

Physics in the XXIst century

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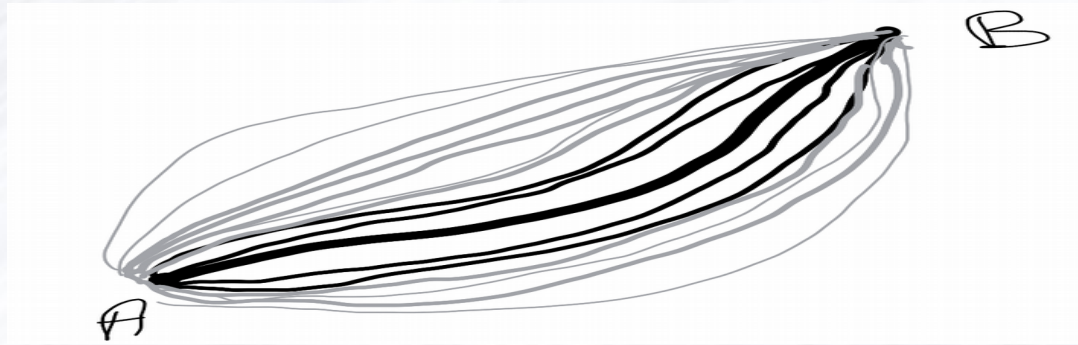
Quantum information

Information is carried by physical objects

David Deutsch

Physics and information

Feynman's interpretation of quantum mechanics : Path integrals



Free evolution of a particle from A to B ... looks like an infinite-number-of-slit experiment.
May be regarded as an equivalent way to perform complex computation.

Claude Shannon's information theory :

Information is proportional to information entropy, a similar definition to that of thermodynamics (log of number of configurations)

New technology revolution ?

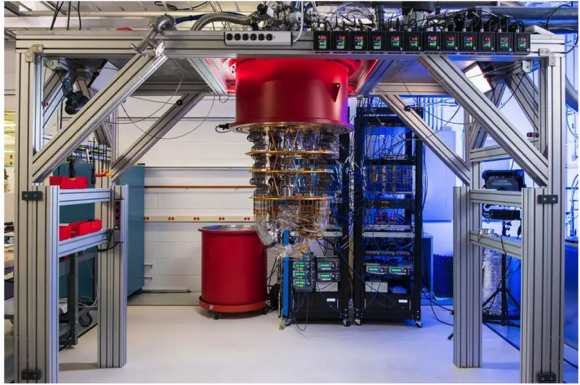
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It's official: Google has achieved quantum supremacy — advantage

PHYSICS 23 October 2019
By Daniel Cossins



Google's quantum computer is a record-breaker
HANNAH BENET/Google

Octobre 2019

Quantum satellite achieves 'spooky action' at record distance



China's quantum satellite achieves 'spooky action' at record distance

By Gabriel Popkin | Jun. 15, 2017, 2:00 PM

June 2017

New technology revolution ?

▼ nature

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NEWS FEATURE · 02 OCTOBER 2019

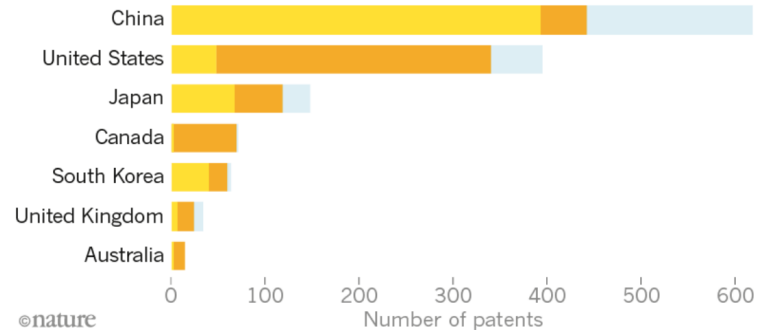
Quantum gold rush: the private funding pouring into quantum start-ups

A *Nature* analysis explores the investors betting on quantum technology.

Quantum patents

An analysis of global patents in quantum technology since 2012 shows China dominating quantum communication, but North America ahead on quantum computing.

- Quantum key distribution (quantum communication)
- Quantum computing (including software)
- Other quantum technology



Source: Martino Travagnin/EC Joint Research Centre

New technology revolution ?

Oct 2017

The Guardian view on quantum computing: the new space race
Editorial

The main use of quantum technology might not be to hack existing systems but to create unhackable communication networks of the future



China will open a \$10 billion quantum computer center and others also investing in quantum computing

Brian Wang | October 10, 2017



Quantum USA Vs. Quantum China: The World's Most Important Technology Race



Moor Insights and Strategy Contributor ©

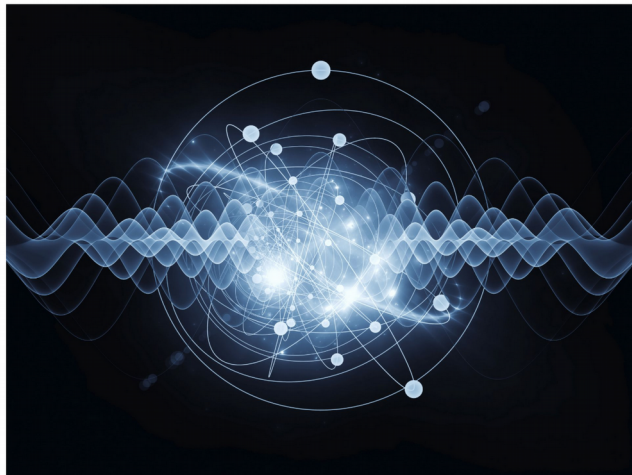
Cloud

Straight talk from Moor Insights & Strategy tech industry analysts

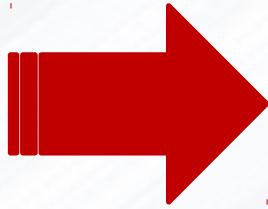
EC Initiative

Quantum Technologies Flagship

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



Is it achievable at all ?



A first quantum revolution led to this !

Physics principles of quantum information

- Coherent state superposition principle
- Entangled states (EPR state)

Qubit

Quantum bit : basic unit of quantum information, or quantum binary digit.

examples are : any quantum system that may exist in two orthogonal states, spin-1/2 particles like electrons, but also photons, quantum dots....

Both states $|\uparrow\rangle$
are represented by $|\downarrow\rangle$

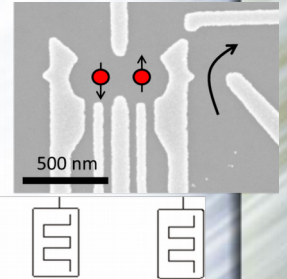
However, the system could be prepared in a coherent superposition such as

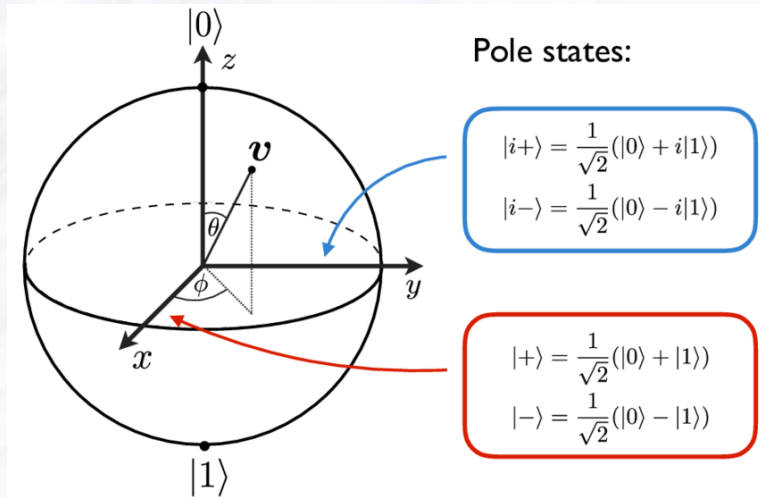
$$|\phi\rangle = a |\uparrow\rangle + b |\downarrow\rangle \quad \text{with : } |a|^2 + |b|^2 = 1$$

