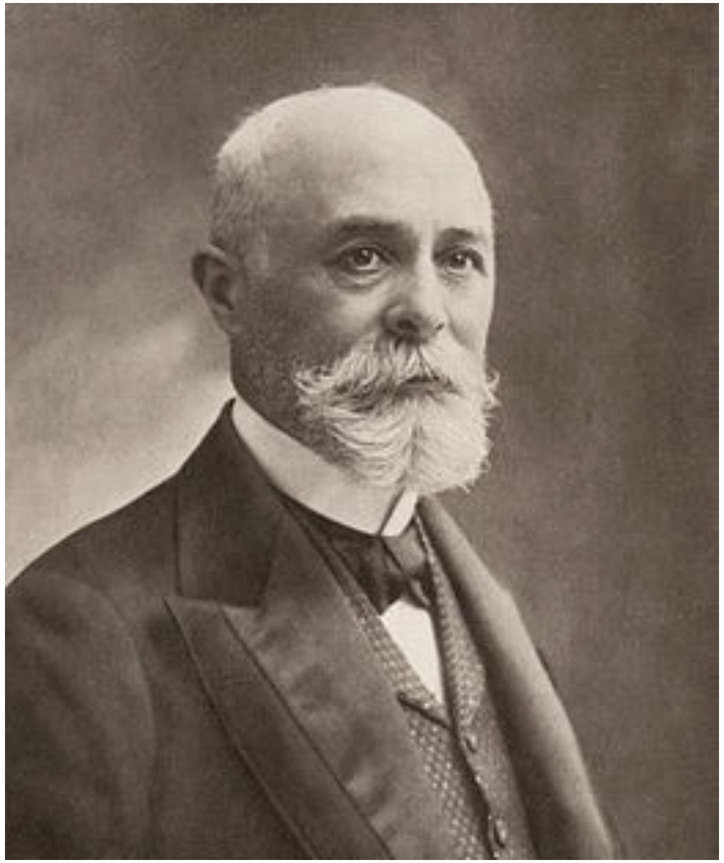
Everything is made of parts,
and
there is a minimum size where our intuition fails.

It all started in the 19th century
Black Body radiation





Spontaneous Radioactivity: Something probabilistic in nature!



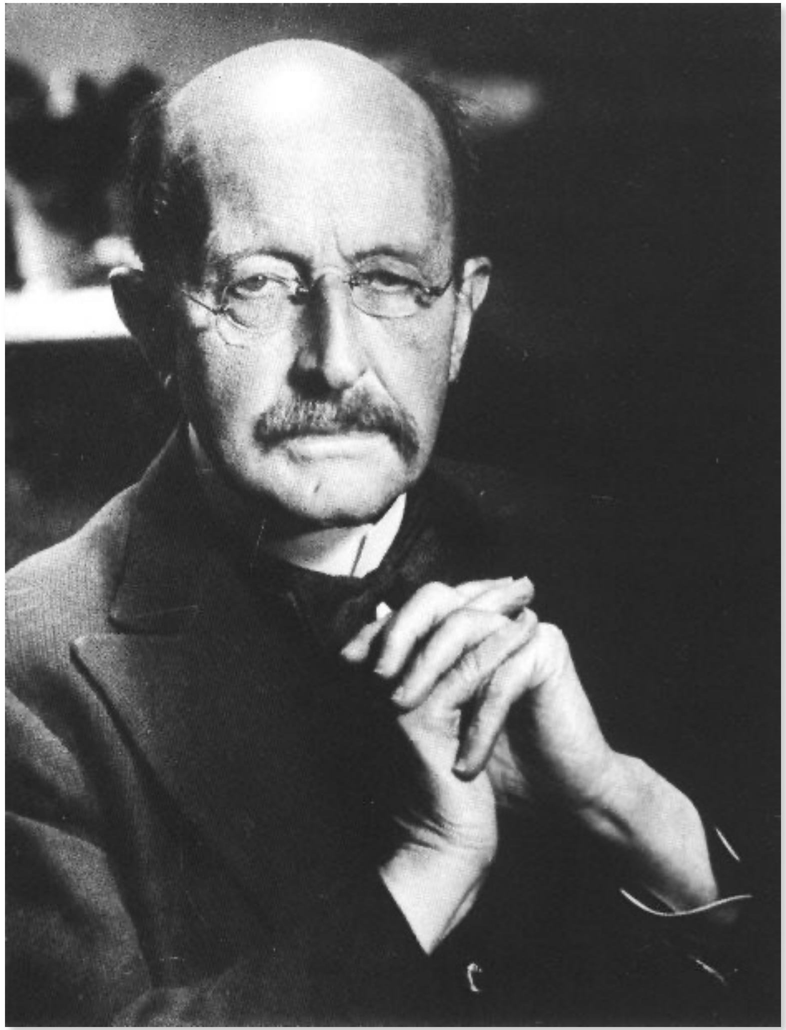
Henry Becquerel

Pierre Curie

Marie Curie

February 27, 1896

The birth of quantum theory on October 7, 1900



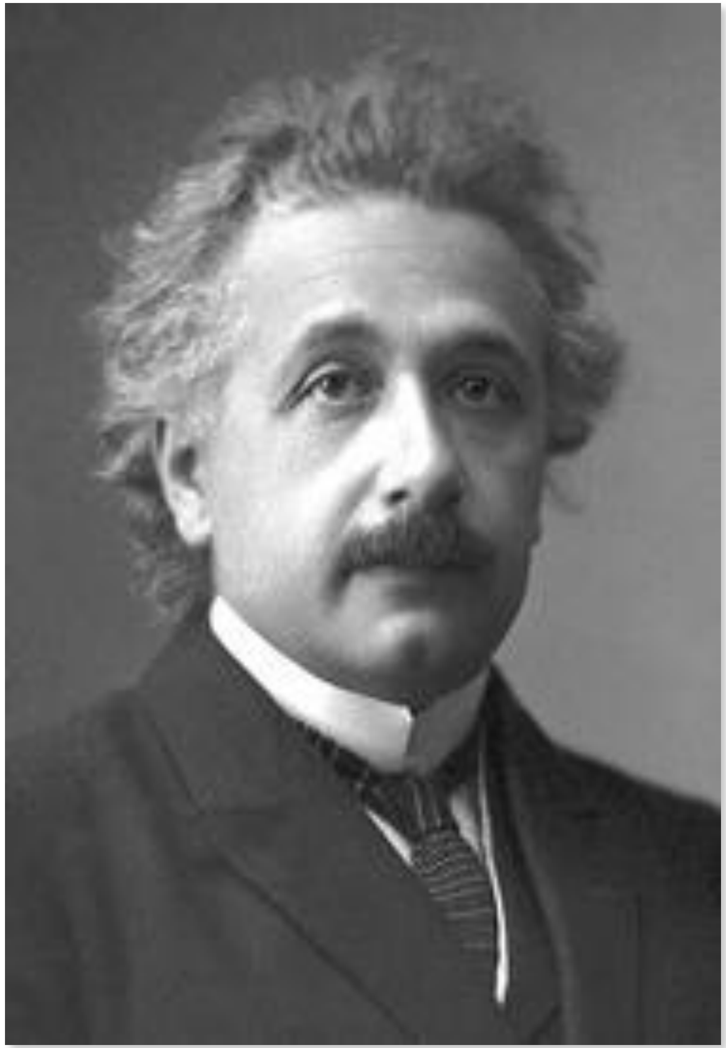
Max Planck

Coffee and cake with the Rubens

$$\rho(\nu,T) = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{h\nu/kT}-1}$$

Plank says that in an act of desperation he assumed:
The energy is also made out of parts and there is one which is the smallest, the quantum of energy.

