THE ART OF QUANTUM
2nd QUANTUM REVOLUTION

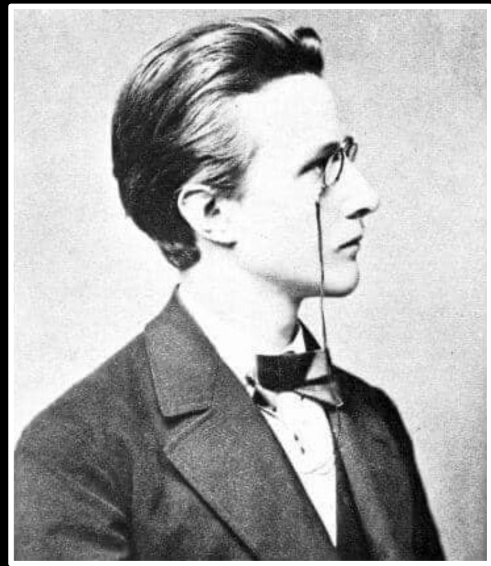
Vienna, 10.09.2025

Vladimír Bůžek

100 YEARS OF QUANTUM PHYSICS

The International Year of Quantum Science and Technology

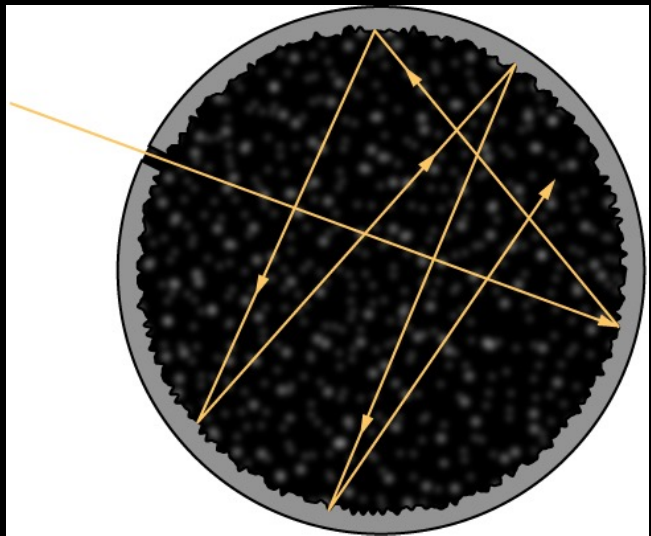
Here, the story starts (1878)

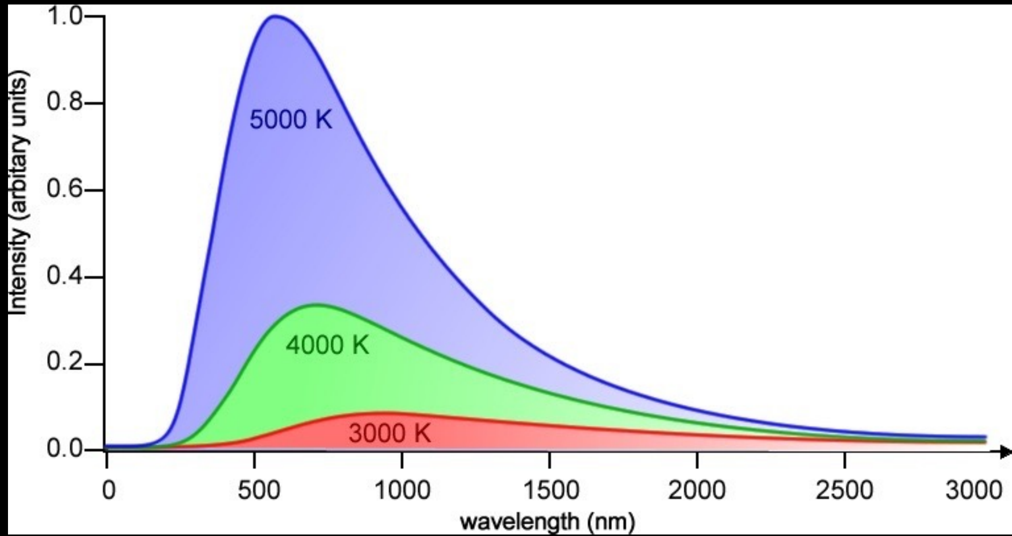


In physics, almost everything is already discovered, and all that remains is to fill a few unimportant holes.

Planck, Max (1933). Wege zur Physikalischen Erkenntnis: Reden und Vortr¨age. Leipzig: Verlag von S. Hirzel.

Black body radiation
(ultraviolet catastrophy)

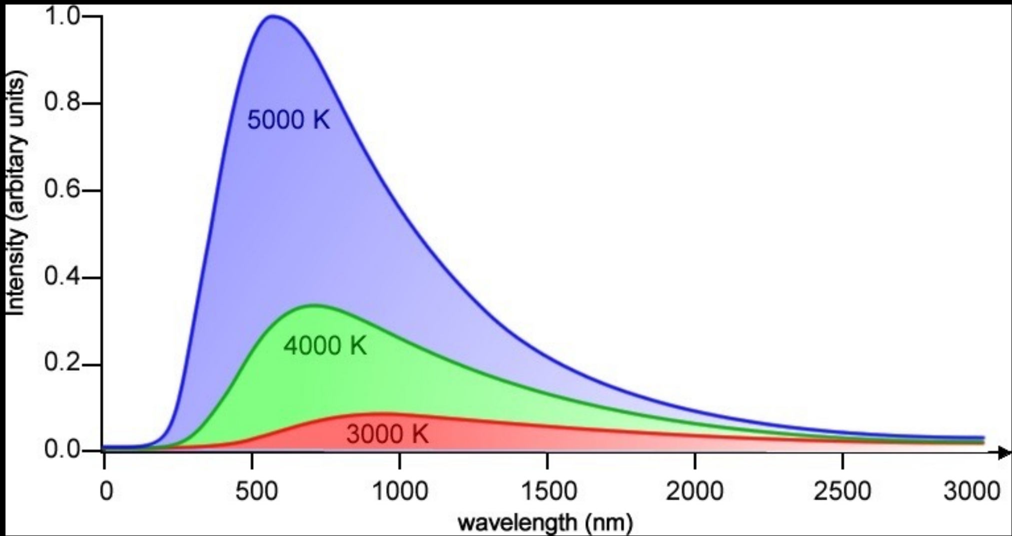




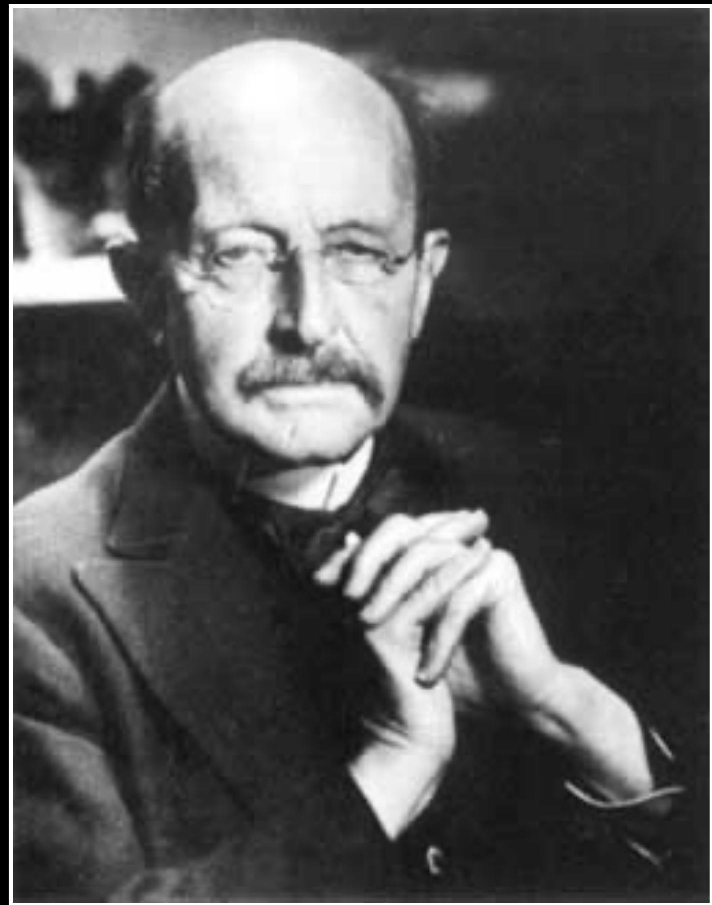
Rayleigh-Jeans

$$B_\lambda(T) = \frac{2ck_{\mathrm{B}}T}{\lambda^4}$$

Max Planck: “Act of desperation“



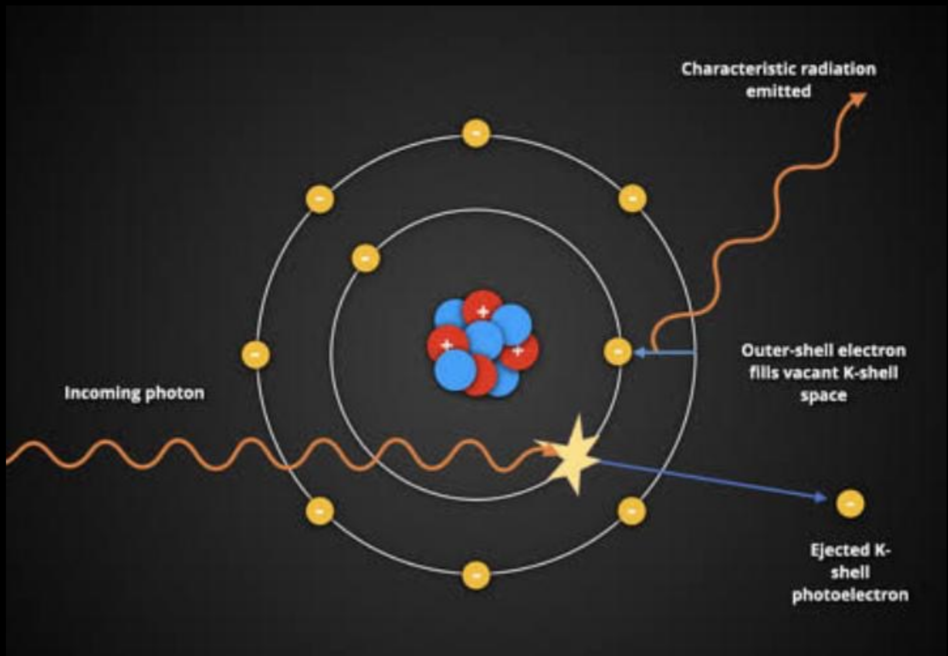
$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/(\lambda k_\mathrm{B} T)} - 1}$$