A measurement (reading) of the qubit leads :

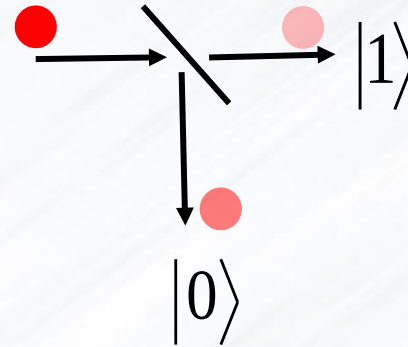
- $|\uparrow\rangle$ with probability $|a|^2$
- $|\downarrow\rangle$ with probability $|b|^2$

After measurement, the qubit gets projected onto one of the two states.





Bloch sphere



Classical BIT $|0\rangle$ $|1\rangle$

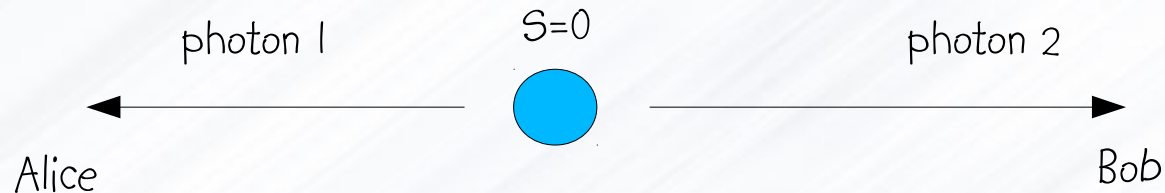
Quantum BIT $\alpha|0\rangle + \beta|1\rangle$

Entangled states (also known as Einstein-Podolsky-Rosen states , EPR states)

Pairs of qubits that are generated in a quantum state such that each qubit cannot be described independently of the state of the other, even when the particles are separated by a large distance.

examples :

pairs of photons or spin-1/2 particles produced by the decay of a spin-0 particle.



When Alice measures spin up or down, she instantaneously knows that Bob will measure down or up, respectively, without exchanging any signal. But Alice does not know in advance if up or down will be measured (50% chance).

Teleportation of a qubit

A qubit cannot be copied (contrary to a classical bit) but it can be teleported !

C.H. Bennett et al, PRL 70-13 (1993) 1895

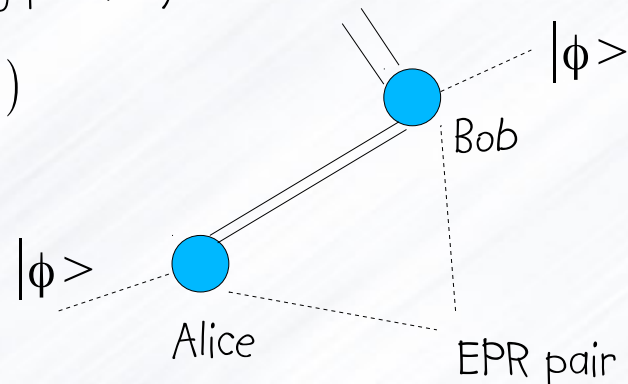
Bob and Alice share a pair of qubits (called qubit 2 and qubit 3) prepared in an EPR singlet state (like produced by spin-0 decaying particle) :

$$|\psi_{23}^-\rangle = \frac{1}{\sqrt{2}} (|\uparrow_2\rangle |\downarrow_3\rangle - |\downarrow_2\rangle |\uparrow_3\rangle)$$

Alice wants to teleport qubit 1 to Bob :

$$|\phi_1\rangle = a |\uparrow_1\rangle + b |\downarrow_1\rangle$$

$$|a|^2 + |b|^2 = 1$$



Teleportation of a qubit

Alice performs a joint (simultaneous) measurement of 1 and 2 in the Bell basis of 12.

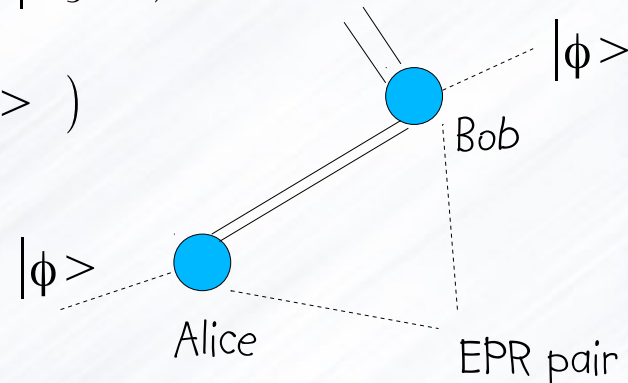
Before measurement, the complete quantum state of 123 can be written as :

$$|\psi_{123}\rangle = \frac{a}{\sqrt{2}} (|\uparrow_1\rangle |\uparrow_2\rangle |\downarrow_3\rangle - |\uparrow_1\rangle |\downarrow_2\rangle |\uparrow_3\rangle) \\ + \frac{b}{\sqrt{2}} (|\downarrow_1\rangle |\uparrow_2\rangle |\downarrow_3\rangle - |\downarrow_1\rangle |\downarrow_2\rangle |\uparrow_3\rangle)$$

Bell basis :

$$|\psi_{12}^{\pm}\rangle = \frac{1}{\sqrt{2}} (|\uparrow_1\rangle |\downarrow_2\rangle \pm |\downarrow_1\rangle |\uparrow_2\rangle)$$

$$|\phi_{12}^{\pm}\rangle = \frac{1}{\sqrt{2}} (|\uparrow_1\rangle |\uparrow_2\rangle \pm |\downarrow_1\rangle |\downarrow_2\rangle)$$



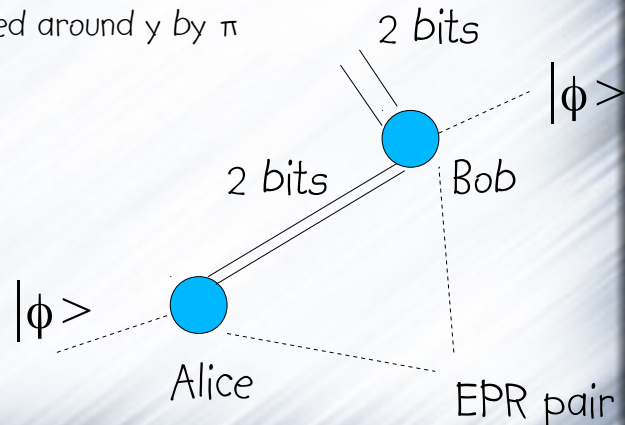
Teleportation of a qubit

In the Bell basis, $|\psi_{123}\rangle$ can be expressed as :

$$\begin{aligned}
 |\psi_{123}\rangle = & 1/2 [\\
 & |\psi_{12}^-\rangle (-a|\uparrow_3\rangle - b|\downarrow_3\rangle) \longrightarrow -|\phi_3\rangle \\
 & + |\psi_{12}^+\rangle (-a|\uparrow_3\rangle + b|\downarrow_3\rangle) \longrightarrow |\phi_3\rangle \text{ rotated around } z \text{ by } \pi \\
 & + |\phi_{12}^-\rangle (a|\downarrow_3\rangle + b|\uparrow_3\rangle) \longrightarrow |\phi_3\rangle \text{ rotated around } x \text{ by } \pi \\
 & + |\phi_{12}^+\rangle (a|\downarrow_3\rangle - b|\uparrow_3\rangle) \longrightarrow |\phi_3\rangle \text{ rotated around } y \text{ by } \pi \\
 &]
 \end{aligned}$$

Alice performs a measurement of 12 in the Bell basis. She obtains one of the 4 possible Bell states. She then knows in which state is 3. She sends that information (2 classical bits) through a conventional transmission link.