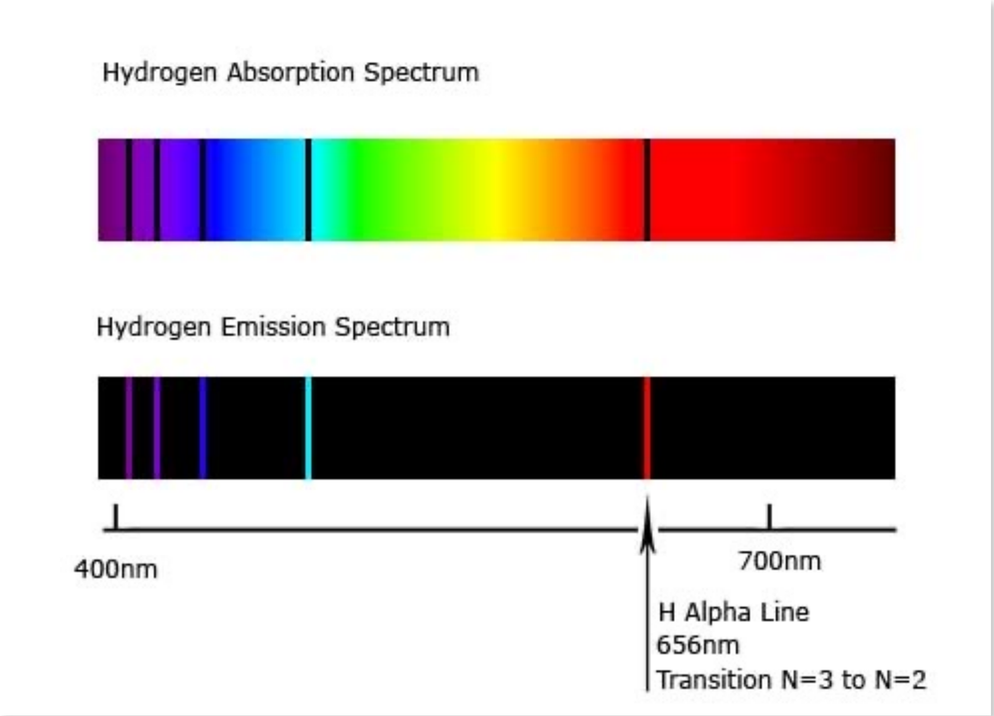
1905 the “photon”, is the quantum of light

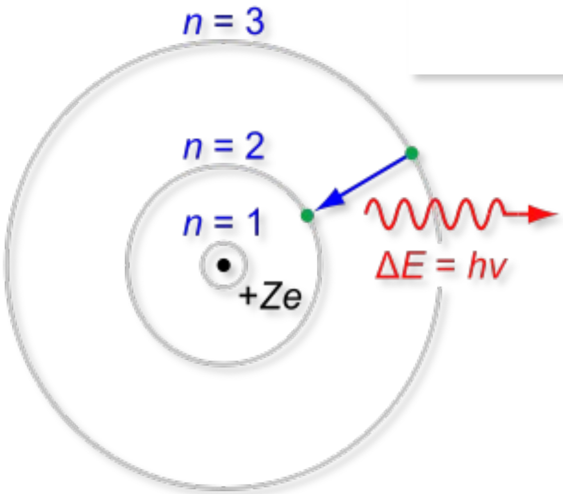


Albert Einstein

1913 visit to Rutherford

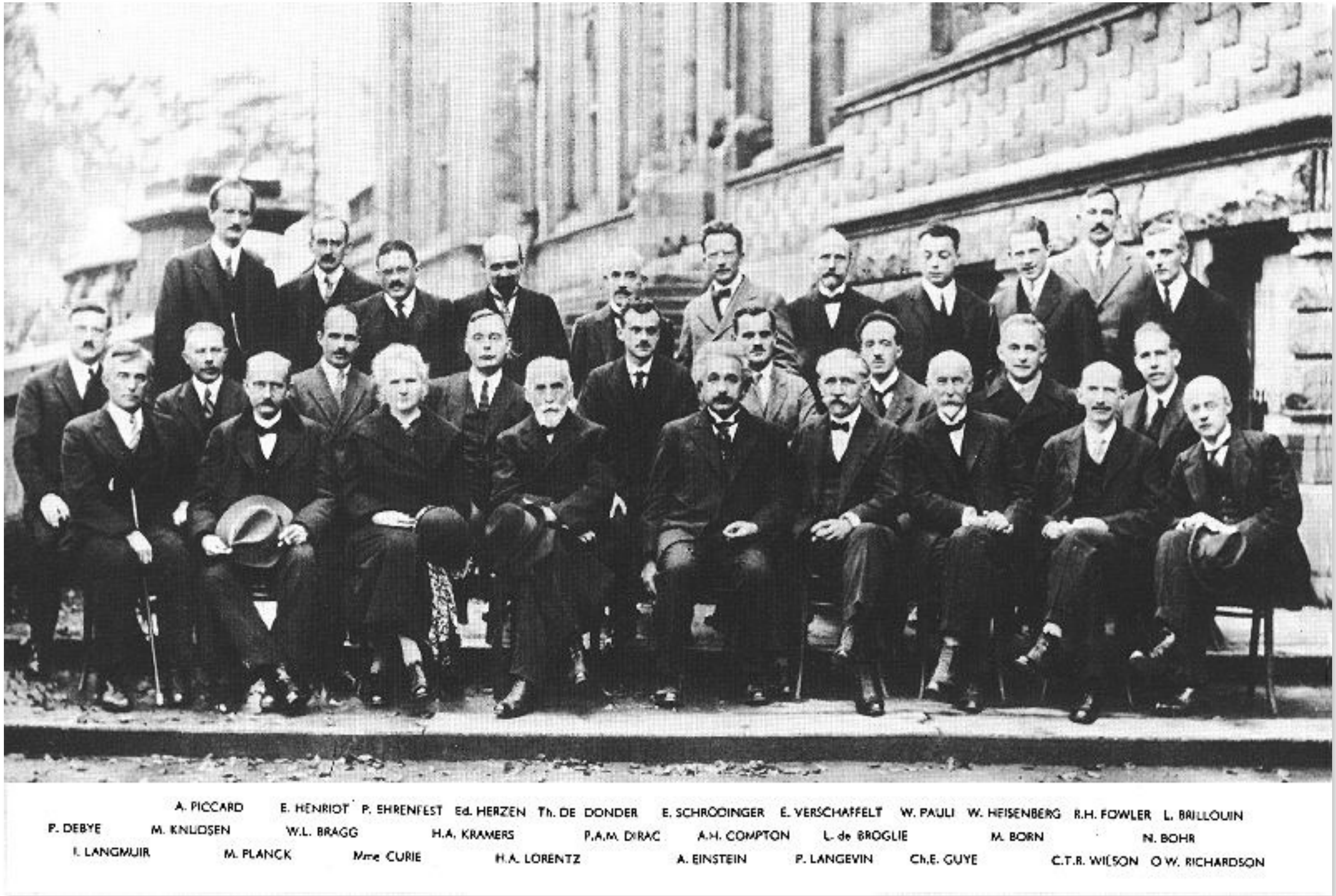
Niels Bohr





Explanation of the spectrum of Hydrogen

1920-1930 – Development of Quantum Mechanics. (Solvay Conference). One particle QM



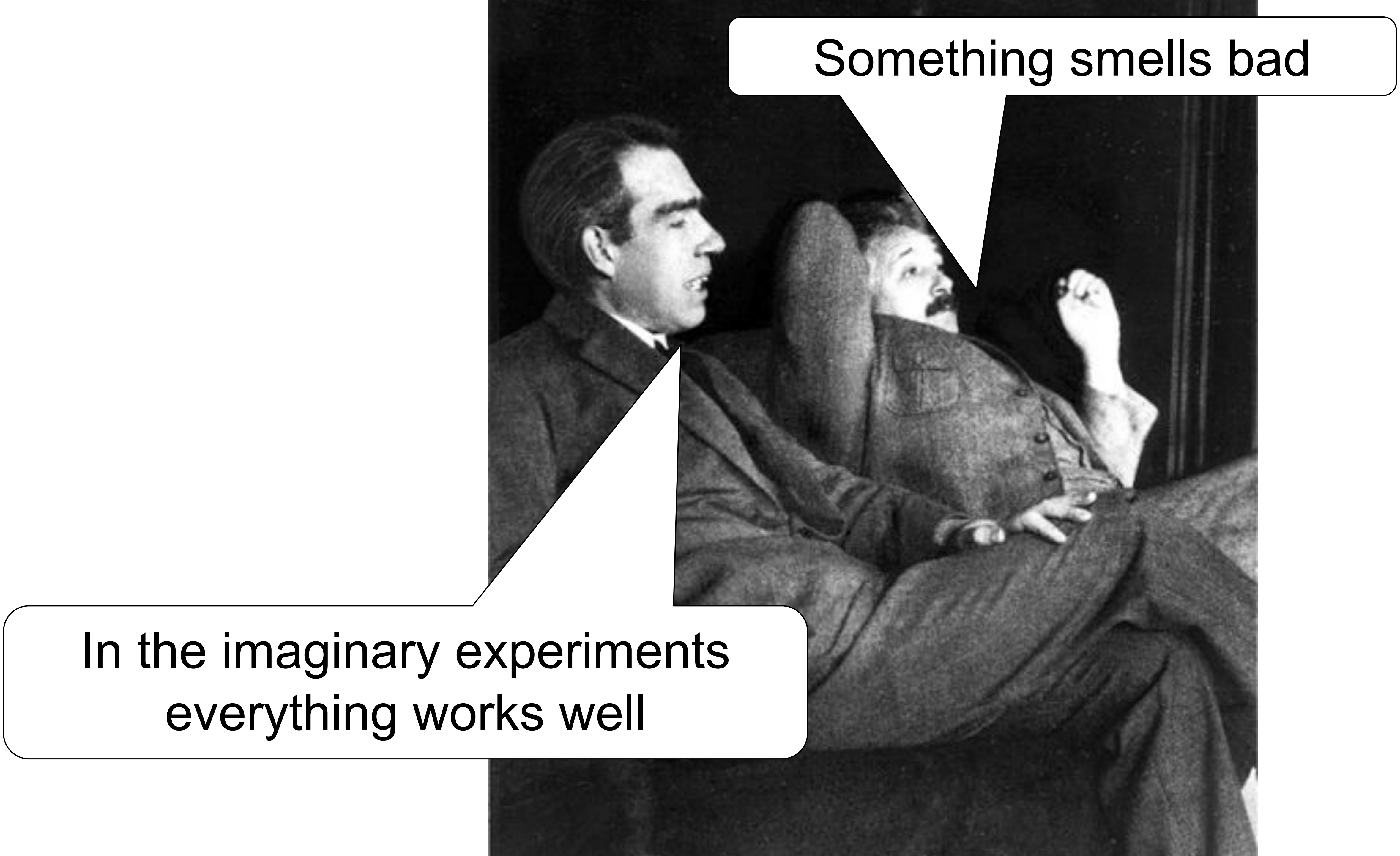
The wave–particle duality.