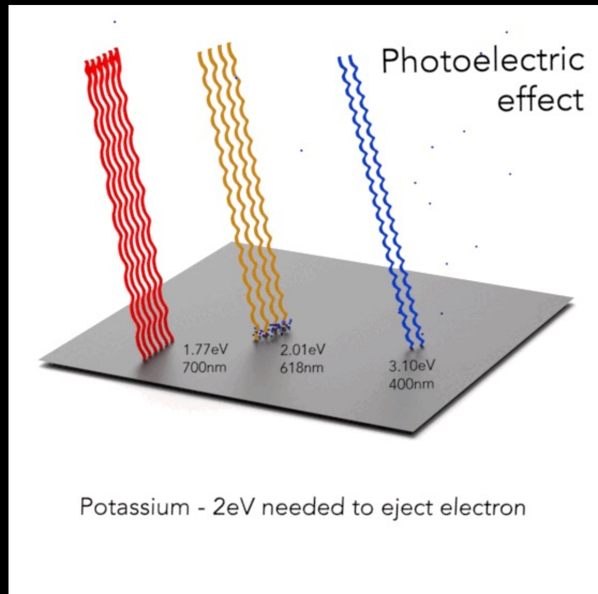


M.Planck 1900

$\hbar$

Photoelectric effect (1905)





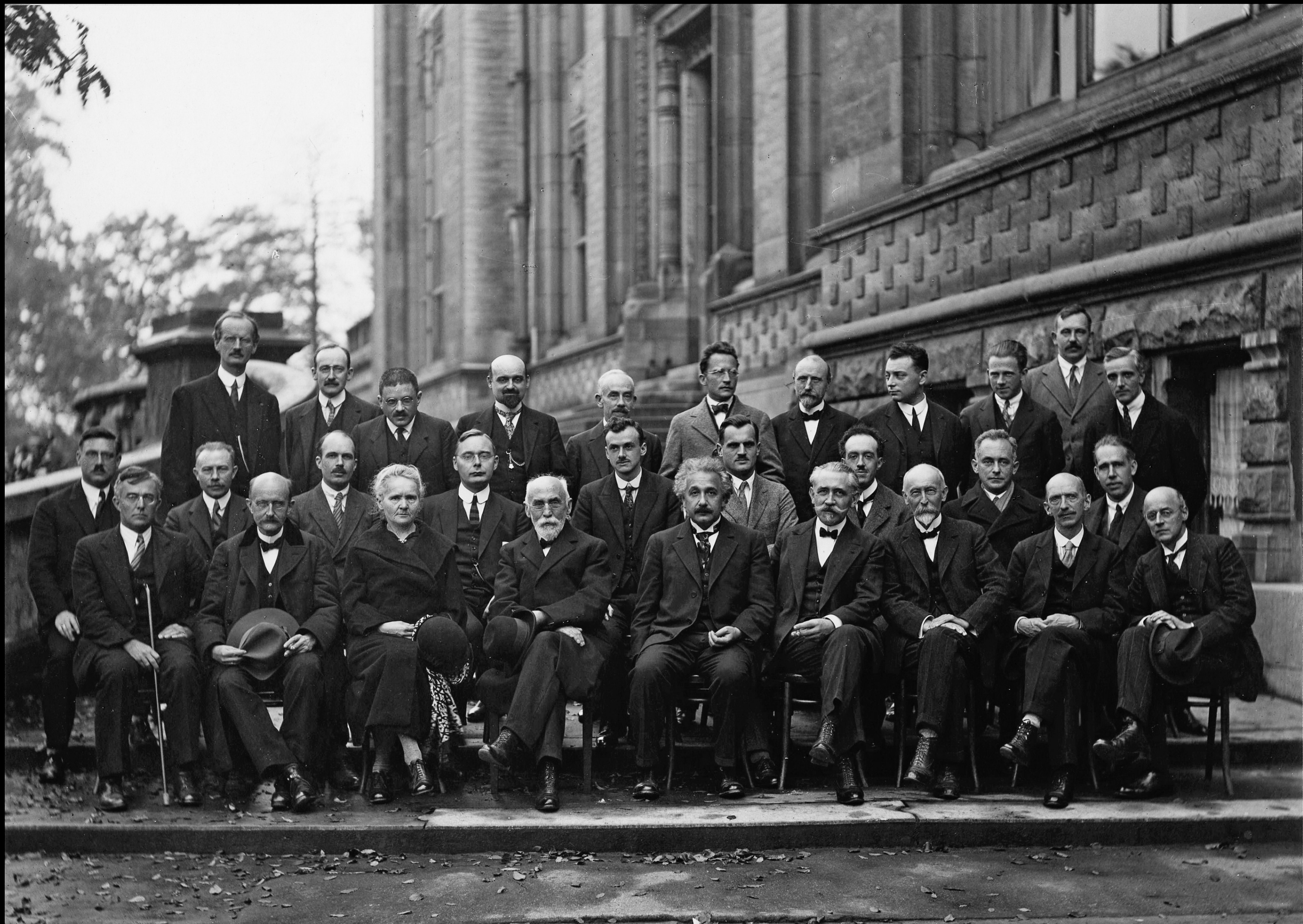
1st QUANTUM REVOLUTION

1925/1926 birth of q-mechanics



- **1925 Werner Heisenberg:** matrix mechanics
- **1926 Erwin Schrödinger:** wave mechanics
- **1926-27 Paul M. Dirac:** unification of matrix and wave mechanics

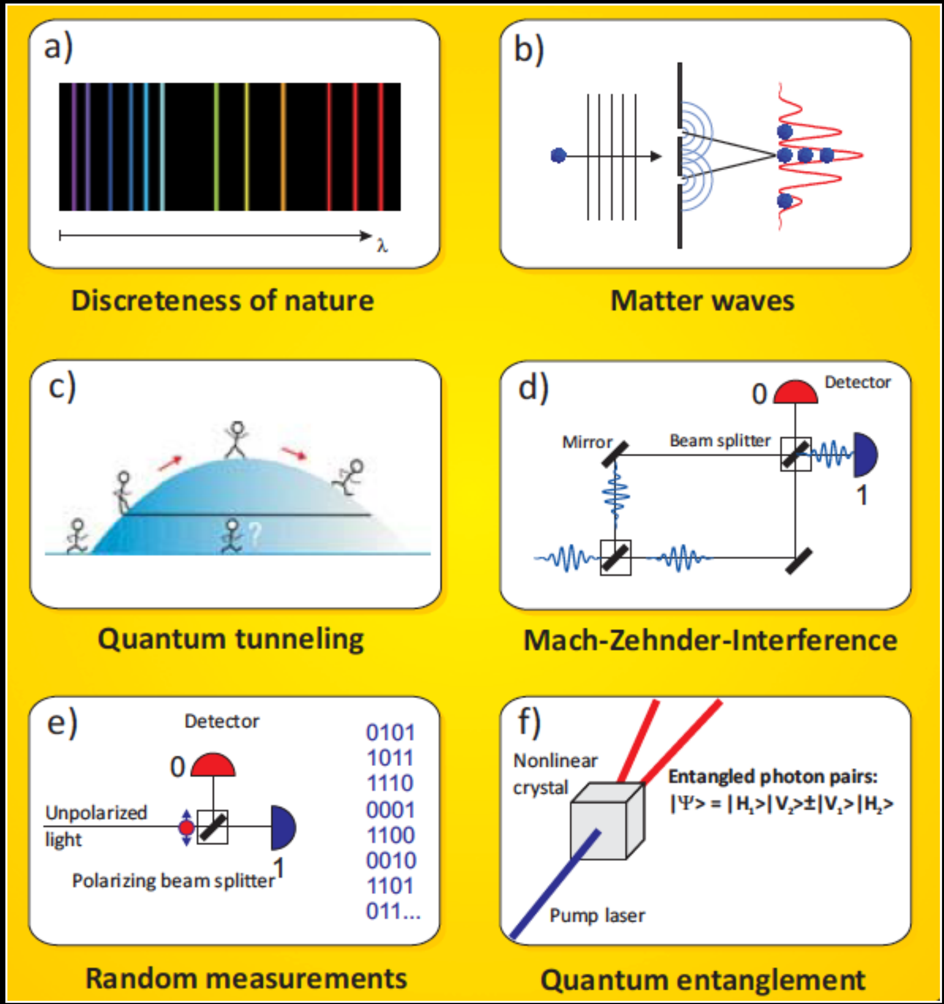
Solvay conference 1927



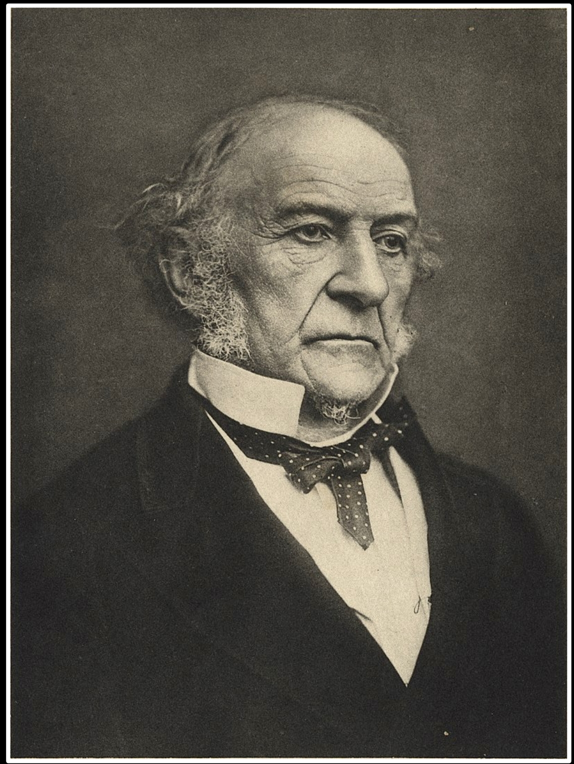
The essence of Q-theory

- **Quantization of energy:** Energy and other properties come in discrete chunks (quanta), not continuous values. Example: Atoms have fixed energy levels, which explains atomic spectra, LEDs, and lasers.
- **Uncertainty principle:** Some properties (like position and momentum) cannot be simultaneously known with arbitrary precision. This is not a limitation of measurement but a fundamental feature of reality.
- **Wave–particle duality:** Light and matter are not strictly “particles” or “waves” — they behave as both, depending on how you look. Example: Electrons make interference patterns like waves, but hit a screen as single particles.