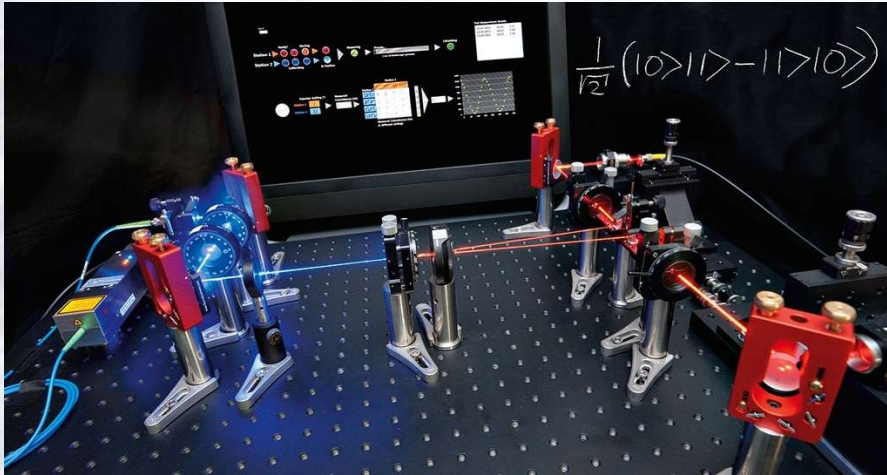
Bob receiving this info knows what transformation to apply to 3 to get a complete replicate of 1. At the moment Alice carries out the measurement, ϕ_1 disappears and gets teleported to ϕ_3 .



Exercise

- Show that the Bell basis is an orthonormal basis of the $1,2$ Hilbert space
- Express each state direct product $|\uparrow_1\rangle|\uparrow_2\rangle \dots$, in terms of Bell states
- Express $|\psi_{123}\rangle$ as a function of the Bell basis states.
- For each $|\phi_3\rangle$ state, find the phase to rotate it in order to retrieve $|\phi\rangle$

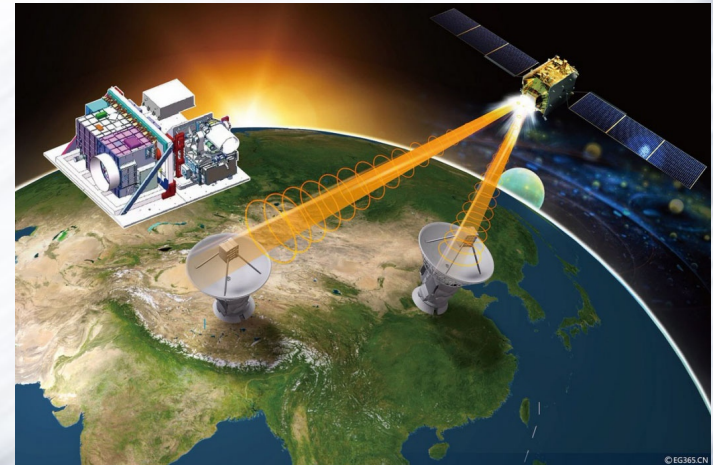
Teleportation in practice



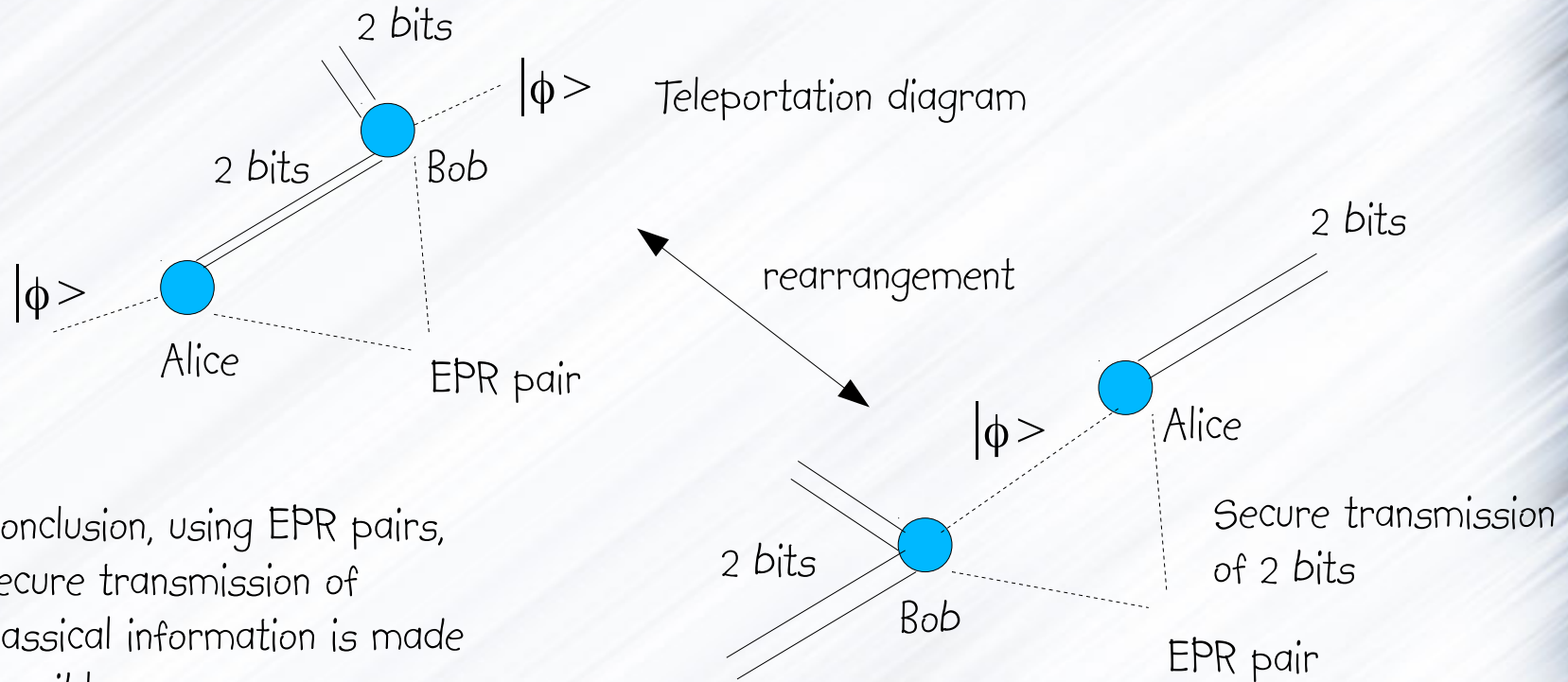
Real teleportation first performed by Anton Zeilinger in 1997