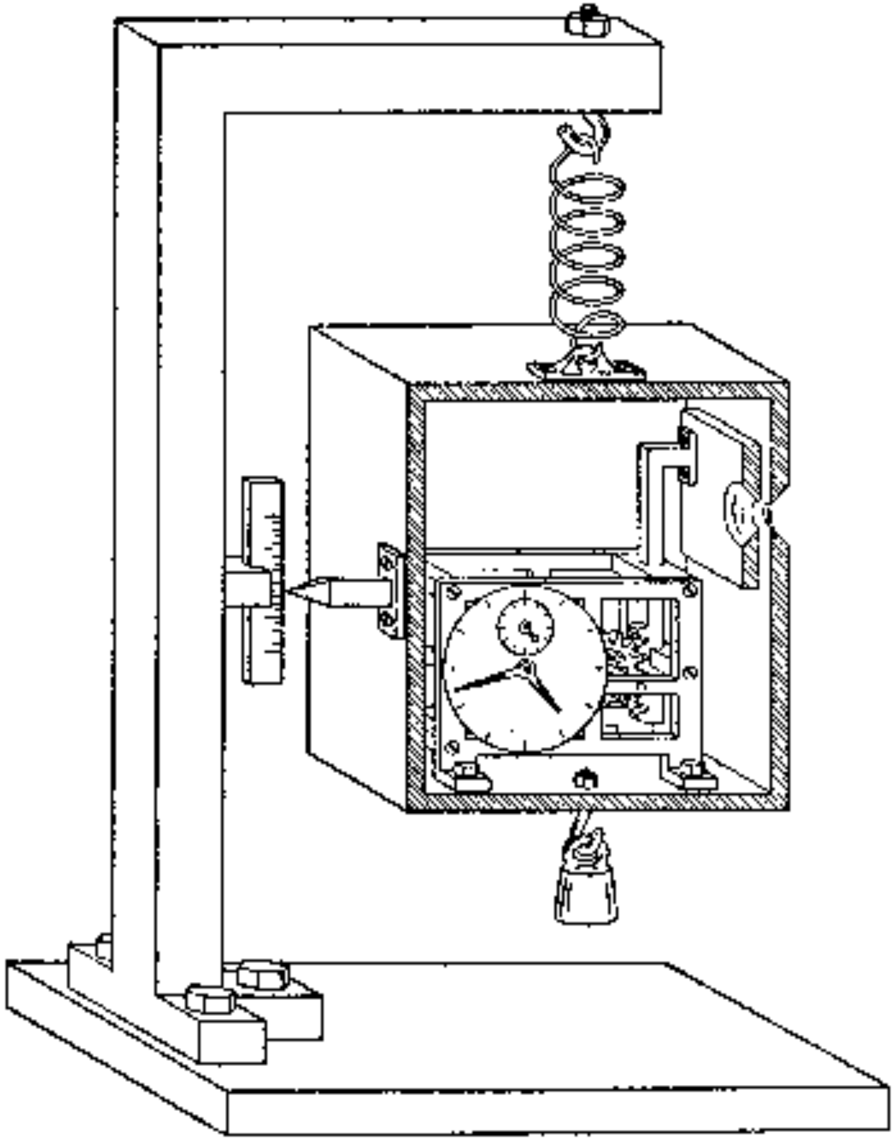
1905 Einstein assigns a particle (photon) to a wave (light)

1924 De Broglie assigns a Wave to a particle (matter)

1925-6 Schrödinger states the wave equation for those waves

But something was strange

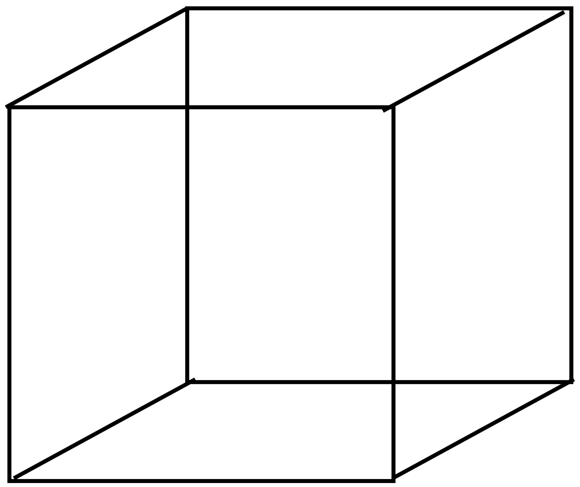

Something smells bad
In the imaginary experiments everything works well



Imaginary experiment by Bohr

One particle quantum weirdness

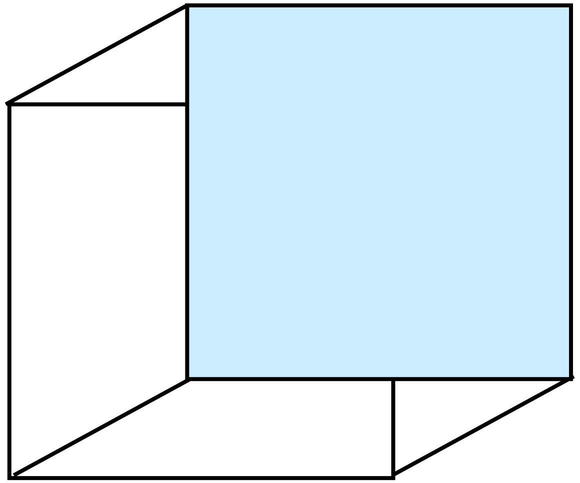
How can something be “in two positions at the same time”?



This “cube” could be

Fred Alan Wolf, "Taking the Quantum Leap"
(Harper & Row, San Francisco, 1981)

this



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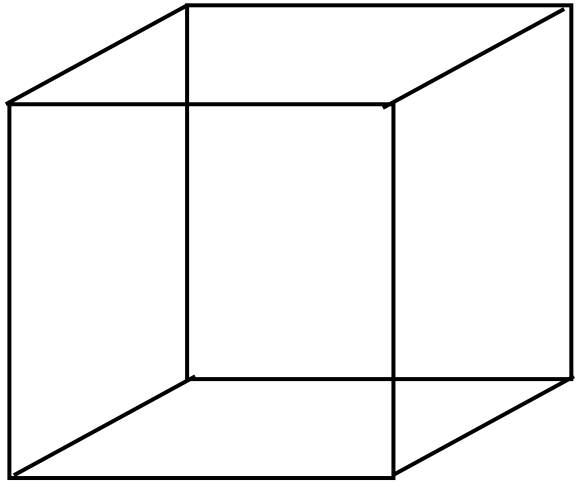