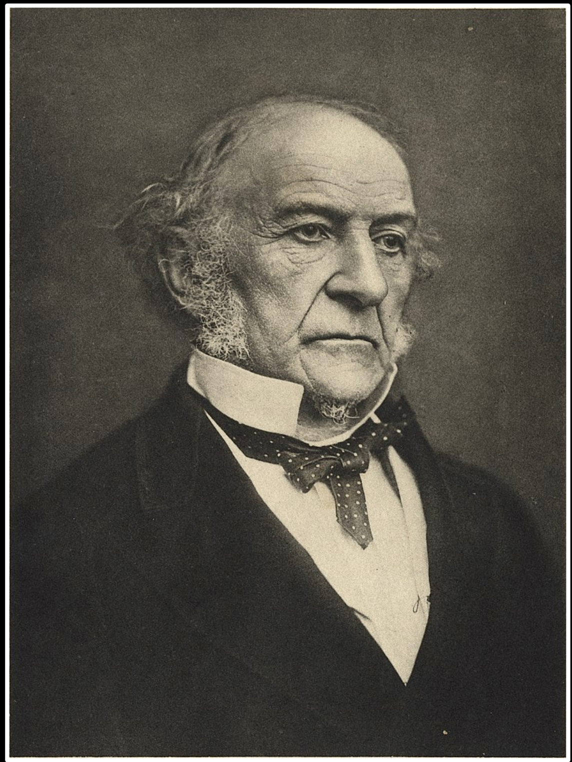
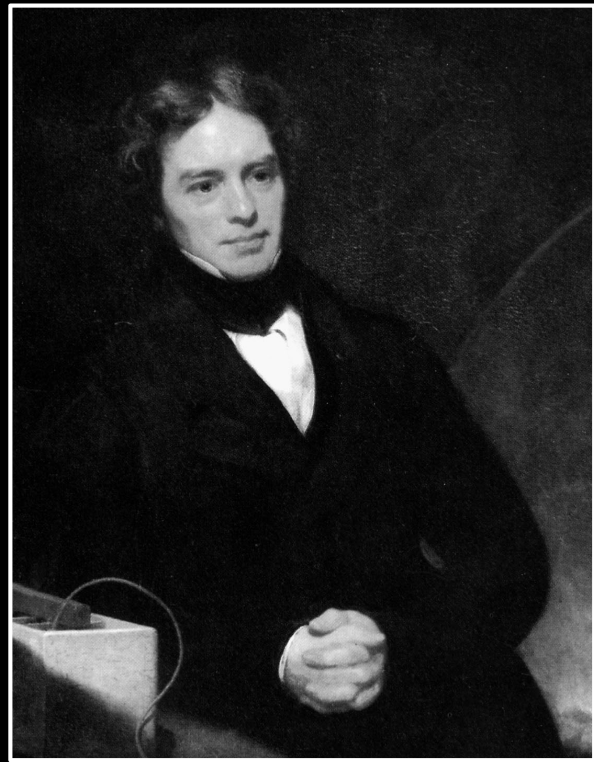
Quantum effects



USEFULNESS OF USELESS



William Gladstone: „*What is the practical value of electricity?*“

William Gladstone: *„What is the practical value of electricity?“*

Michael Faraday: *„I do not know, but I am sure one day, sir, you may tax it.“*

Quantum ...

What has quantum mechanics ever done for us!

Everyday Technologies

- **Semiconductors / Transistors / Microchips:** The foundation of all computers, smartphones, and digital electronics; quantum mechanics of electrons explains their operation in solids.
- **LEDs & OLEDs** used in screens, lighting, and displays rely on quantum transitions in semiconductors.
- **Lasers:** Barcode scanners, DVD/Blu-ray players, laser printers, fiber optics, industrial cutting tools.
- **Solar Cells (Photovoltaics):** Convert sunlight into electricity through the quantum photoelectric effect.

Medical & Scientific Tools

- **Electron microscopes:** Exploit the wave nature of electrons to resolve atoms and nanostructures.
- **PET & SPECT scanners:** Use quantum processes like positron annihilation and gamma photon detection.
- **Magnetic Resonance Imaging** The transition used for atomic clocks is a "hyperfine" transition, which comes from a small energy shift depending on how the spin of an electron is oriented relative to the spin of the nucleus of the atom. Those spins are an intrinsic quantum phenomenon. The MRI works by flipping the spins in the nuclei of hydrogen atoms. A clever arrangement of magnetic fields allows us to measure the concentration of hydrogen appearing in different parts of the body.

Communication & Navigation

- **Lasers and Telecommunications: P**hysics of the laser is contained in a 1917 paper Einstein wrote on the statistics of photons and their interaction with atoms. This introduces the idea of stimulated emission.
- **Atomic Clocks and GPS:** The GPS trilateration relies on the constant speed of light to convert time to distance. The timing accuracy of the satellite signals needs to be really good, so each satellite in the GPS constellation contains an ensemble of atomic clocks - the "ticking" of the clock is the oscillation of microwaves driving a transition between two particular quantum states in a cesium atom (or rubidium, in some of the clocks).

Quantum-related Nobel Prizes

Early Foundations of Q-Physics

- **1901 – Wilhelm Röntgen:** Discovery of X-rays (later explained with quantum theory).
- **1905 – Philipp Lenard:** Work on cathode rays → connected to the photoelectric effect.
- **1918 – Max Planck:** For discovering energy quanta (foundation of quantum theory).
- **1921 – Albert Einstein:** Photoelectric effect, a direct quantum phenomenon.
- **1929 – Louis de Broglie:** Discovery of matter waves (wave-particle duality)

Development of Q-Mechanics

- **1932 – Werner Heisenberg:** Creation of quantum mechanics (matrix mechanics).
- **1933 – Erwin Schrödinger, Paul Dirac:** Wave mechanics & relativistic quantum theory.
- **1945 – Wolfgang Pauli:** Exclusion principle, explaining quantum structure of matter.

Quantum in Matter & Materials

- **1956 – William Shockley, John Bardeen, Walter Brattain:** Transistor effect, based on quantum semiconductors.
- **1972 – John Bardeen, Leon Cooper, John Schrieffer:** Theory of superconductivity (BCS theory).
- **1986 – Ernst Ruska:** Electron microscope (relies on quantum wave properties of electrons).
- **1987 – J. Georg Bednorz, K. Alex Müller:** Discovery of high-temperature superconductors.

Q-Optics & Precision Measurement

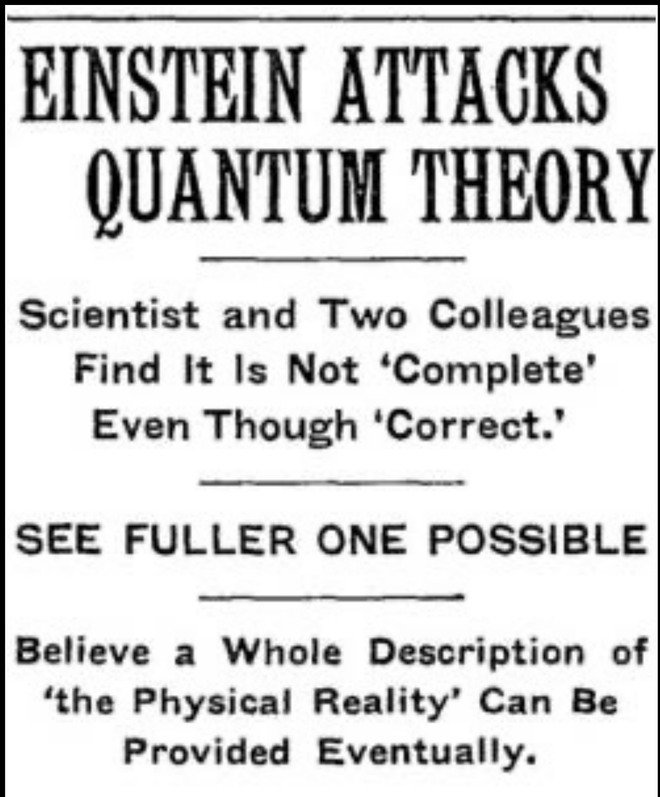
- **1964 – Nicolay Basov, Aleksandr Prokhorov, Charles Townes:** Development of masers/lasers.
- **1997 – Steven Chu, Claude Cohen-Tannoudji, William D. Phillips:** Laser cooling & trapping of atoms.
- **2001 – Eric Cornell, Wolfgang Ketterle, Carl Wieman:** Bose–Einstein condensates.
- **2005 – Roy Glauber, John Hall, Theodor Hänsch:** Quantum optics and precision laser spectroscopy.