Source of entangled photons non linear optics

Ques : Quantum Experiment at Space Scale led by China. EPR photon pairs distribution over 1200 km ! achieved in 2017 Satellite nicknamed Micius (Mozi) who found in fifth century BCE that light travels in straight lines



Secure transmission of classical information

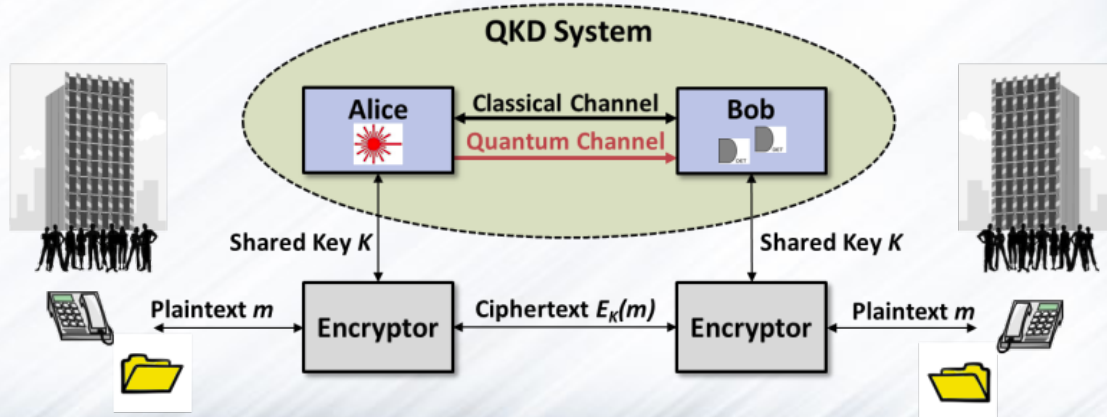


Quantum Key distribution

Unbreakable cryptography key distribution for secure information transfer

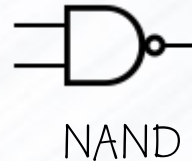
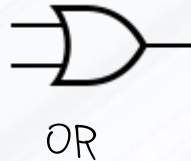
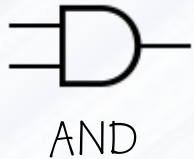
Entering commercial market

ID Quantique (Geneva), but also SeQureNet (Paris),
MagiQ Technologies, Inc. (New York), Quintessence Labs (Australia)

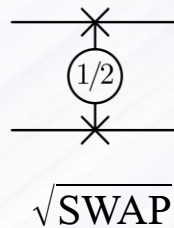
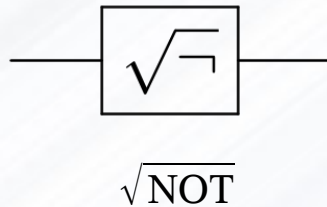


Quantum computing

Classical computing is based on binary digits (bits) processed by classical logical gates :



Quantum computing is based on qubits processed by quantum logical gates :