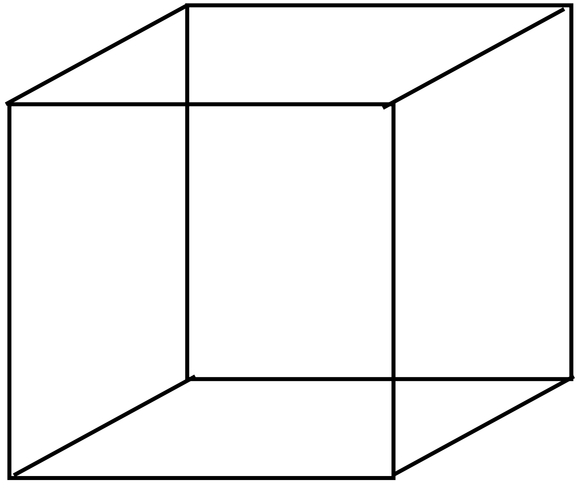

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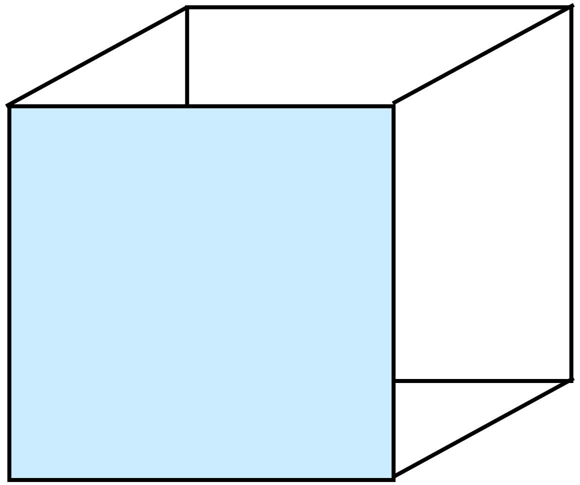

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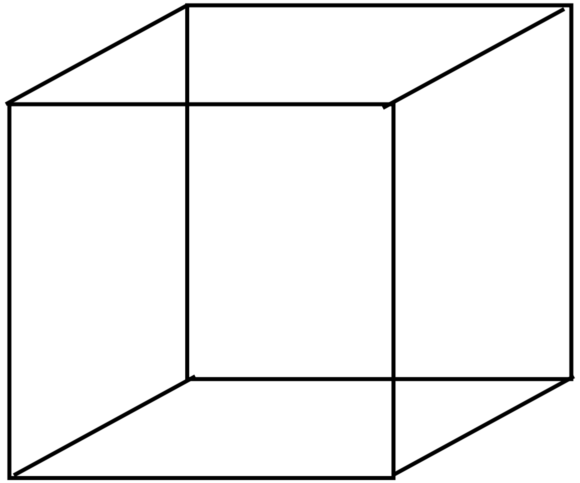
How can something be “in two positions at the same time”?

but



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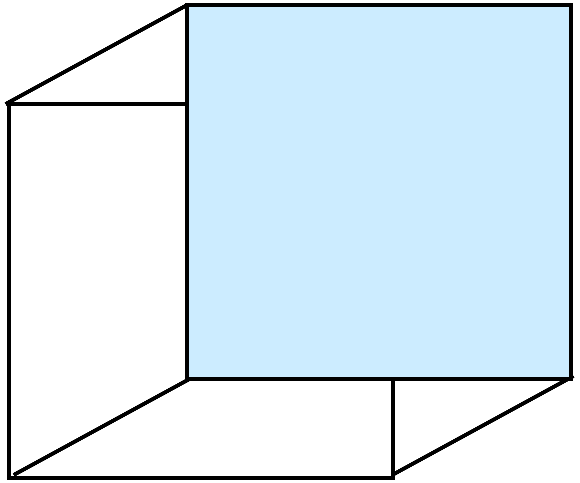

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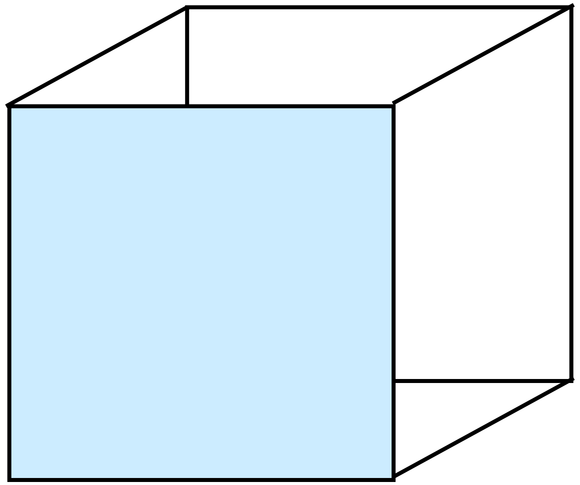

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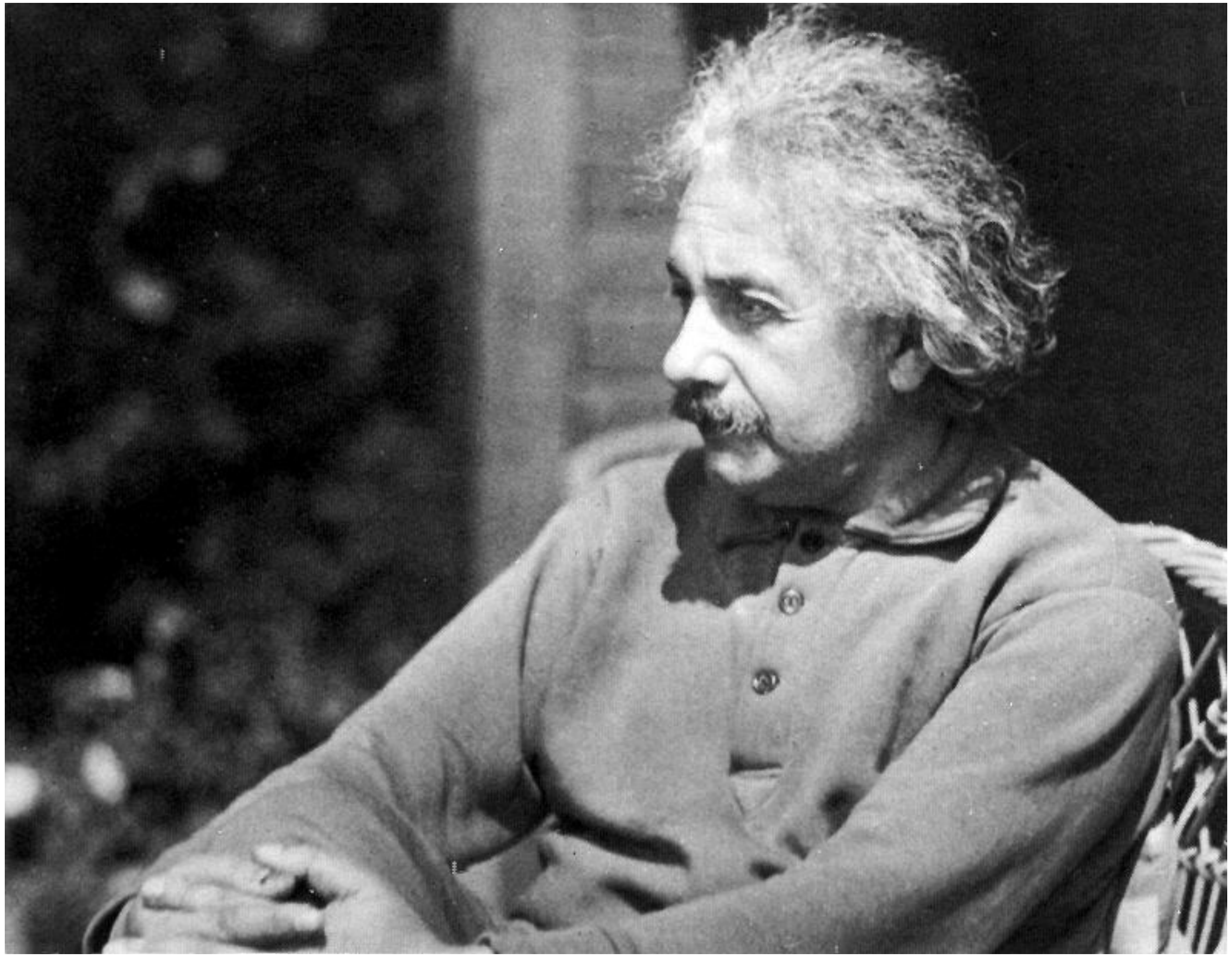
No classical analog for matter to superposition exists.

Two or more particles quantum weirdness



Einstein was not happy with the consequences of quantum mechanics

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)

EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

New York Times 4 Mayo 1935

Schroedinger reacted to the questions of Einstein with the term Entanglement.

A Probability Problem

LIBERTY
IN GOD WE TRUST
P
1985
UNITED STATES OF AMERICA
E PLURIBUS UNUM
QUARTER DOLLAR

If I flip a coin there is a 50% chance that it will come up heads and a 50% chance of tails

$p_1(H)=1/2$, $p_1(T)=1/2$. The sum is 1

If I take a second coin and toss it in the air, there is a 50% chance that it will come out heads and 50% tails:

$p_2(H)=1/2$, $p_2(T)=1/2$. The sum is1

If I toss the two coins in the air then
The results may be:

HH TT HT TH

Probabilities:

¼ ¼ ¼ ¼ Total sum 1

$$p_1(H)p_2(H)+p_1(T)p_2(T)+p_1(H)p_2(T)+p_1(T)p_2(H)=$$

$$(p_1(H)+p_1(T))\ (p_2(H)+p_2(T))$$

The result is factorizable into the probabilities of each coin.
Probability is the product of probabilities.