But the problems remain.

(Einstein-Podolsky-Rosen)

QUANTUM ENTANGLEMENT

"spooky action at distance"



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.

Can Quantum-Mechanical Description of Physical Reality be Considered Complete?
A.Einstein, B. Podolsky, N Rosen:
Physical Review. 47 (10): 777–780 (1935)

THREE PILLARS OF QUANTUM

- **Quantum superposition principle**
- **Quantum measurements**
- **Quantum correlations – quantum entanglement**

CLASSICAL BIT

0

either / or

1

QUANTUM SUPERPOSITION

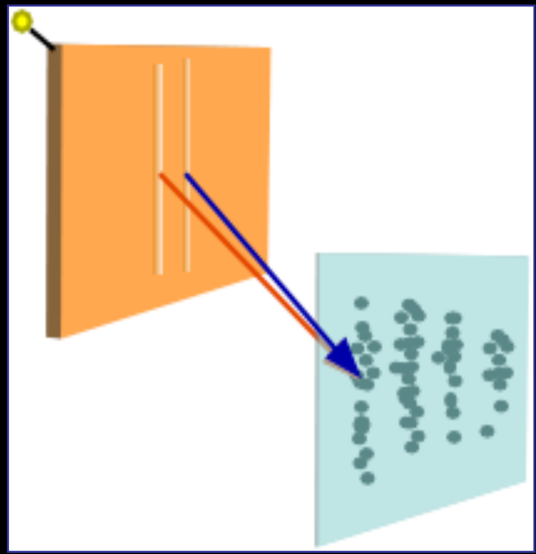
QUBIT

0

simultaneously

1

Quantum superpositions



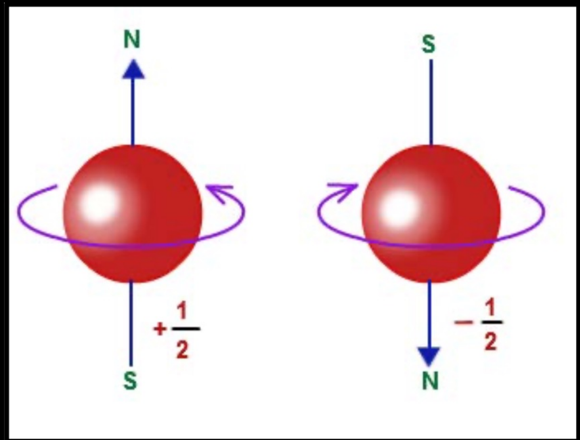
"The double-slit experiment has in it the heart of quantum mechanics. In reality, it contains the only mystery."

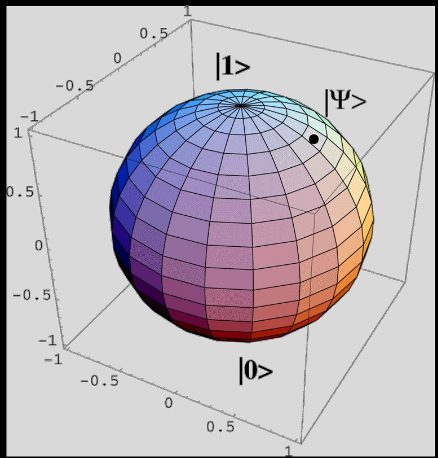
Richard Feynman

Quantum superposition: Bit vs Qubit

Pure state of a spin -1/2 particle

$$|\psi\rangle = \cos(\vartheta/2)\,|1\rangle + e^{i\varphi}\sin(\vartheta/2)\,|0\rangle$$





State space – Poincaré sphere

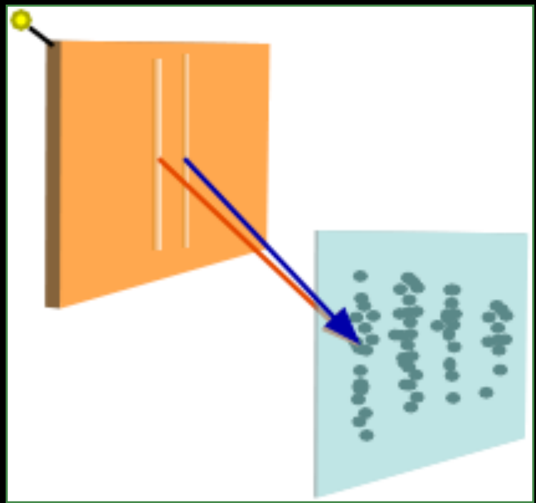
QUANTUM MEASUREMENTS

- **Outcome of a measurement performed on a quantum system can only be predicted statistically – with some probability.**
- **Quantum world at a level of classical description is random.**
- **By performing a measurement on a single qubit we obtain a result either "0" or "1", but we can't predict it with certainty.**
- **Information gain *vs* disturbance. Measured quantum system collapses into the state that is registered on the measurement device.**
- ***Properties that were determined by quantum measurements did not exist before the measurements were performed.***