R_ϕ

phase shift gates

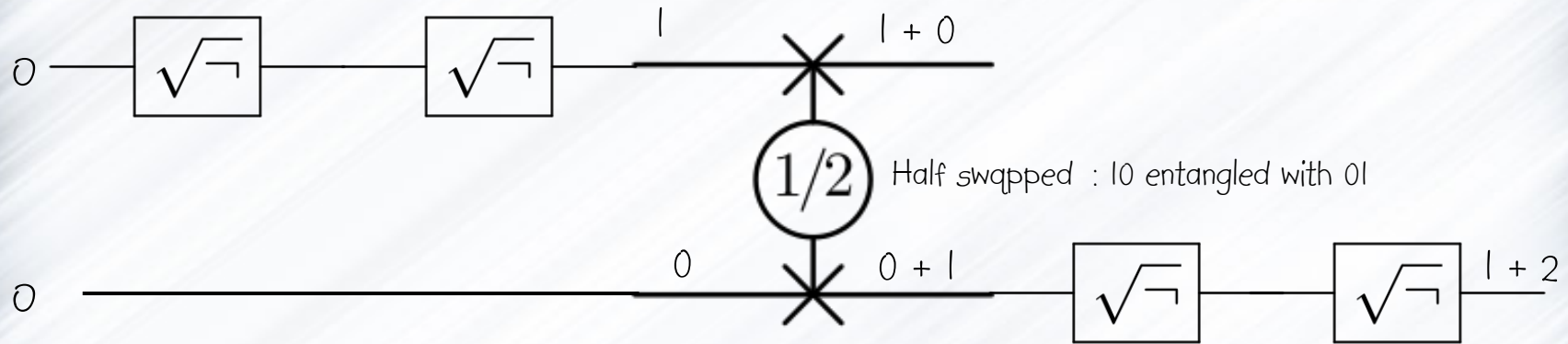
R. Feynman 1981

D. Deutsch 1985

P. Shor 1994 (factorization algorithm)

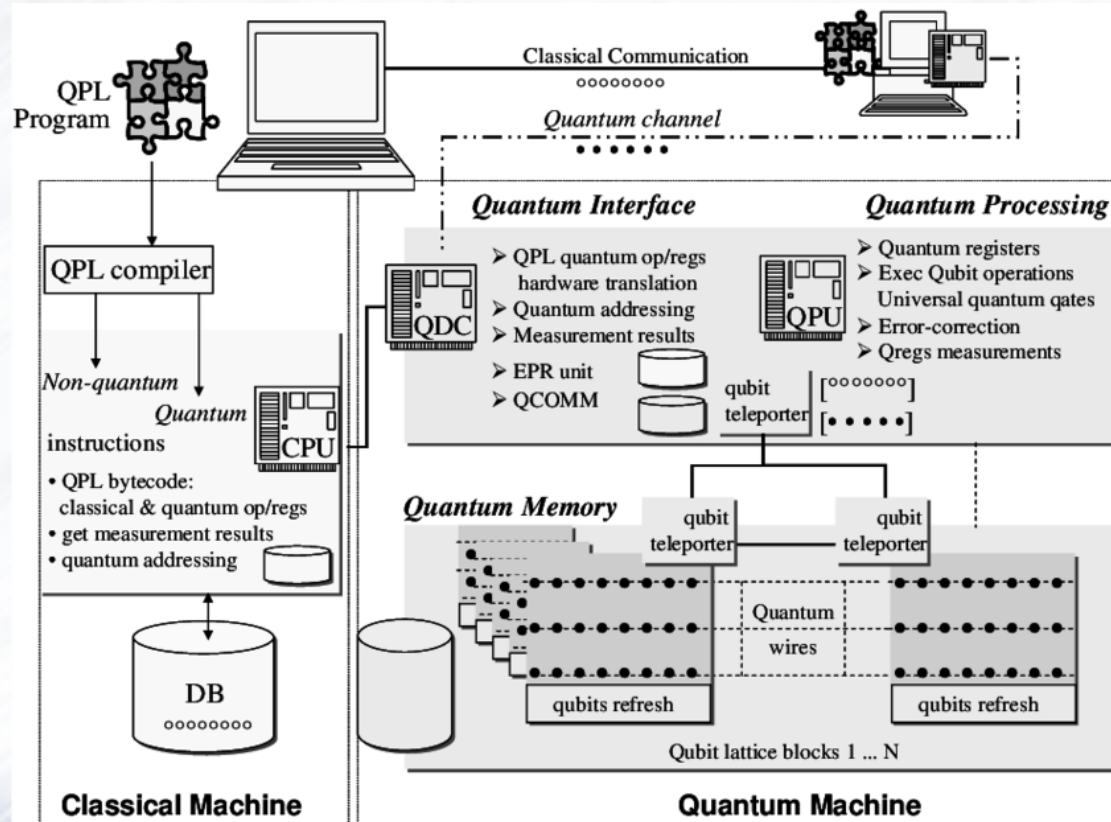
L. Grover 1996

An example

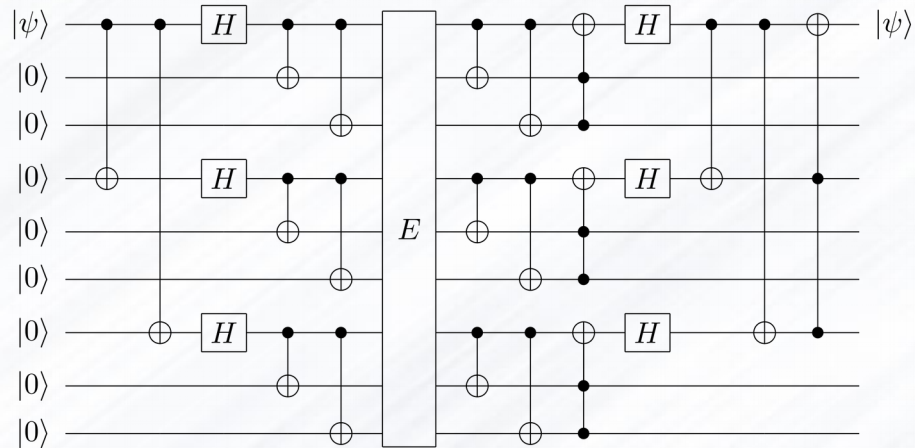


Convert a 00 into an entangled state of 00 and 11

Quantum computer architecture



Shor code for arbitrary single-qubit error correction



Error correction:

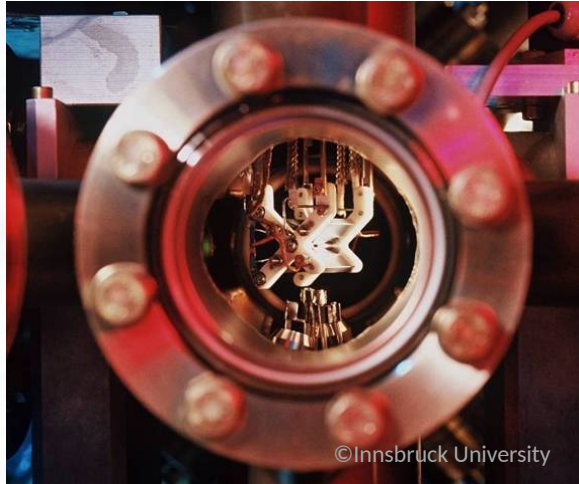
- Additional quantum bits
- Additional gates

Main implementation technologies



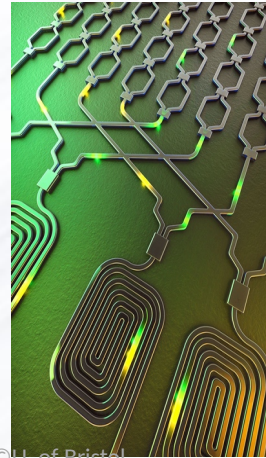
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Superconducting qubits



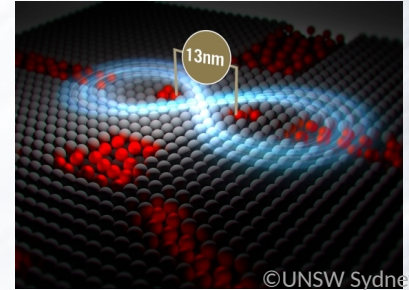
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Trapped ions



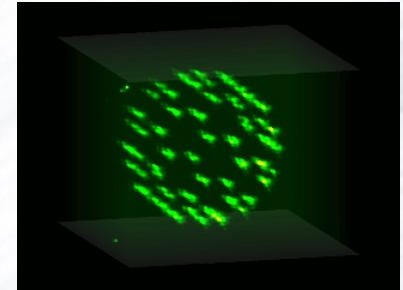
©U. of Bristol

Photons



©UNSW Sydney

Si Qubits



Neutral Atoms

Quantum computing

quantum register made
of L qubits

qubit₁ qubit₂ ----- qubit _{L}

Can be used to store
 2^L numbers at once

But if read, only one number out
of 2^L possibilities will be extracted !

However, quantum algorithms may process 2^L numbers at the same time, instead of 2^L computing steps as would be required on a conventional computer.

Could be used for highly time-consuming computing problems like integer number factorization.

On conventional computers, factorization of a L -digit number grows as $\exp(L)$. The factorization of a 80-digit number would take more than the age of the Universe !

On a quantum computer, the factorization of a L -digit number would grow at most as L^3 .
A 1000-digit integer would then require less than 1 second !

Quantum advantage

Quantum advantage more than quantum supremacy

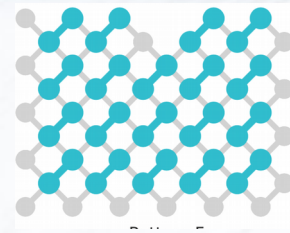
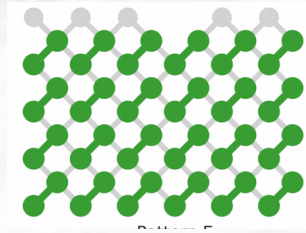
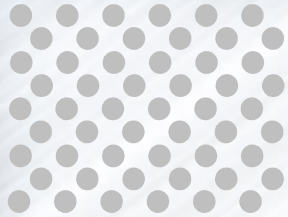


John Preskill, Caltech
in 2011

Run an algorithm on a quantum computer which solves problems with a super-polynomial speedup relative to classical computers.

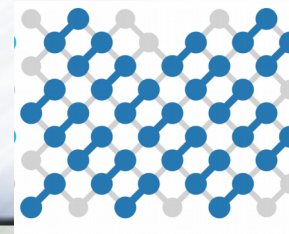
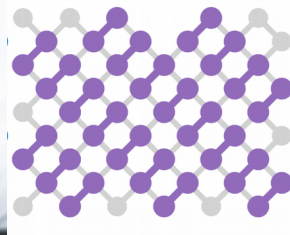
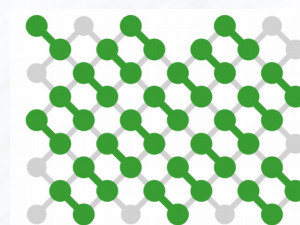
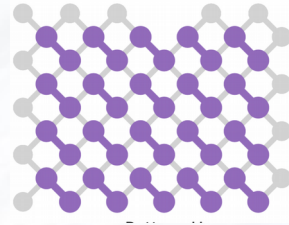
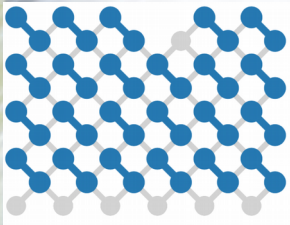
(irrespective of the usefulness of the problem)