If the result were:

HH 50% TT 50%

$$p_1(H)p_2(H)+p_1(T)p_2(T)= 1$$

It would be weird, it is not factorizable but the sum gives 1
Missing cross-terms to factor probability
What would we think about the coins?

There is a strange correlation

We let them interact and then separate them a long way

The same results follow
It seems like there is something inside that we donot see that creates the correlation.

Think of two twins separated at birth.
They share the DNA of their chromosomes, they are highly correlated

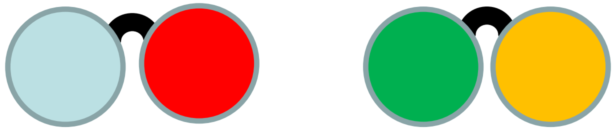
If the coins are separated, and I know they are highly correlated, as soon as I get H, I know that the other is also H.

I make one prediction based on measuring the other.
Einstein was bothered by that.

The result is random but highly correlated
The same thing happens with twins when we ask them certain questions about preferences and tastes, we donot know the answer but it will surely be the same in both.

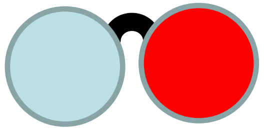
The coins are entangled.

Change the heads or tails to colors, use two different pairs separable with glasses.

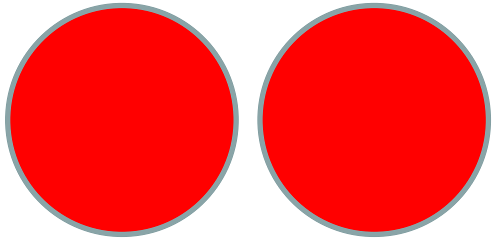


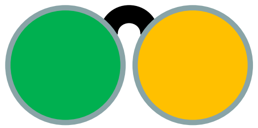
Blue and Red

Green and Orange

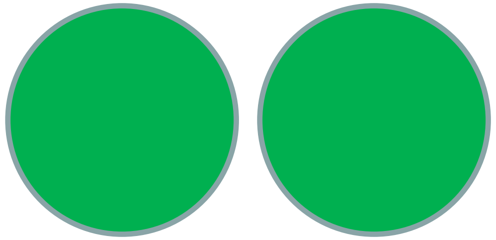


With the first pair of glasses
If I see red, the other is red.
If I change glasses
If I see the first one green, the second one is green





No matter the glasses, the correlation remains



Therein lies the objection of Einstein, red is red from the start. Not dependent on glasses used to observe them.
That does not happen with twins.

Is entanglement (two or more particles) a resource?

1964 John Bell:

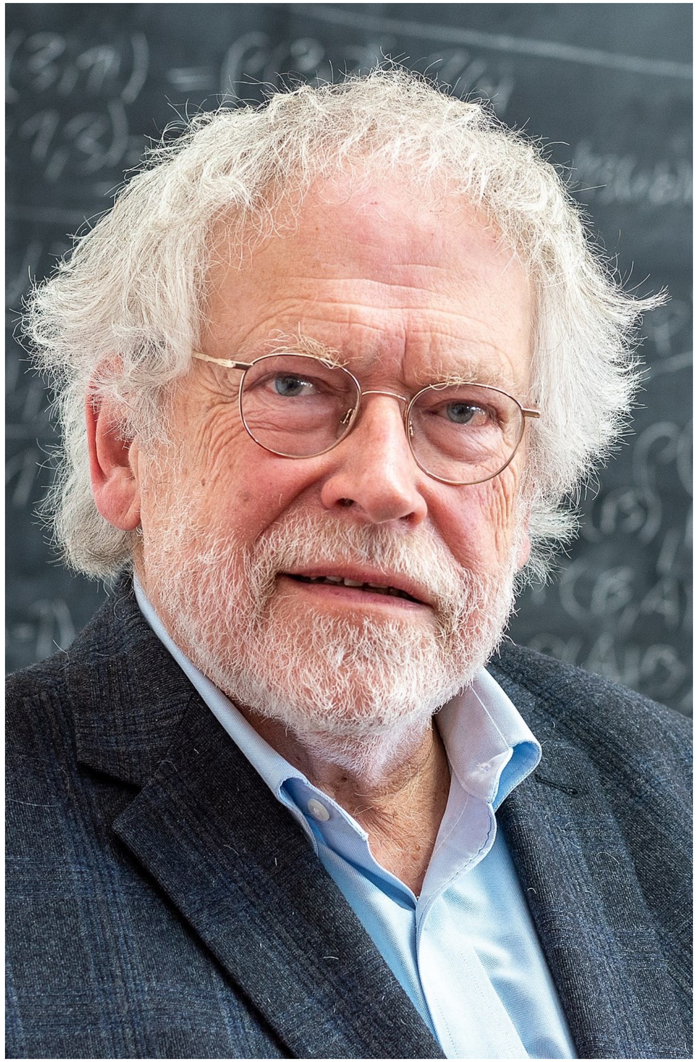
Is entanglement measurable?

It can be a resource!

John Clauser

Alain Aspect

Anton Zeilinger



2022 Nobel Prize in Physics

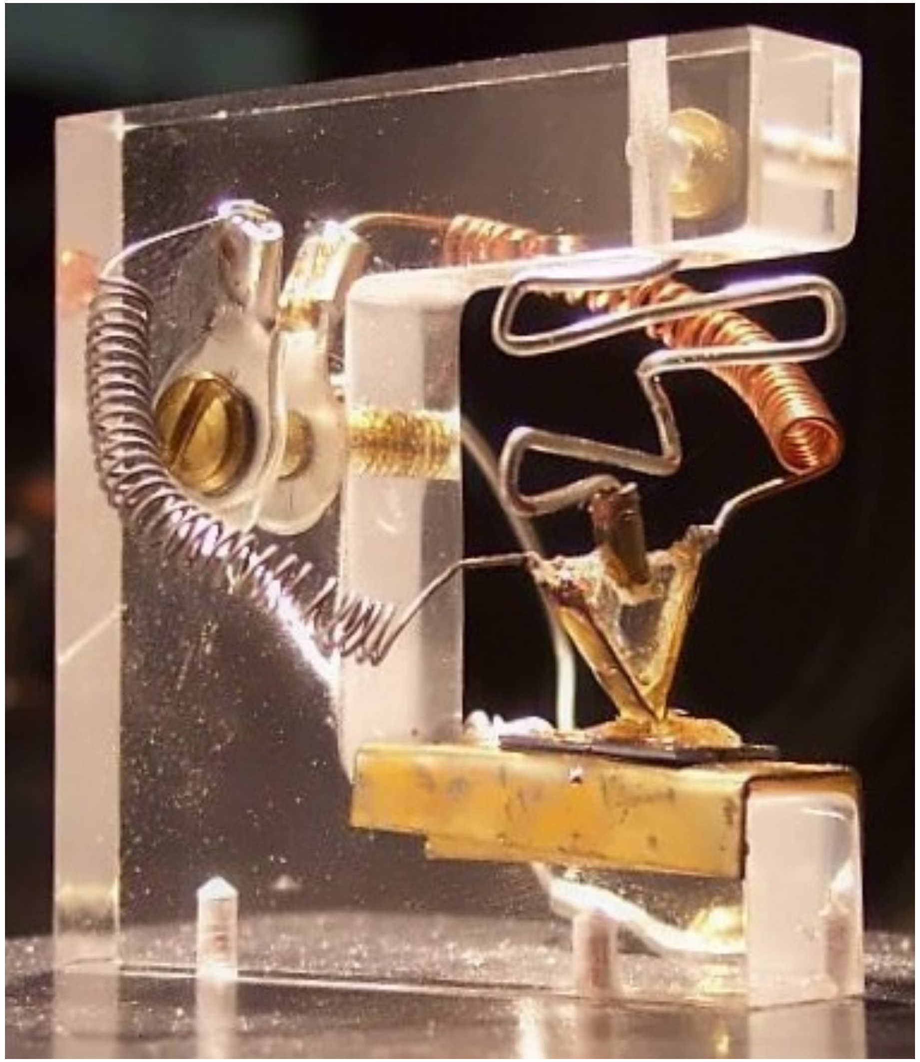
Quantum mechanics

- It is the language of microscopic nature.
- It follows a mathematical structure, Hilbert space.
- Predictions checked to more than twelve digits.
- It may not be able to describe everything and can have contradictions (it is a language).
- We do not know yet how to write the general theory of relativity with quantum mechanics.