Chris Fuchs

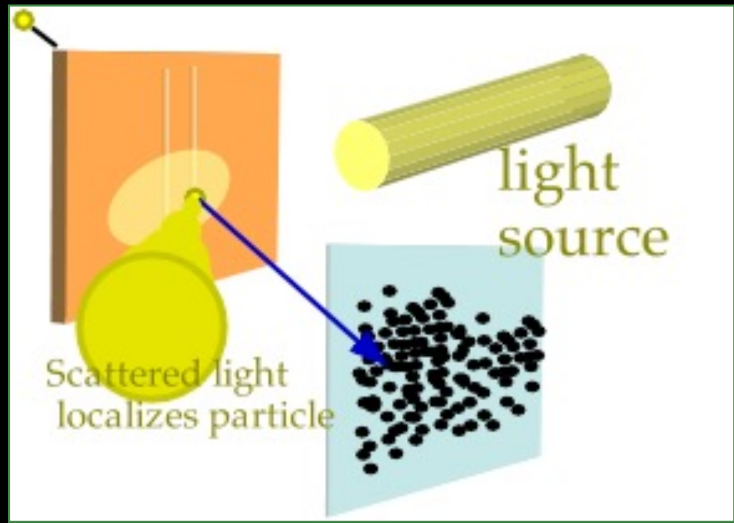
Quantum interference & dualism

wave



Q-superposition of states

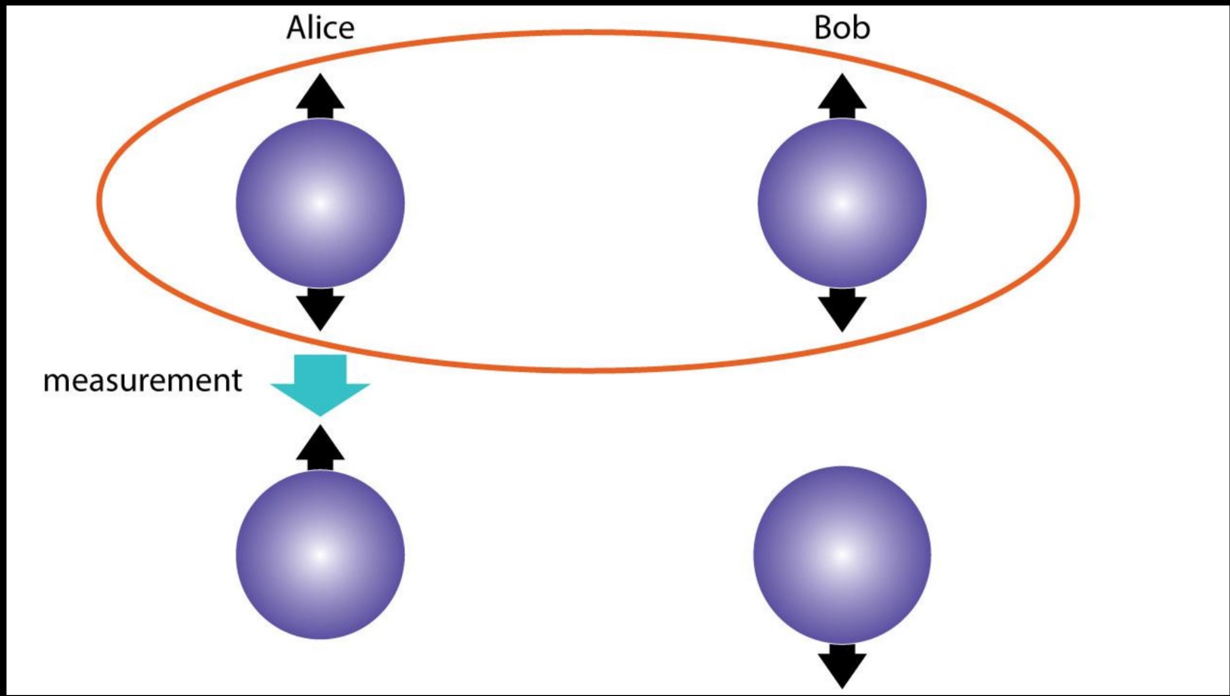
particle



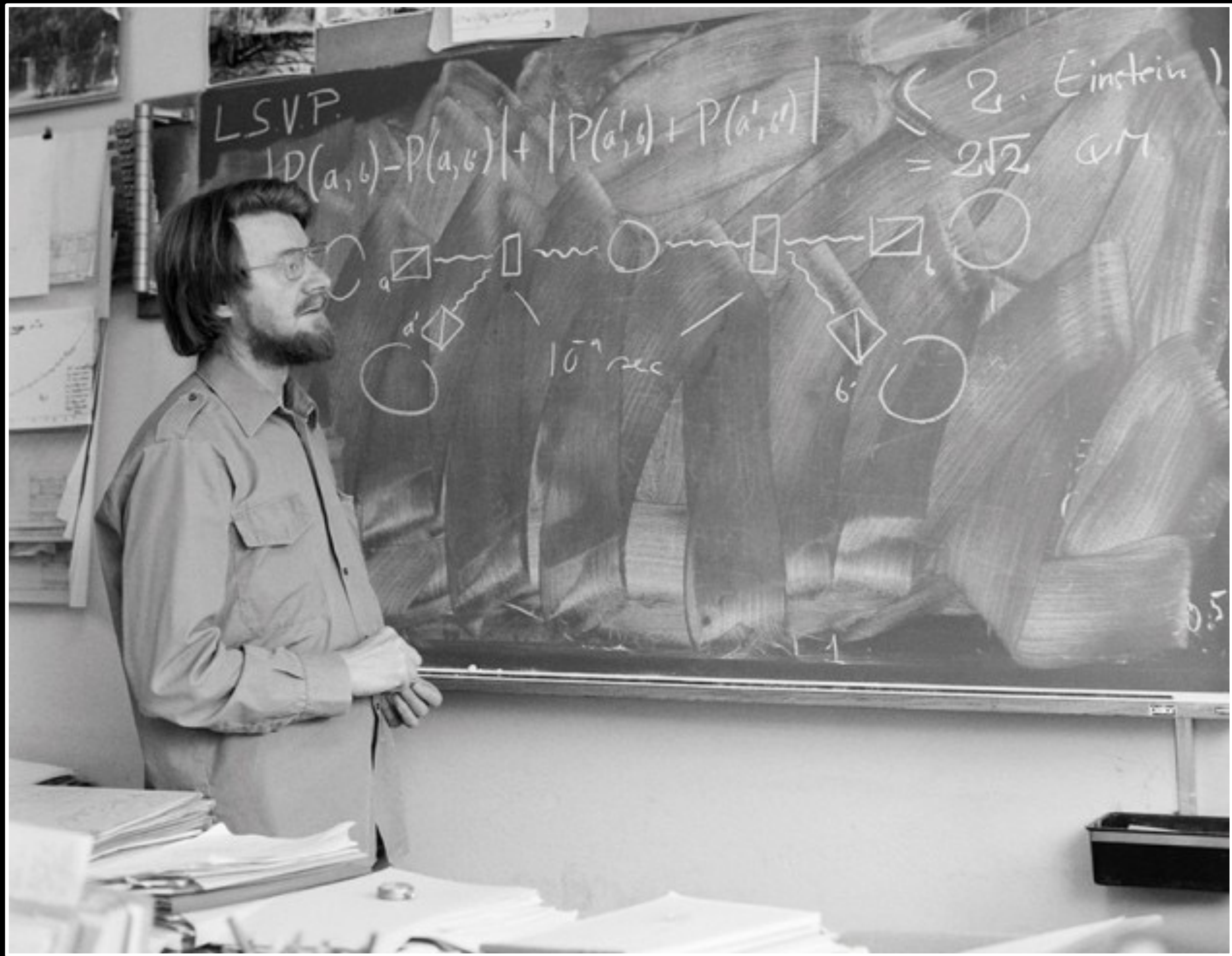
Quantum entanglement

Quantum objects sometime behave like waves, sometime like particles. Their „behaviour" depends on how we measure them.

QUANTUM ENTANGLEMENT



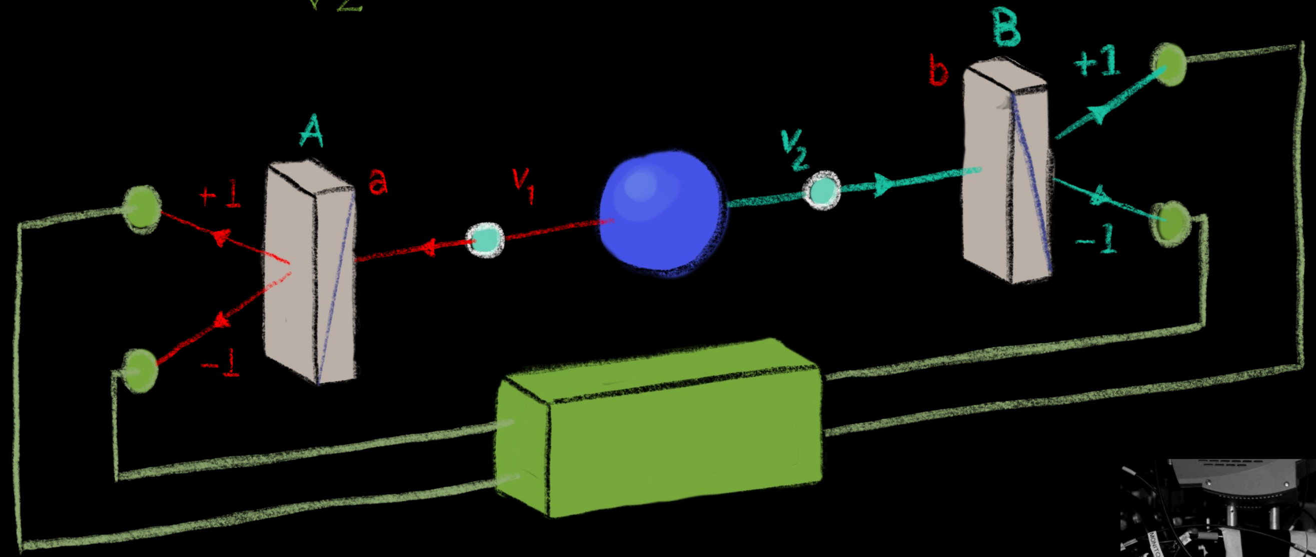
BELL INEQUALITIES

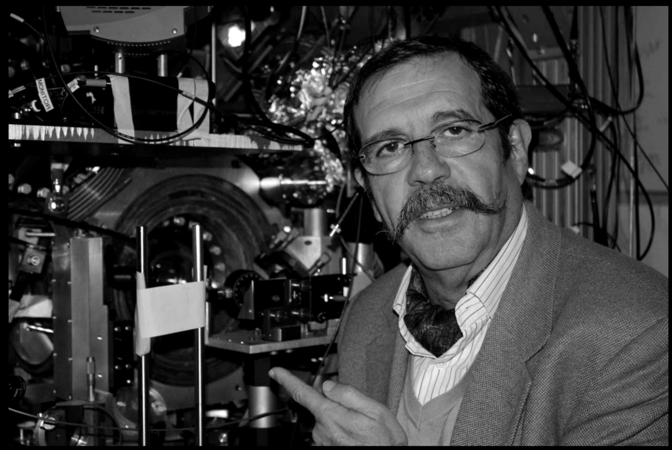


On the Einstein-Podolsky-Rosen paradox
John S Bell
Physics Physique Fizika 1 (3), 195 (1964)

ASPECT'S EXPERIMENT

$$|\Psi(\nu_1, \nu_2)\rangle = \frac{1}{\sqrt{2}} \{|x, x\rangle + |y, y\rangle\}$$





https://physics.aps.org/articles/v8/123

"If you think you understand quantum mechanics, you don't understand quantum mechanics."

Richard Feynman

2nd QUANTUM REVOLUTION

MANIPULATIONS WITH INDIVIDUAL Q-SYSTEMS

In the first place it is fair to state that we are not experimenting with single particles, any more than we can raise Ichthyosauria in the zoo. We are scrutinizing records of events long after they have happened."

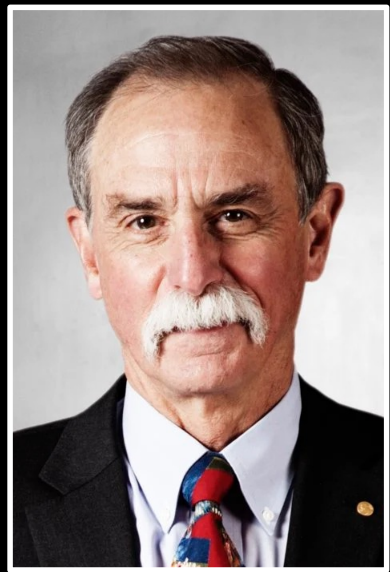
E. Schrödinger, 1952

We are all agreed that your theory is crazy. The question that divides us is whether it is crazy enough to have a chance of being correct.

Niels Bohr

Nobel Prize in Physics 2012

Serge Haroche



David Wineland

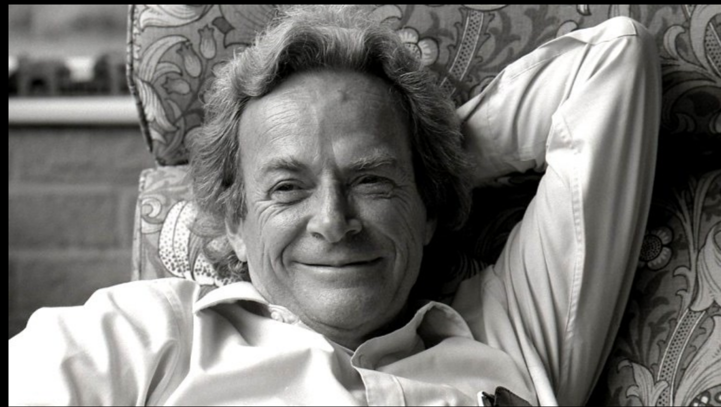
The Nobel Prize in Physics 2012 was awarded jointly to Serge Haroche and David J. Wineland "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

Tomorrow's computer, yesterday

Simson Garfinkel, MIT Technology Review, April 19 2021

Quantum computers? 1981

“...trying to find a computer simulation of physics, seems to me to be an excellent program to follow out...and I'm not happy with all the analyses that go with just the classical theory, because nature isn’t classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look so easy.”