Random quantum circuit sampling

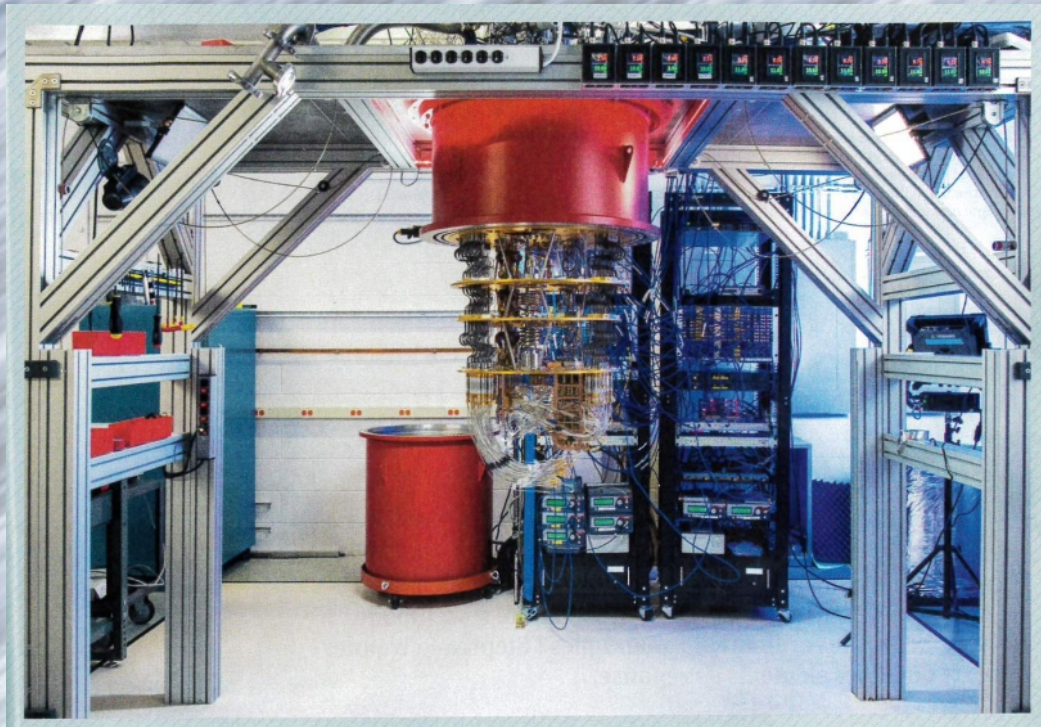


Nature 574, 505 (2019)

Random alternate
one and two qubit
gates cycles



Time



Quantum advantage

Sycamore : Google's 53 superconducting qubit quantum computer.

200 s were needed on Sycamore (Google's quantum processor) to obtain a million circuit samples for 53 qubits and 20 cycles, whereas 10,000 years would be needed on a super classical computer (a million core computer).

Complexity

The true state of every natural system of interest

We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes.

Pierre-Simon de Laplace, A Philosophical Essay on Probabilities[3]

This philosophical confidence in determinism and predictability was soon to be questioned because of :

- Atomic / statistical mechanics : Ludwig Boltzmann (1844 - 1906)
- Discovery of chaos in the three-body problem in celestial mechanics : Henri Poincaré (1864-1912)

Complexity is a topic under intense work that involves all scientific domains. No general and complete framework has been established so far.

