The quantum legacy

Mauro Paternostro
Queen's University Belfast

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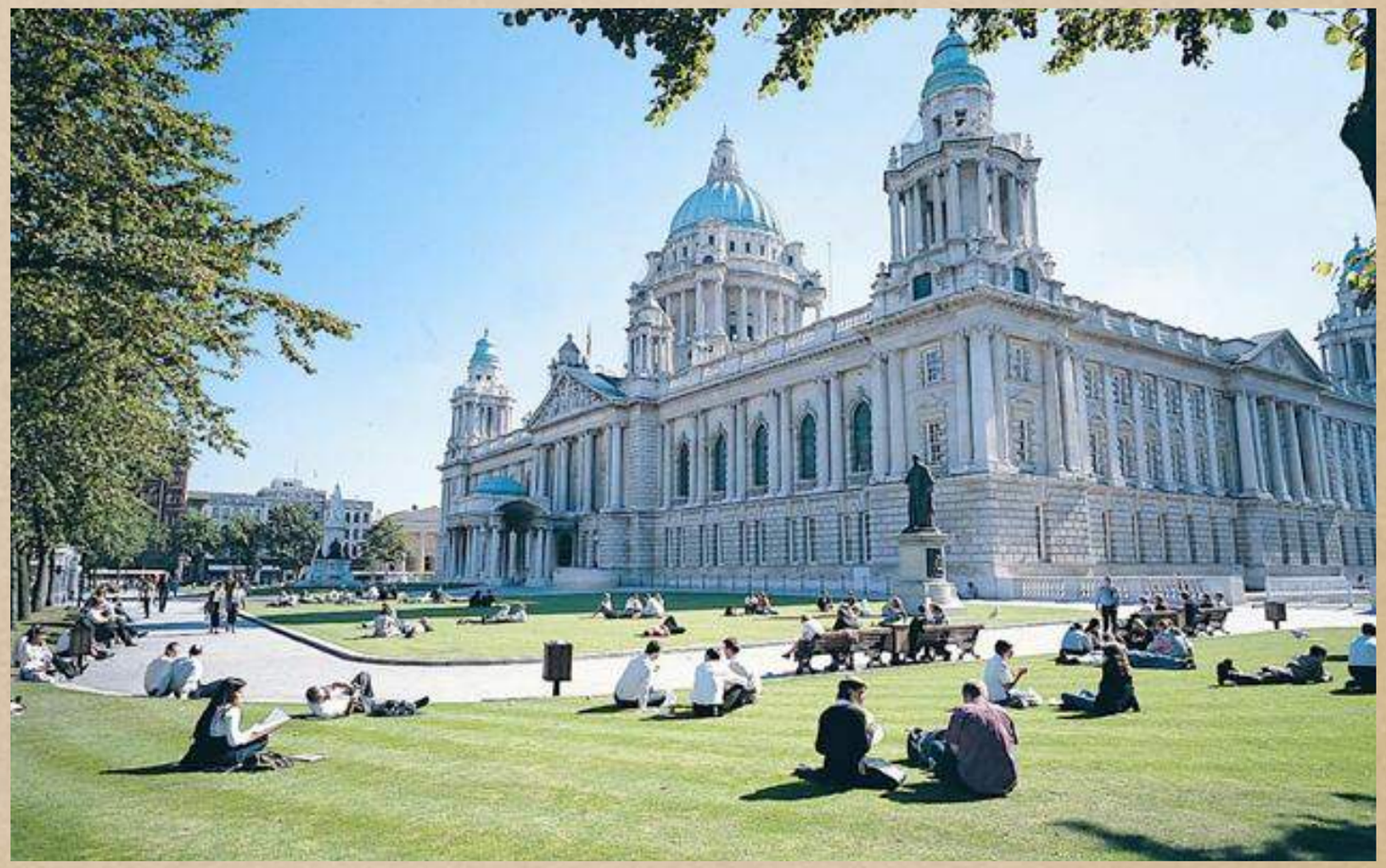
Belfast



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Titanic

BELFAST TITANIC SOCIETY
Incorporating The Ulster Titanic Society

"...the world commemorates the tragedy; only we can celebrate the triumph..."