Quantum mechanics is a language to describe our (incomplete) knowledge of nature, not of nature itself.

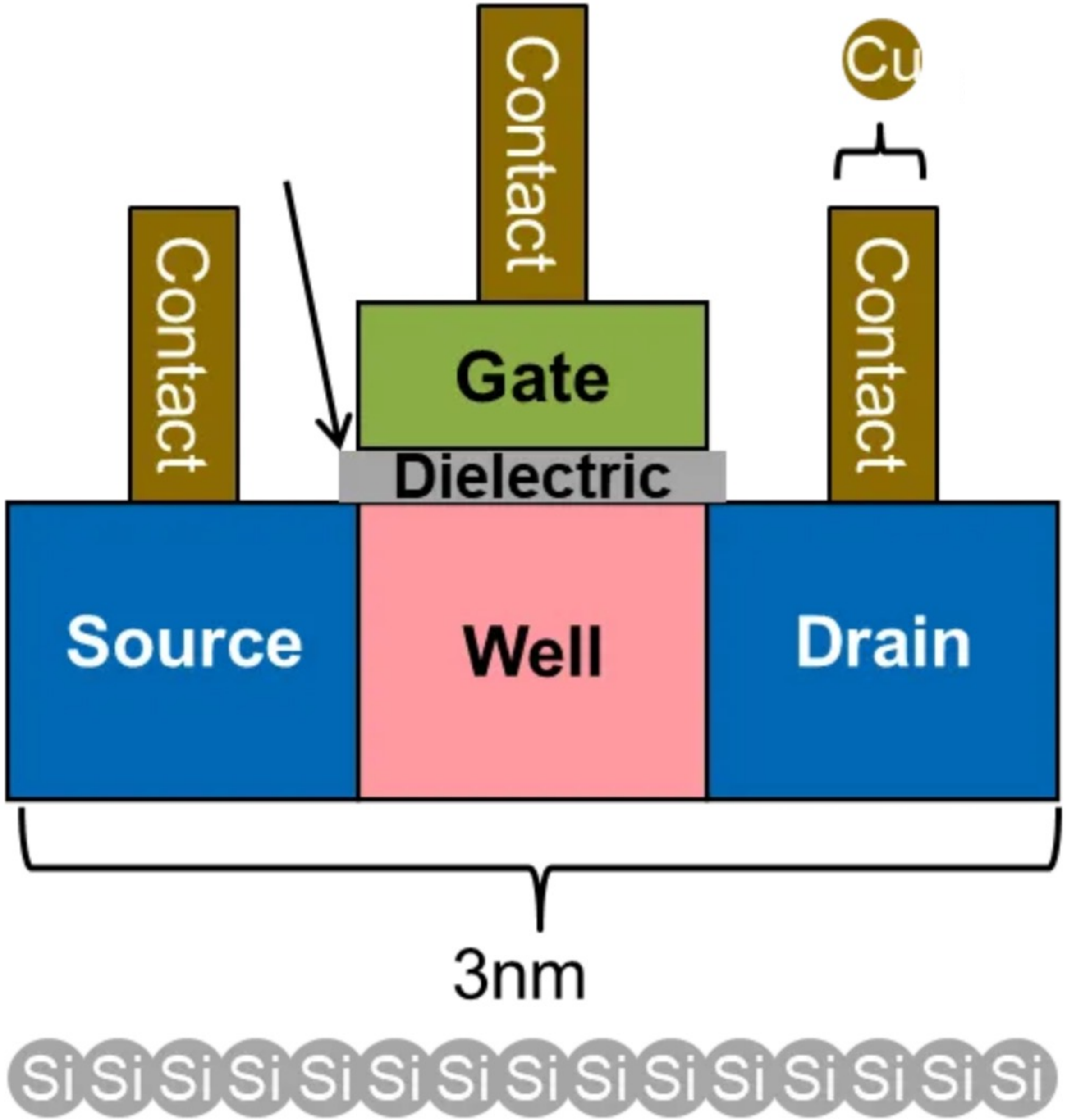
It is the best tool (language) we have to explain (predict) detections (outcomes) in the laboratory.

First quantum revolution



The first transitor

Superb understanding of chemistry and materials

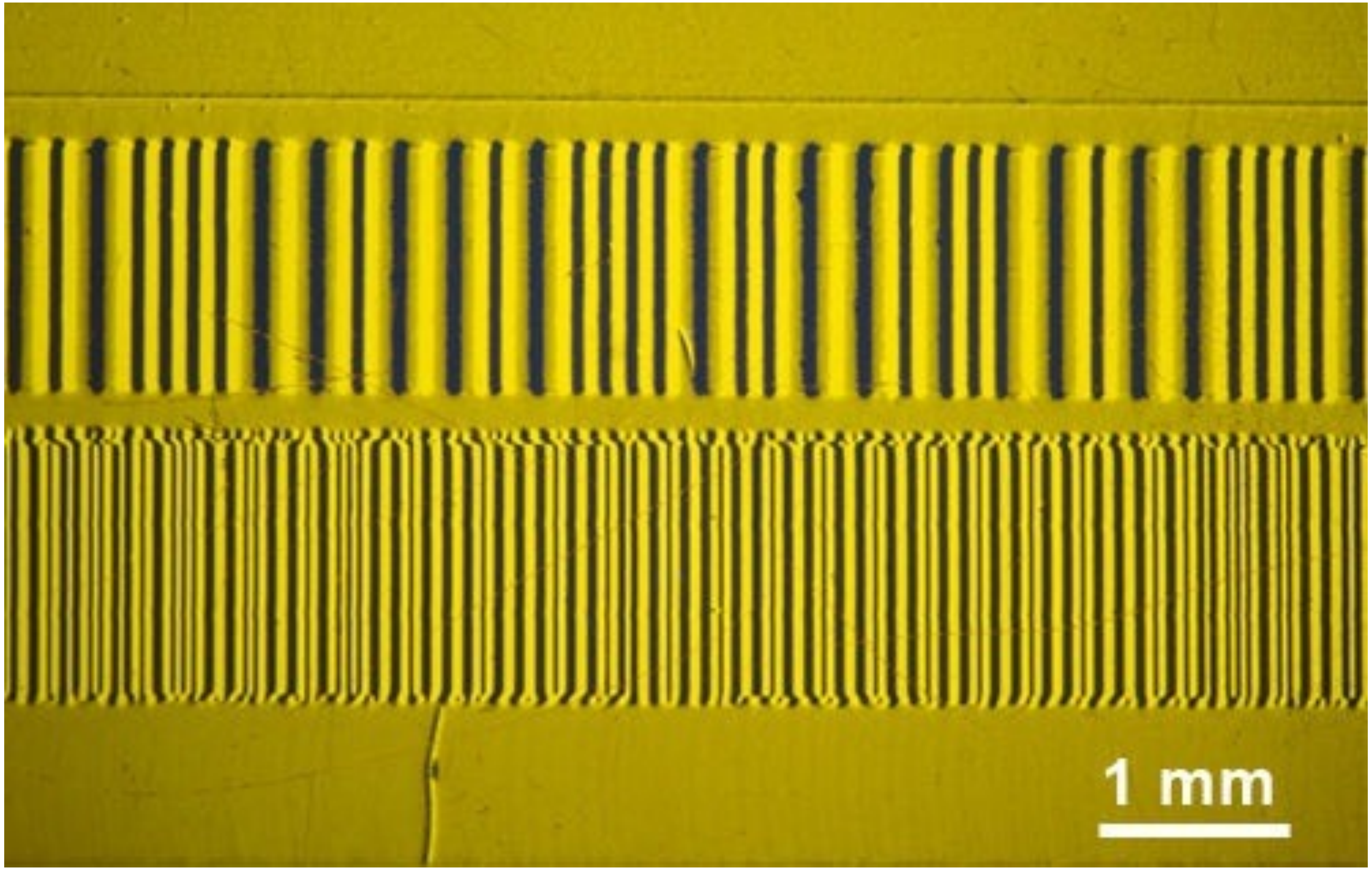


Single Particle Quantum Mechanics has made possible

- The transistor (1948)
- Microelectronics (~1950s)
- The laser (1960)
- Magnetic memories (~1960s)

Everything is made of parts,
even information

Codified information in 0 and 1



Information in physical

Second quantum revolution

Technological uses of entanglement and superposition:

QKD (Quantum Key Distribution)