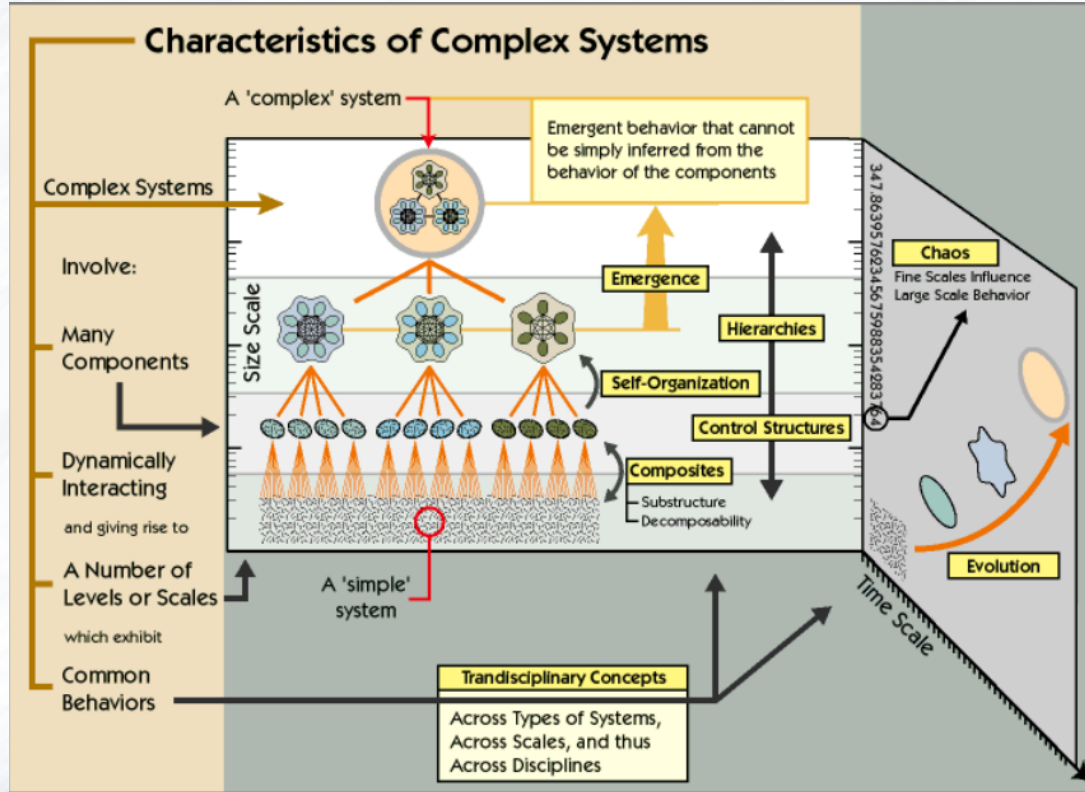
Chaos in simple systems

double-rod
pendulum



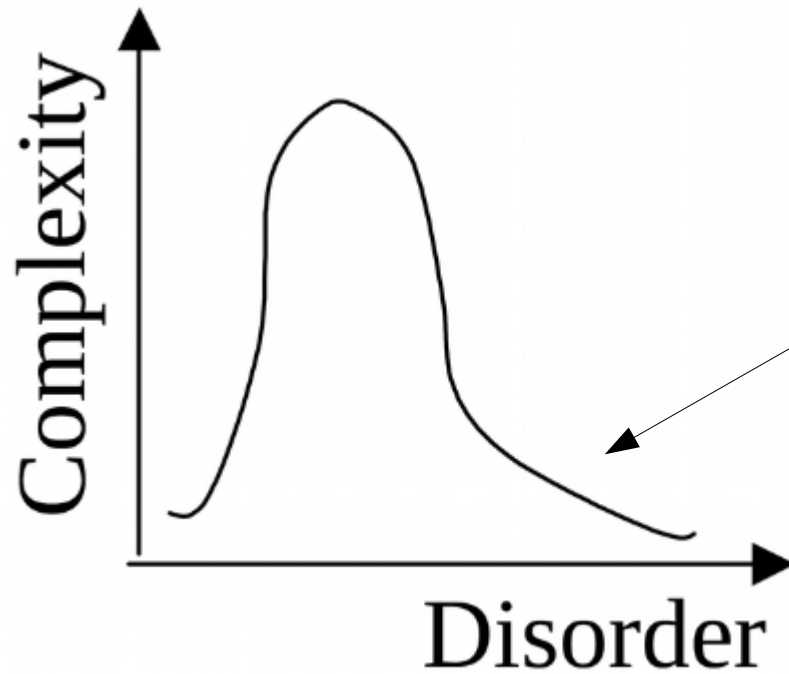
Complex systems characteristics

© Pedro Ferreira



Complexity and disorder

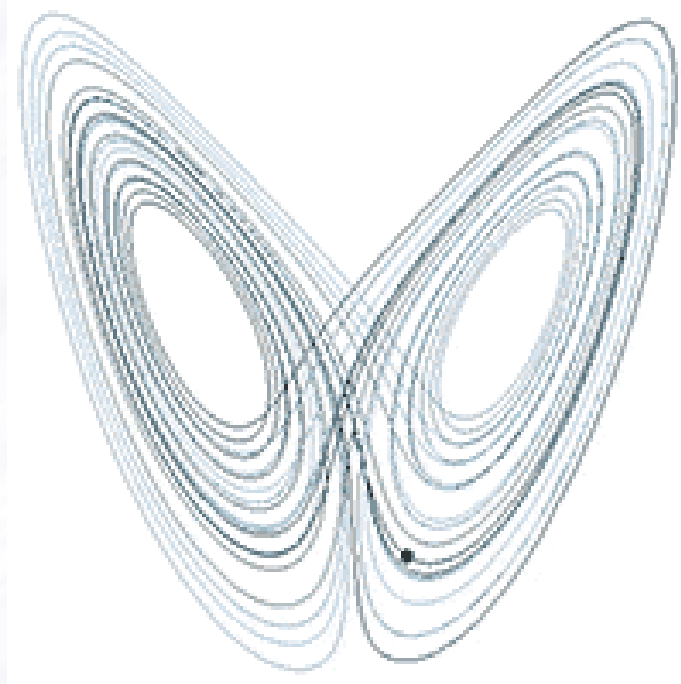
© Pedro Ferreira



Random
systems

Attractors

A Lorenz attractor with only 3 dynamical variables $x(t)$, $y(t)$, $z(t)$ coupled in a system of differential equations



$$\frac{dx}{dt} = \sigma(y - x)$$

$$\frac{dy}{dt} = x(\rho - z) - y$$

$$\frac{dz}{dt} = xy - \beta z$$

Fractal structures - geometries

scale factor

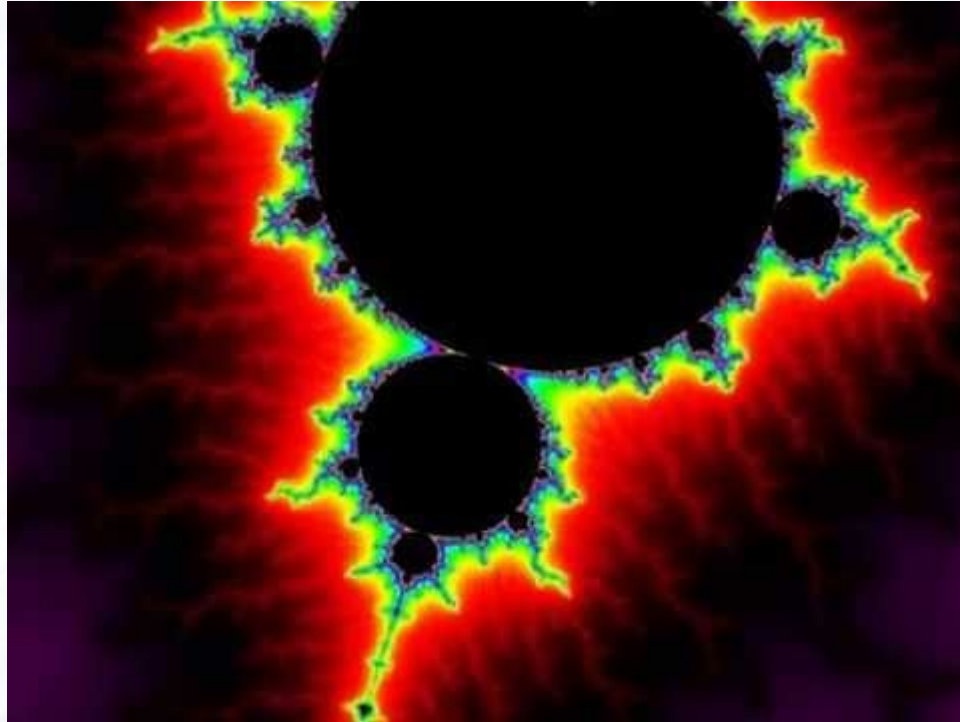
dimension

$$N = f^d$$

number of sub-objects

example : cube , $d = 3$

Fractal structures have
non-integer d values



Aperiodic tiling

Penrose tiling exhibiting
fivefold symmetry



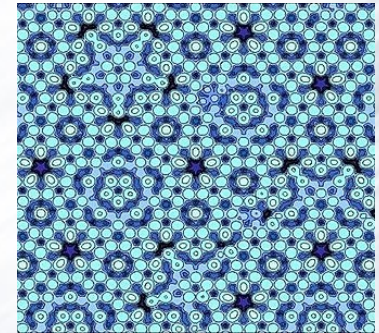
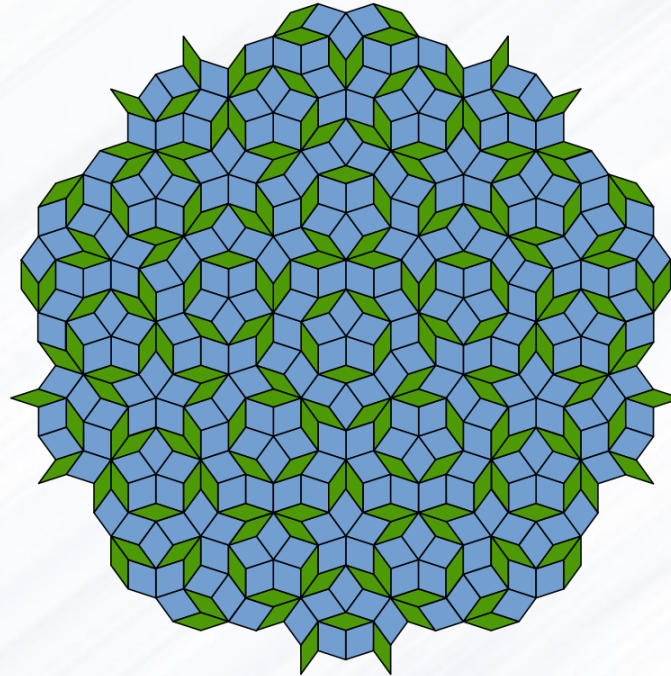
R. Penrose
2020 Nobel Prize in physics

Two-dimensional cross section
of a 4-d periodic structure

Quasicrystals as
hyperlattices with 4 or more
dimensions.