Richard Feyn***man***

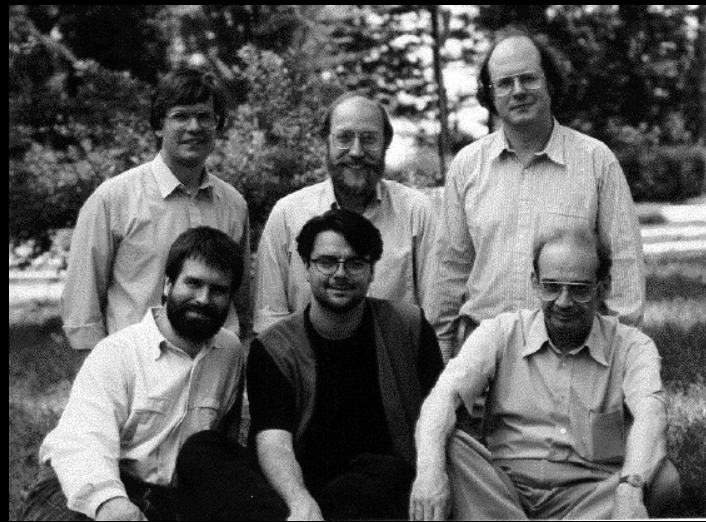
Simulating physics with computers,
Int. J. Theor. Phys. **21**, 467 (1982).

MIT Endicott House 1981

Simson Garfinkel, MIT Technology Review, April 19 2021

Quantum cryptography 1983

When elementary quantum systems … are used to transmit digital information, the uncertainty principle gives rise to novel cryptographic phenomena unachievable with traditional transmission media, e.g. a communications channel on which it is impossible in principle to eavesdrop without a high probability of disturbing the transmission in such a way as to be detected. Such a quantum channel can be used in conjunction with ordinary insecure classical channels to distribute random key information between two users with the assurance that it remains unknown to anyone else…



Richard Josza, Bill Wootters, Charles Bennett
Gil Brassard, Claude Crepeau, Asher Peres

Bennett, C. H., G. Brassard, S. Breidbart and S. Wiesner, “Quantum Cryptography, or Unforgeable Subway Tokens”, Advances in Cryptography: Proceedings of CRYPTO 82, Plenum Press, pp. 267–275 (1983).

Universal quantum computer 1985

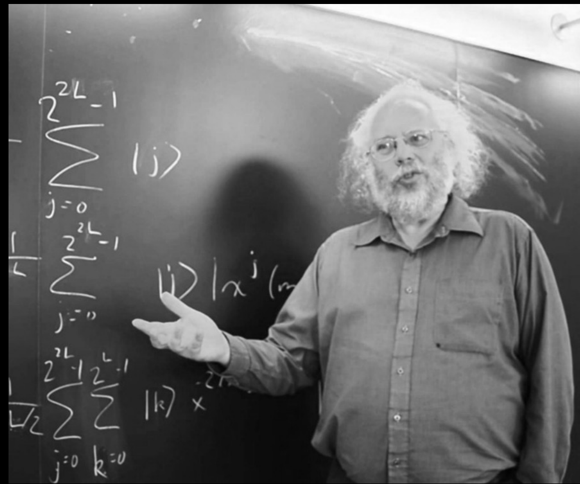
"A class of model computing machines that is the quantum generalization of the class of Turing machines is described, and it is shown that quantum theory and the 'universal quantum computer' are compatible with the principle. Computing machines resembling the universal quantum computer could, in principle, be built and would have many remarkable properties not reproducible by any Turing machine … but they do include 'quantum parallelism', a method by which certain probabilistic tasks can be performed faster by a universal quantum computer than by any classical restriction of it."

David Deutsch

Quantum theory, the Church–Turing principle and the universal quantum computer
Prof. Roy. Soc. Vol. 400, issue 1818 (1985)

Quantum factorization 1994

A computer is generally considered to be a universal computational device; i.e., it is believed able to simulate any physical computational device with a cost in computation time of at most a polynomial factor: It is not clear whether this is still true when quantum mechanics is taken into consideration. This paper gives Las Vegas algorithms for finding discrete logarithms and factoring integers on a quantum computer that take a number of steps which is polynomial in the input size. These two problems are generally considered hard on a classical computer and have been used as the basis of several proposed cryptosystems. We thus give the first examples of quantum cryptanalysis



Peter W. Shor

Algorithms for quantum computation: discrete logarithms and factoring
Proceedings 35th Annual Symposium on Foundations of Computer Science, 20-22 Nov 1994
10.1109/SFCS.1994.365700

Q-comp with Cold Trapped Ions 1995

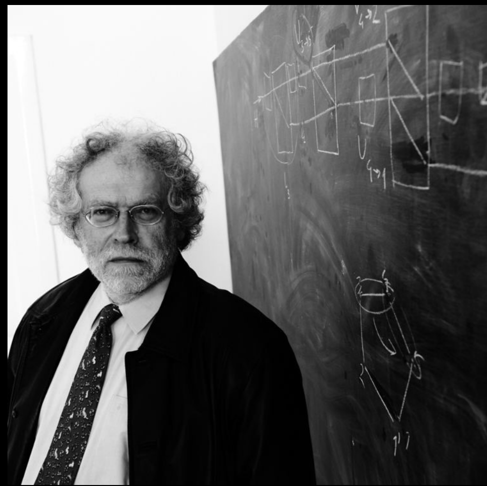
A quantum computer can be implemented with cold ions confined in a linear trap and interacting with laser beams. Quantum gates involving any pair, triplet, or subset of ions can be realized by coupling the ions through the collective quantized motion. In this system decoherence is negligible, and the measurement (readout of the quantum register) can be carried out with a high efficiency.

Ignacio Cirac Peter Zoller

Quantum Computations with Cold Trapped Ions
Phys. Rev. Lett. 74, 4091 (1995)

Experimental q-teleportation 1997

Quantum teleportation — the transmission and reconstruction over arbitrary distances of the state of a quantum system — is demonstrated experimentally. During teleportation, an initial photon which carries the polarization that is to be transferred and one of a pair of entangled photons are subjected to a measurement such that the second photon of the entangled pair acquires the polarization of the initial photon. This latter photon can be arbitrarily far away from the initial one. Quantum teleportation will be a critical ingredient for quantum computation networks.