Quantum Sensing

Quantum Simulation

Quantum Computing

…

QKD

Use entanglement to ensure security

⟨InfiniQuant⟩

agnostiq

IDQ

MagiQ

国盾量子
QuantumCTek

Quantum Sensors

Many companies around the world

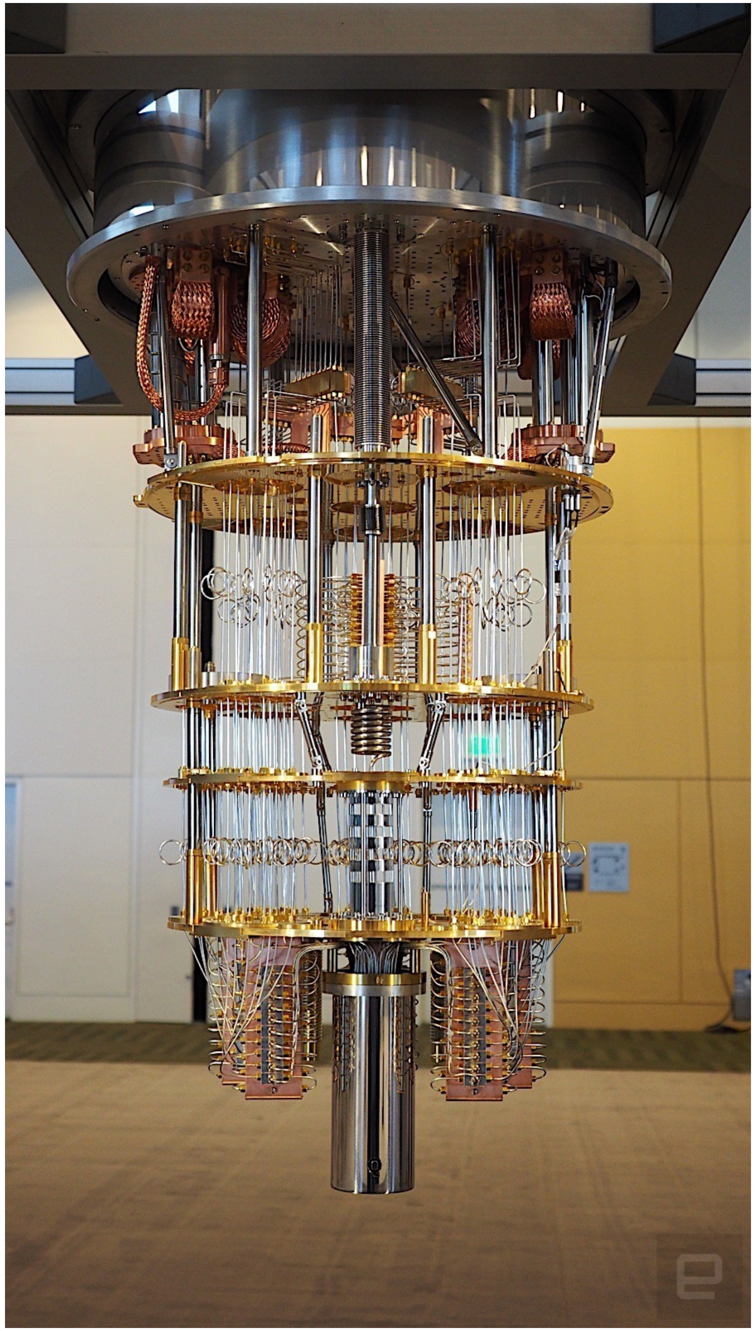
Atoms are very sensitive magnetometers, uses from medical, measuring the currents in the brain to microscopy.

Quantum Computer

IBM Quantum Experience (QX)

01 2018

50 Qubit



Development Roadmap

IBM **Quantum**

	2016–2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2033+
	Run quantum circuits on the IBM Quantum Platform	Release multi-dimensional roadmap publicly with initial aim focused on scaling	Enhancing quantum execution speed by 100x with Qiskit Runtime	Bring dynamic circuits to unlock more computations	Enhancing quantum execution speed by 5x with quantum serverless and Execution modes	Improving quantum circuit quality and speed to allow 5K gates with parametric circuits	Enhancing quantum execution speed and parallelization with partitioning and quantum modularity	Improving quantum circuit quality to allow 7.5K gates	Improving quantum circuit quality to allow 10K gates	Improving quantum circuit quality to allow 15K gates	Improving quantum circuit quality to allow 100M gates	Beyond 2033, quantum-centric supercomputers will include 1000's of logical qubits unlocking the full power of quantum computing
Data Scientist						Platform						
						Code assistant	Functions	Mapping Collection	Specific Libraries			General purpose QC libraries
Researchers					Middleware							
					Quantum Serverless	Transpiler Service	Resource Management	Circuit Knitting x P	Intelligent Orchestration			Circuit libraries
Quantum Physicist			Qiskit Runtime									
	IBM Quantum Experience		QASM3	Dynamic circuits	Execution Modes	Heron (5K) Error Mitigation 5k gates 133 qubits Classical modular 133x3 = 399 qubits	Flamingo (5K) Error Mitigation 5k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (7.5K) Error Mitigation 7.5k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (10K) Error Mitigation 10k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (15K) Error Mitigation 15k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Starling (100M) Error correction 100M gates 200 qubits Error corrected modularity	Blue Jay (1B) Error correction 1B gates 2000 qubits Error corrected modularity
	Early: Canary 5 qubits, Albatross 16 qubits, Penguin 20 qubits, Prototype 53 qubits	Falcon Benchmarking 27 qubits		Eagle Benchmarking 127 qubits								

Innovation Roadmap

	2016–2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2033+
Software Innovation	IBM Quantum Experience	Qiskit: Circuit and operator API with compilation to multiple targets	Application modules: Modules for domain specific application and algorithm workflows	Qiskit Runtime: Performance and abstract through Primitives	Serverless: Demonstrate concepts of quantum centric-supercomputing	AI enhanced quantum: Prototype demonstrations of AI enhanced circuit transpilation	Resource management: System partitioning to enable parallel execution	Scalable circuit knitting: Circuit partitioning with classical reconstruction at HPC scale	Error correction decoder: Demonstration of a quantum system with real-time error correction decoder			
Hardware Innovation	Early: Canary 5 qubits, Penguin 20 qubits, Albatross 16 qubits, Prototype 53 qubits	Falcon: Demonstrate scaling with I/O routing with Bump bonds	Hummingbird: Demonstrate scaling with multiplexing readout	Eagle: Demonstrate scaling with MLW and TSV	Osprey: Enabling scaling with high density signal delivery	Condor: Single system scaling and fridge capacity	Flamingo: Demonstrate scaling with modular connectors	Kookaburra: Demonstrate scaling with nonlocal c-coupler	Kookaburra: Demonstrate path to improved quality with logical memory	Cockatoo: Demonstrate path to improved quality with logical communication	Starling: Demonstrate path to improved quality with logical gates	
						Heron: Architecture based on tunable-couplers	Crossbill: m- coupler					

Executed by IBM

On target

Quantum Error correction is necessary

Uses entanglement thoroughly.
Recent demonstration with programable atomic arrays by the group of Misha Lukin at Harvard.

- IBM offers cloud-based quantum computing services.
- Google Quantum AI focuses on integrating quantum computing with machine learning.
- Microsoft develops quantum software and hardware.
- AWS (Amazon Braket) provides a platform for accessing various quantum computers through the cloud.
- Alibaba Group has established a quantum computing laboratory.
- Atos Quantum (EVIDEN) offers the Quantum Learning Machine.
- Baidu runs the Baidu Quantum Computing Institute, developing quantum computing software and hardware.
- Intel, known for semiconductor expertise, is working on ‘hot’ silicon spin-qubits and other quantum technologies.