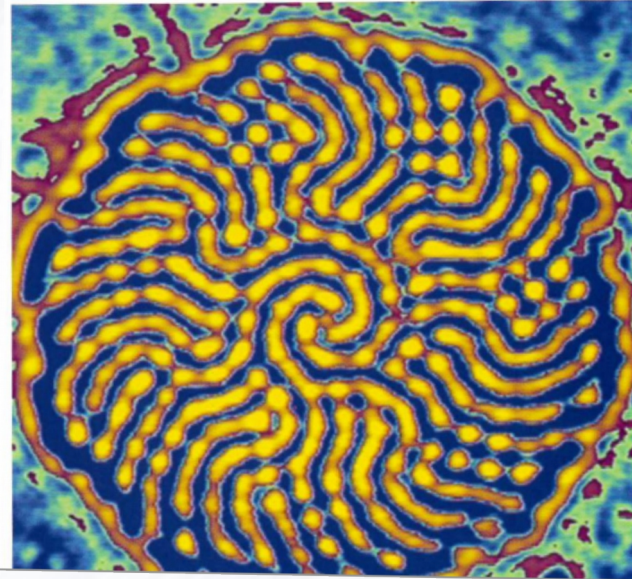
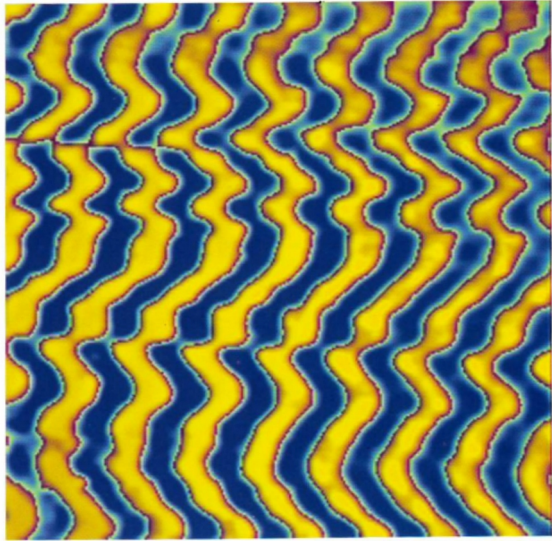


2011 Nobel Prize in chemistry : Dan Shechtman



Al-Pd-Mn alloy

Transverse electric field in a laser beam interacting with liquid crystal



Solidification of organic alloy between two glass plates



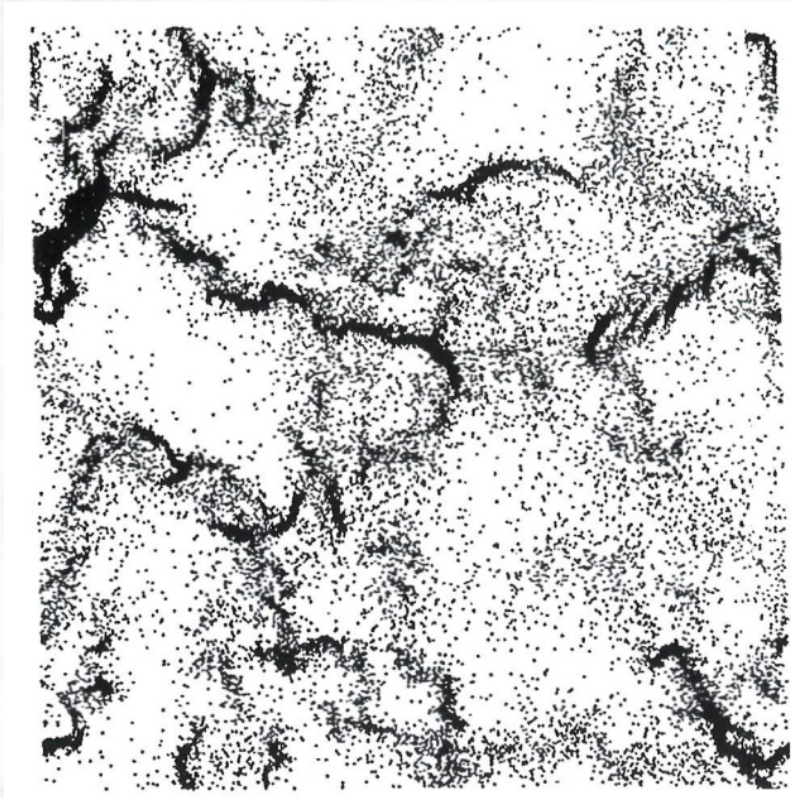
Turbulence of a water jet



Blowing air into a 0.13 mm oil layer between glass plates



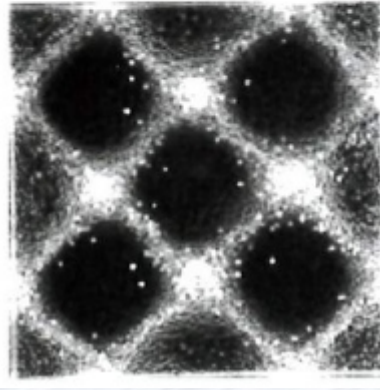
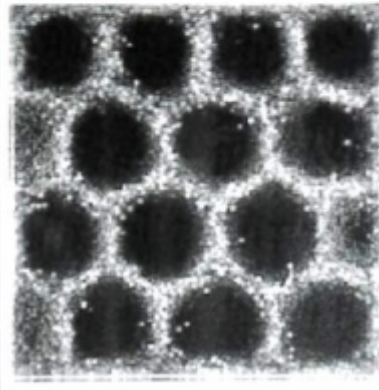
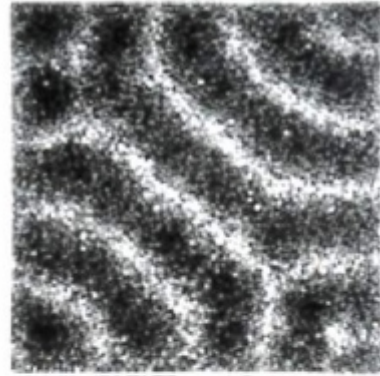
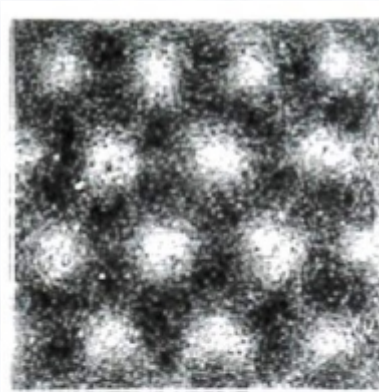
Granular particles interaction



configuration of 40,000 particles
after 500 collisions each, with
dissipative interaction

Sand on a vibrating plate

Various patterns
observed depending
on the vibration
amplitude.



The relation to ultimate reality

If we ask the question : "What is ultimate reality ?" , we find a delightful ambiguity :

- Is it fundamental physics that allows all this to happen ? - its physical causal foundations ?
- Is it the highest level of structure and complexity it achieves ? - which is the ultimate in emergent structure and behavior ?
- Is it the ethical basis that ultimately determines the outcome of human actions and hence of social life, and whatever may underlie this basis ?
- Is it the metaphysical underpinning of the fundamental physics ; on the one hand, and of cosmology on the other - whatever it is that "makes these physical laws fly" (as John Wheeler put it), rather than any others ?

Georges Ellis

2021 Nobel prize in physics : Complex physical systems



Syukoro Manabe 1931 -



Klaus Hasselmann 1931 -

Physical modelling of Earth's climate,
quantifying variability and reliably predicting
global warming



Giorgio Parisi 1948 -

Discovery of the interplay of disorder and
fluctuations in physical systems from atomic
to planetary scales

For further reading :

- The new physics for the twenty-first century : edited by Gordon Fraser, Cambridge University Press
- Introduction to Quantum Information Science, Vlatko Vedral, Oxford Graduate Text
- Physique Quantique, Information et Calcul, des concepts aux applications : P. Degiovanni, N. Portier, C. Cabart, A. Feller et B. Roussel, CNRS éditions