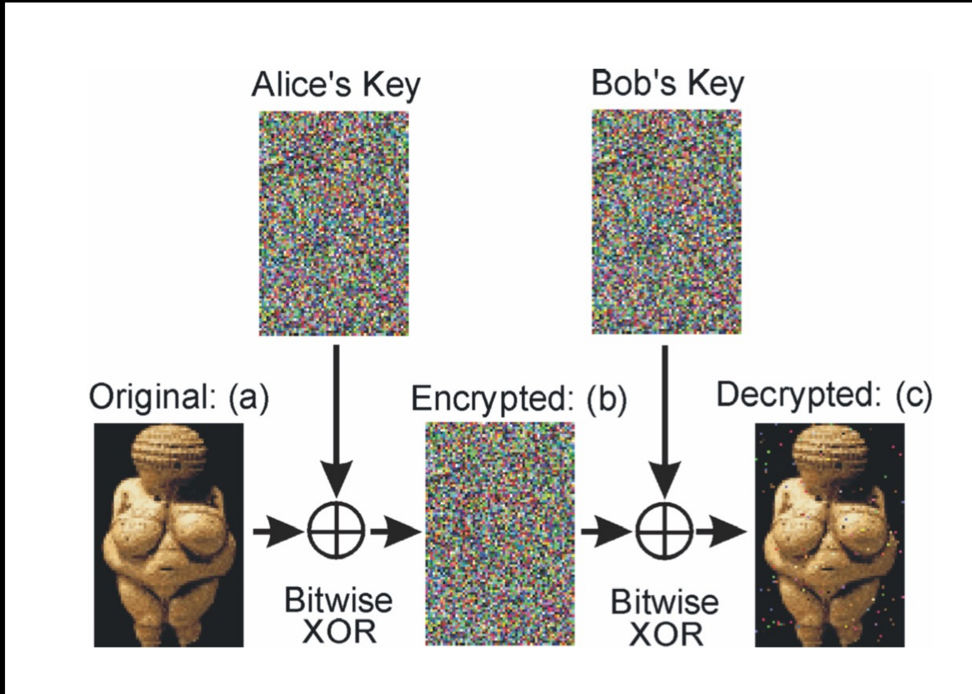


Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter & Anton Zeilinger

Experimental quantum teleportation
Nature 390 (6660), 575-579

QKD with entangled photons 2000

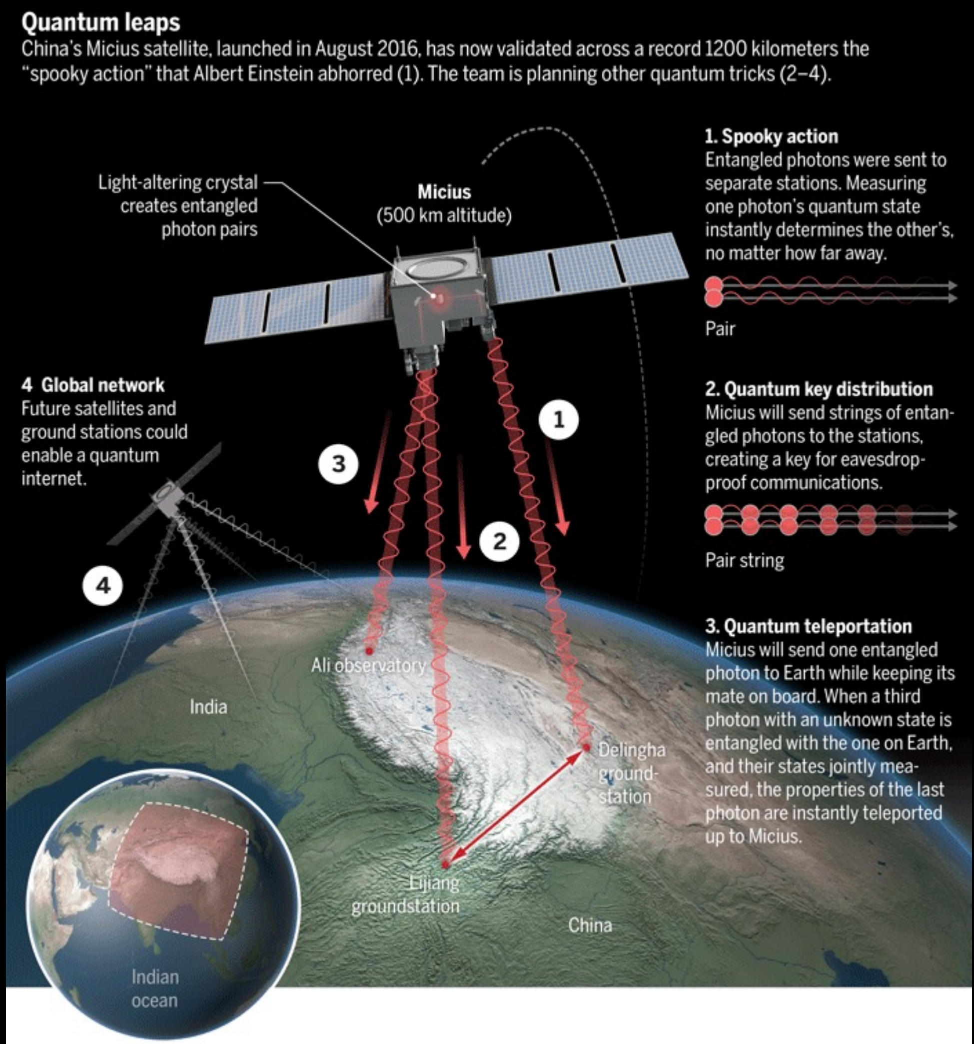
In the first entanglement-based quantum cryptography experiment, an image of the "Venus von Willendorf" effigy was transmitted. Alice and Bob initially generated a raw key of ~ 80.000 bits of length with a quantum bit error rate of 2,5%. This was distilled to ca. 50.000 bits of error corrected key with a bit error rate of 0,4%. The transmitted image itself was 43.200 bits large



T. Jennewein, C. Simon, G. Weihs, H. Weinfurter & A. Zeilinger

Quantum Cryptography with Entangled Photons Phys. Rev. Lett. 84, 4729-4732 (2000).

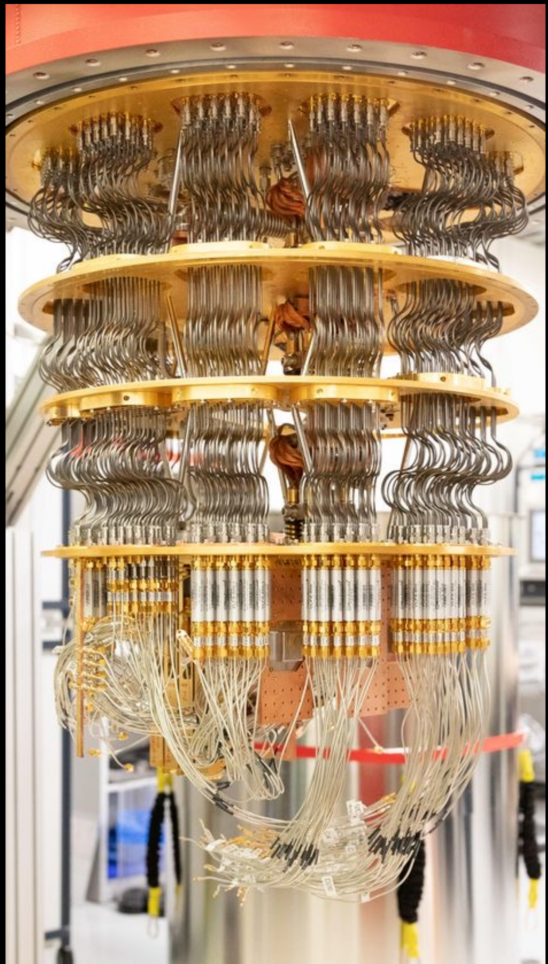
Quantum satellite 2016

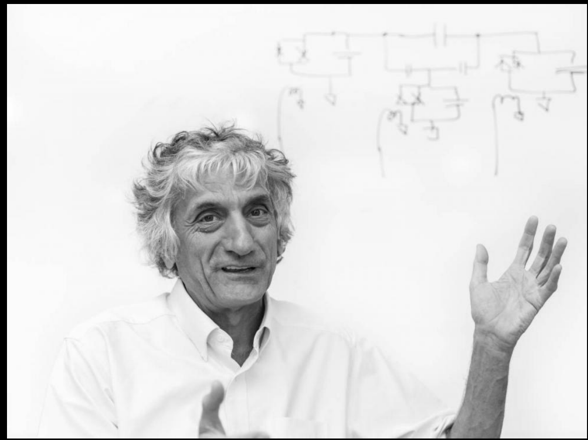


Jian-Wei Pan

Jian-Wei Pan, a physicist at the University of Science and Technology of China in Shanghai, got the chance to test the idea when the Micius satellite, named after an ancient Chinese philosopher, was launched in August 2016. The satellite is the foundation of the $100 million Quantum Experiments at Space Scale program, one of several missions that China hopes will make it a space science power on par with the United States and Europe.

Google quantum supremacy 2019





John Martinis

In a world first, a team led by John Martinis, an experimental physicist at the University of California, Santa Barbara, and Google in Mountain View, California, says that its quantum computer carried out a specific calculation that is beyond the practical capabilities of regular, ‘classical’ machines. The same calculation would take even the best classical supercomputer 10,000 years to complete, Google estimates.

NP for Quantum Information

- **2012 – Serge Haroche David Wineland:** Quantum state manipulation of individual systems.
- **2018 – Arthur Ashkin, Gérard Mourou, Donna Strickland:** Laser physics (enabling quantum experiments).
- **2022 – Alain Aspect, John Clauser, Anton Zeilinger:** Experiments on entanglement & Bell’s inequalities (foundations of quantum information).
- **2023 – Pierre Agostini, Ferenc Krausz, Anne L'Huillier:** Attosecond laser pulses for the study of electron dynamics in matter

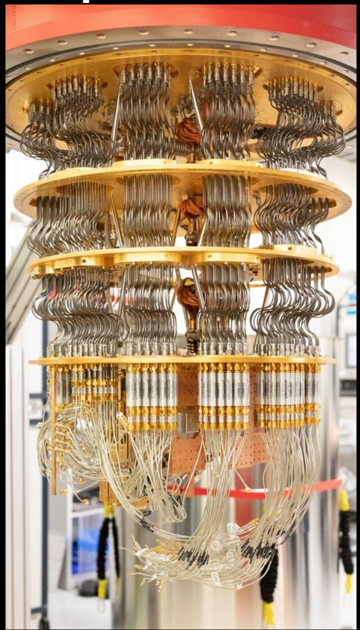
QUANTUM INFORMATION TECHNOLOGIES

“[QIT] is a radical departure in information technology, more fundamentally different from current technology than the digital computer is from the abacus”.

William D. Phillips,1997 Physics Nobel Laureate

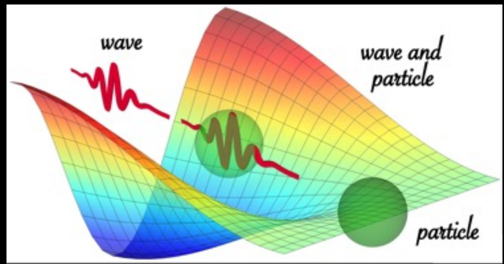
QUANTUM ENTANGLEMENT

Q-processors

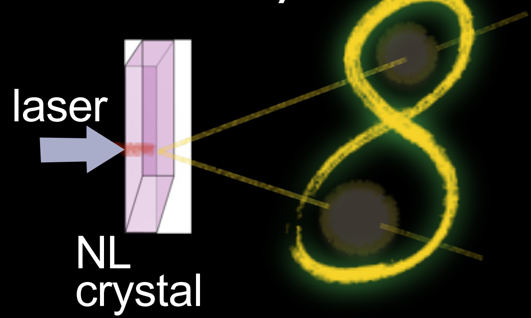


Fundamental studies

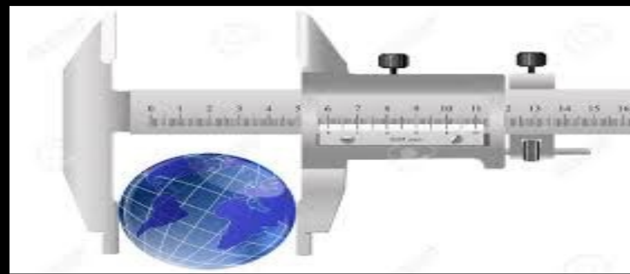
Duality



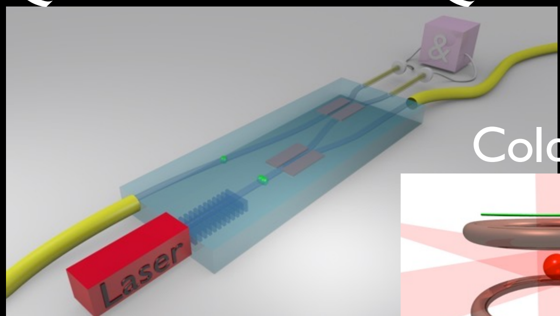
Non-locality



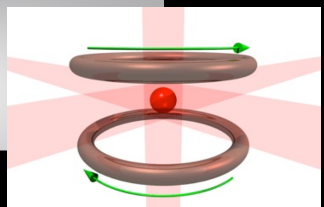
Q-metrology

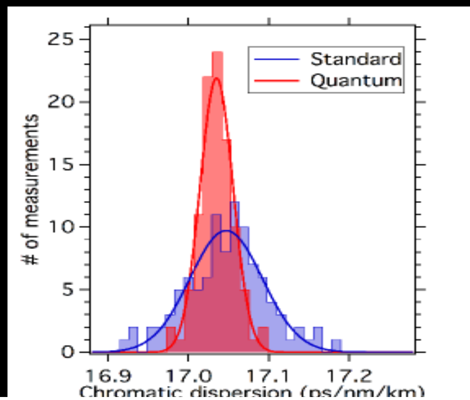


Q-memories & Q-repeaters

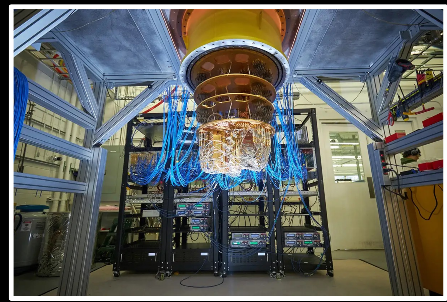


Cold atoms





QUANTUM PROCESSORS



Atoms and ions

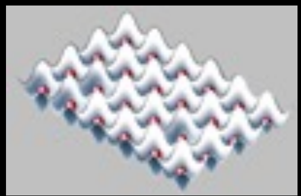
trapped ions and atoms, BEC in optical lattices, atom chips, cavity QED, NMR