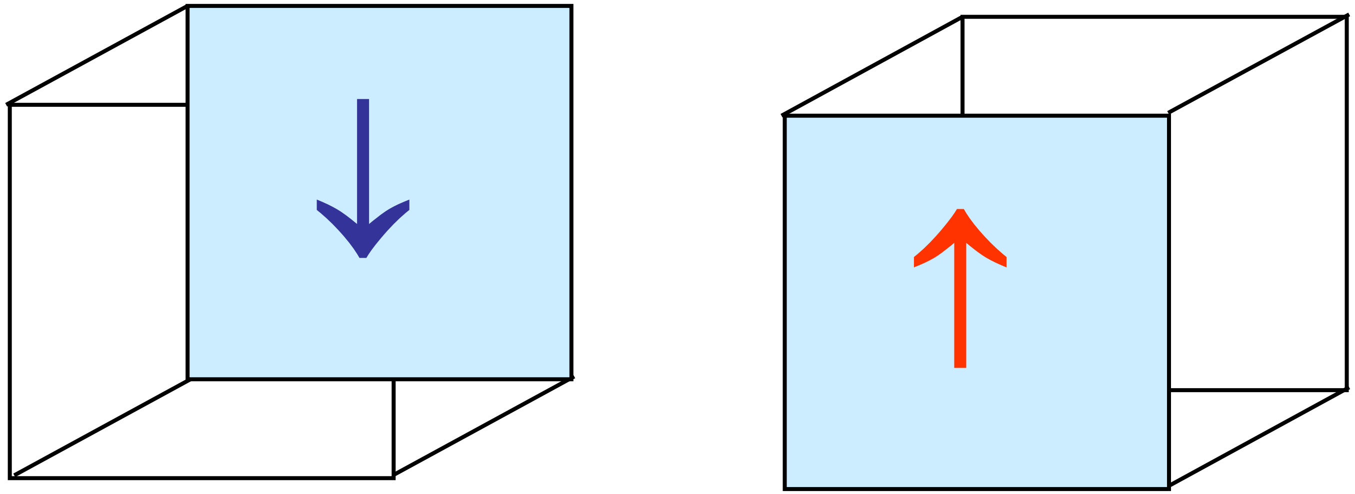
The Second Quantum Revolution is here

THANK YOU

Classical bits vs quantum bits

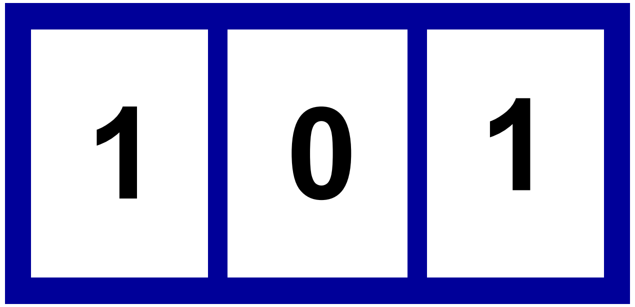
Classical bit: 0 <u>or</u> 1; ↓ <u>or</u> ↑

Quantum bit (qubit) is in a superposition:



$$|\psi\rangle_{qubit} = |\downarrow\rangle + |\uparrow\rangle$$

Classical: a 3-bit register can store one number from 0 to 7



one N-bit number

Quantum: a register of 3 entangled qubits can store numbers in superposition:

$$a|000\rangle + b|001\rangle + c|010\rangle + d|011\rangle + e|100\rangle + f|101\rangle + g|110\rangle + h|111\rangle$$

2^N (all possible) N-bit numbers

Summary of quantum mechanics:

- Describe probabilities.
- The uncertainty principle: two properties (position and velocity) can not be known simultaneously with arbitrary precision, there is always intrinsic noise.

- Superposition - systems can be in two (or more) states at the same time

- There are strong correlations: entanglement

- Wave-particle duality

- The result of a measurement changes the knowledge of the state of a system.

- Nature answers the questions we ask

Quantum Information

From imaginary experiments
by Niels Bohr

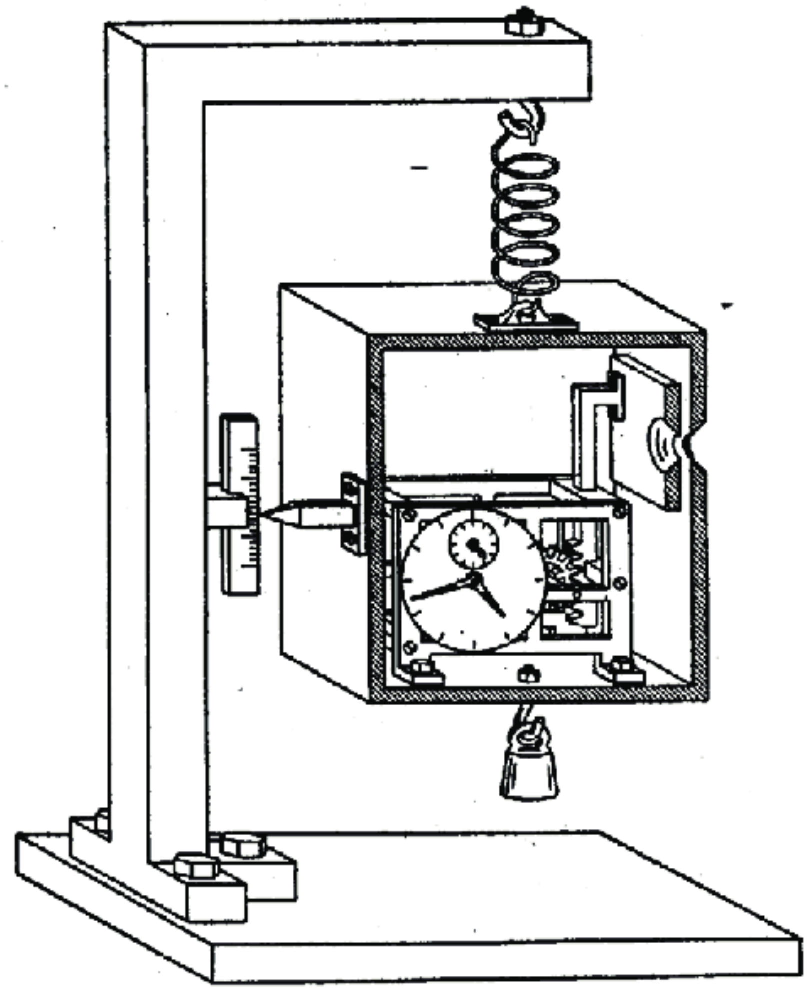
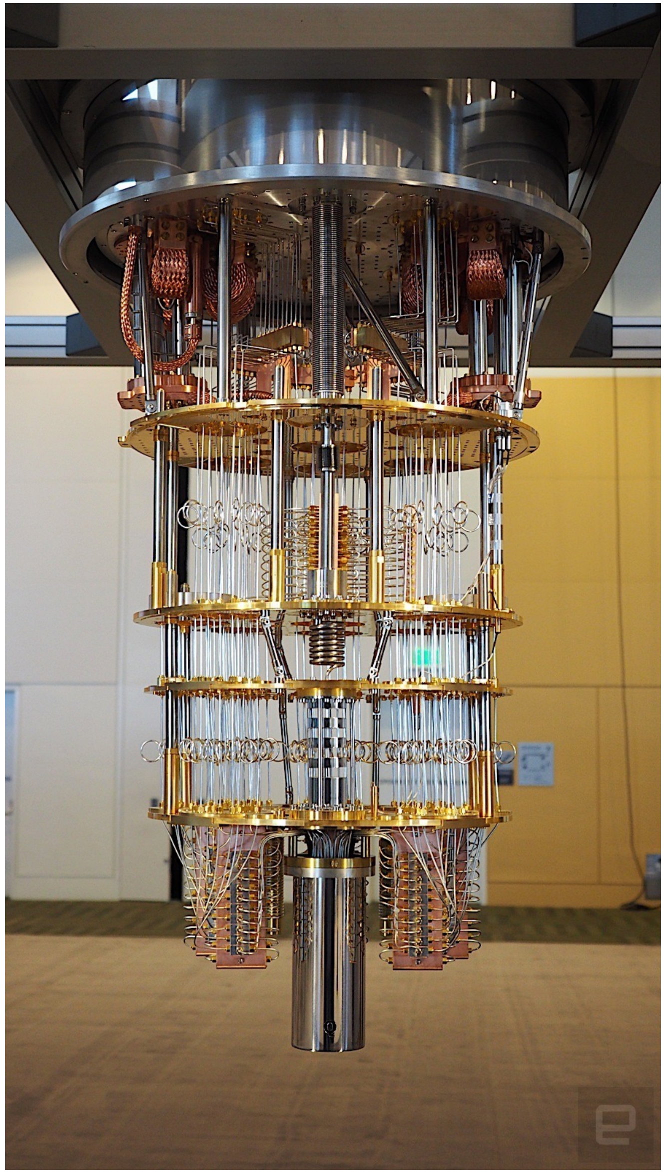
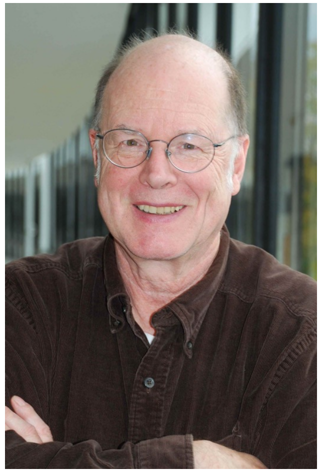


FIG. 8

To quantum information by IBM





Bennett
(1982)

Landauer
(1961)

Benioff
(1982)

Reversible computing (thermodynamics)

Quantum simulations

Feynman
(1982)

Quantum Information

Model of a universal quantum circuit

Deutsch
(1985)