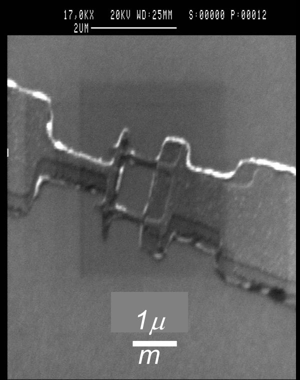
Solid states

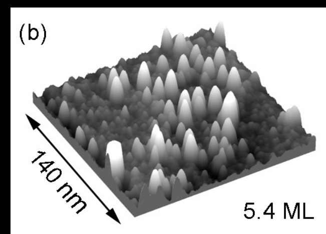
quantum dots, super-conducting qubits systémy, electron spins, nuclear spins

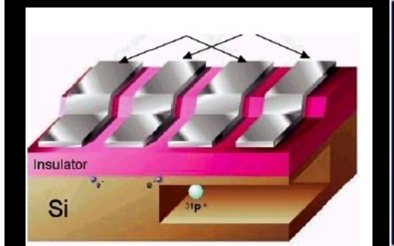
Optical systems

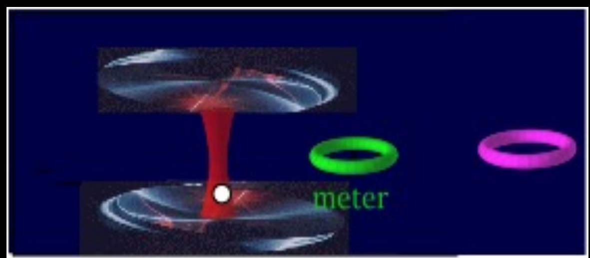
polarization states of photons, KLM scheme, q-crypography

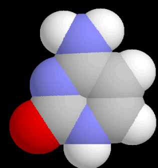


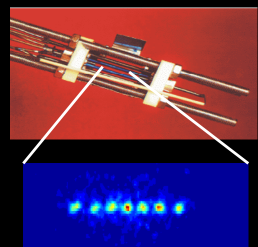


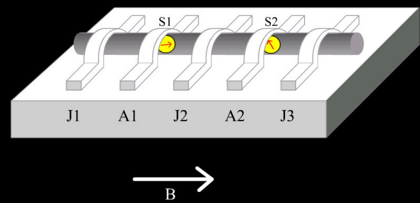












q-Seismology

What can the quantum do for us?

Quantum technologies could transform seismology by:

- Detecting earthquakes earlier and more reliably.
- Mapping underground structures with unprecedented resolution.
- Providing better monitoring of volcanoes and fault systems.
- Enhancing global warning systems and disaster preparedness.

- Quantum Gravimetry
- Quantum Accelerometers and Gyroscopes
- Quantum Magnetometers
- Quantum Clocks
- Quantum Communication
- Quantum Computers

Quantum Gravimetry

How it works:
Uses quantum sensors based on atom interferometry to measure tiny changes in gravity caused by underground mass movements.

Benefit for seismology:

- It can detect density changes in the Earth's crust before earthquakes occur (precursors).
- Helps in mapping fault lines and monitoring magma movement in volcanoes.
- Non-invasive exploration for underground structures (oil, gas, water, or geothermal sources).

Device Type	Sensitivity (Δg)	Stability	Practical Issues
Classical spring gravimeter	$\sim 10^{-8}$ g	Poor (drifts)	Needs frequent calibration
Superconducting gravimeter	$\sim 10^{-9}$ g	Very stable, but cryogenic.	Not portable
Quantum gravimeter (lab)	$\sim 10^{-11}$ g	Excellent	Needs lasers & vacuum
Quantum gravimeter (portable)	$\sim 10^{-9}$ g	Excellent	Already commercial

In

Quantum Magnetometers

How it works:

Detects extremely small changes in magnetic fields using quantum states of atoms or defects in diamond (NV centers)

Benefit for seismology:

- Earthquakes and volcanic activity can generate electromagnetic signals; quantum magnetometers could capture them with greater precision.
- Early warning by monitoring magnetic anomalies before major seismic events.

Device Type	**Sensitivity (Δg)**	Temperature	**Practical Issues**
Hall-effect sensor	~nT (10^{-9} T)	Room T.	Cheap, robust, common
Fluxgate magnetometer.	~10 pT (10^{-11} T)	Room T	Widely used in geophysics
SQUID (quantum)	~fT (10^{-15} T)	Cryogenic	Extremely sensitive, bulky
OPM (quantum)	~fT (10^{-15} T)	Room T	Now portable, MEG & defense
NV-diamond (quantum)	pT–nT	Room T	Nanoscale - best for q-scale imaging

Classical magnetometers reach the picotesla range (10^{-12} T).
Quantum magnetometers (SQUIDs, OPMs) reach the femtotesla range (10^{-15} T)
NV-diamond sensors trade raw sensitivity for nanoscale resolution, letting you see single spins or molecules.

Quantum Clocks (Timing Networks)

How it works:
Ultra-precise atomic clocks can synchronize seismic sensor networks at the nanosecond level.

Benefit for seismology:

- Enables more accurate triangulation of earthquake epicenters.
- Improves large-scale seismic tomography (3D imaging of the Earth's interior).
- Enhances coordination across global seismic observatories.

Clock Type	**Relative precision**	Drift equivalent
Mechanical pendulum or quartz clocks	$\sim 10^{-6}$ - 10^{-9}	*s* per day to *s* per year
Microwave Cesium Atomic Clocks.	$\sim 10^{-15}$	1 second drift in ~30 million years
Optical Lattice Clocks	$\sim 10^{-18}$	1 second in ~14 billion years
Single-Ion Optical Clocks	$\sim 10^{-18}$ - 10^{-19}	1 second in ~14 billion years
Quantum Nuclear Clocks	$\sim 10^{-20}$	

Quantum clocks are about 1,000–100,000 × more sensitive than classical cesium clocks, and billions of times more precise than quartz or pendulum-based devices. It allows measurements of gravitational time dilation over just centimeters of height, opening applications in navigation, geodesy, and tests of fundamental physics.

Quantum Accelerometers and Gyroscopes

How it works:
Leverages ultra-cold atoms to measure acceleration and rotation with high precision, without needing GPS.

Benefit for seismology:

- Improves the detection of ground motion in real time, even in remote areas with no GPS access.
- Provides more stable and drift-free long-term measurements compared to classical sensors.
- Enhances seismic networks in oceans (where GPS is unavailable) to monitor tectonic activity at plate boundaries.

Quantum Communication

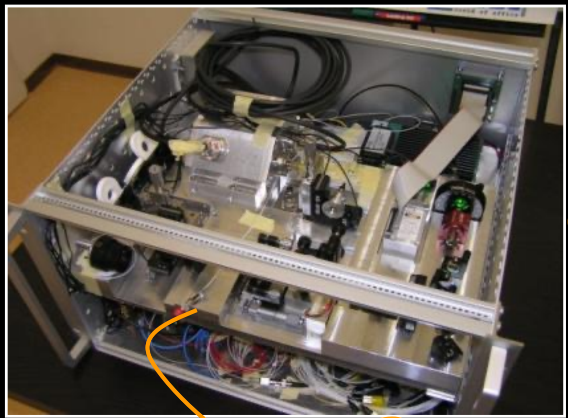
How it works:
Uses quantum entanglement and secure quantum channels for transmitting data..

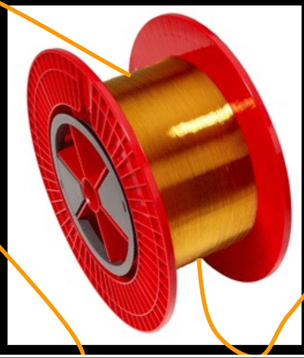
Benefit for seismology:

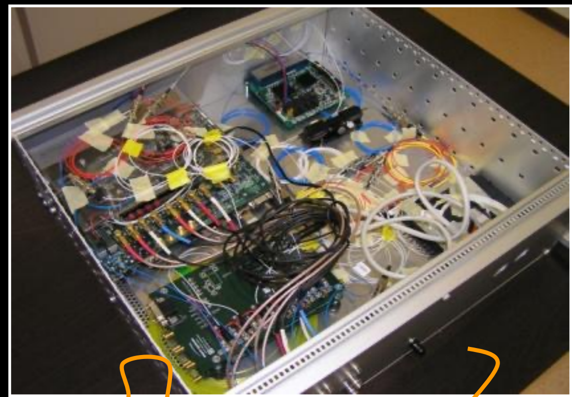
- Ensures secure, tamper-proof communication of seismic alerts.
- Helps establish resilient global earthquake early warning systems.

QKD Wien-Bratislava 2020
QUTE.SK

Fully integrated QKD system at telecom wavelengths







Alice

Standard telecom fiber

Bob

Sun’c said: The art of quantum is the most important art for the state.

Sun’c
The Art of War
Chapter I, Planning