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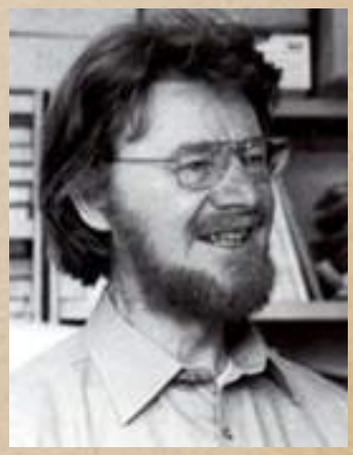
Queen's University Belfast

Joseph Larmor



John Stuart Bell

David Bates, FRS

Harrie Massey

Lord Kelvin

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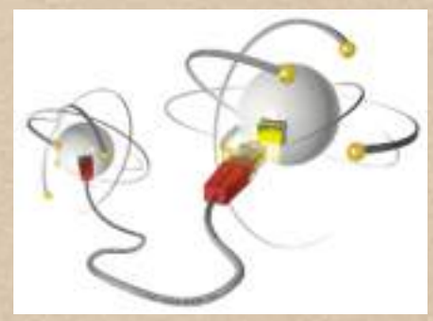
Quantum information theory

What happens when we encode information in quantum systems?



Quantum technologies

Quantum many-body systems

Ultra-cold atoms

Quantum optomechanics

Foundations of quantum theory

Quantum thermodynamics

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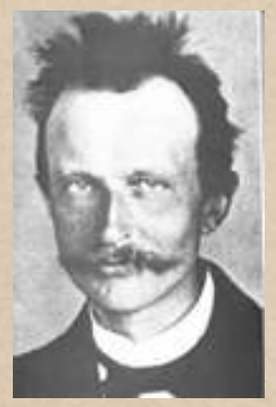
Physics & Social services

My dad works on things that nobody can see, writes strange symbols, and talks often to his computer.

Sara, 6 years

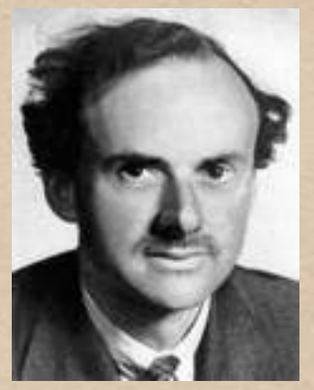
The first quantum revolution



Planck

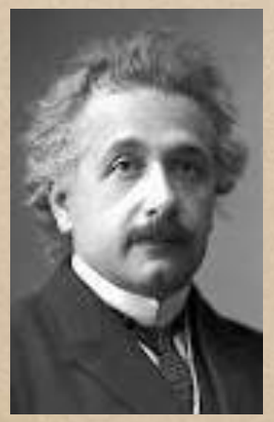
Schroedinger

Heisenberg



Dirac

Einstein



Bohr

Fermi

Pauli

New laws that rule the physical world

The first quantum revolution

$|\psi\rangle$ state vector (or ket)

$i\hbar\partial_t|\psi\rangle = \hat{E}|\psi\rangle$ Schroedinger eq.

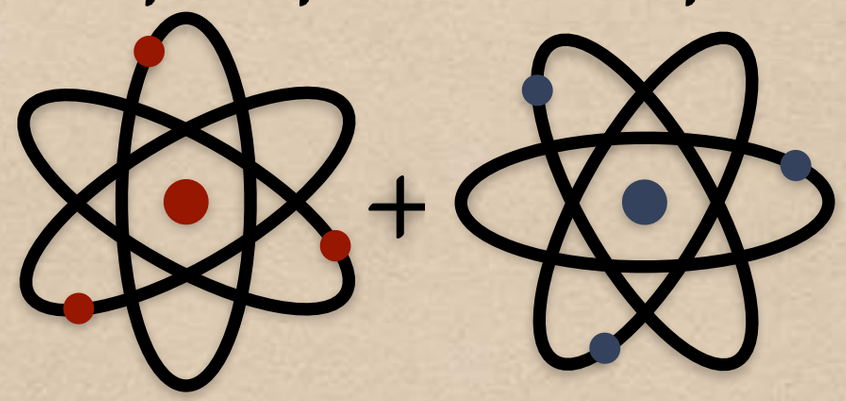
ρ density matrix

It does not evolve according to the Schroedinger eq.

New laws that rule the physical world

What set the quantum and classical worlds apart?

The superposition principle



$$|\psi\rangle = \frac{|\text{Rosso}\rangle + |\text{Blue}\rangle}{\sqrt{2}}$$

When applied to more than a single particle

it implies <u>entanglement</u>

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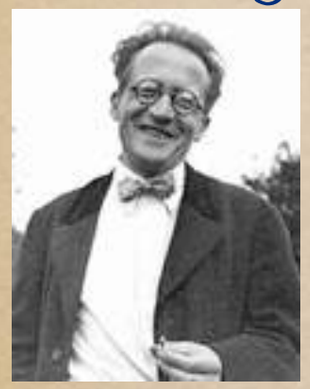
Entanglement

Schroedinger



E. Schroedinger,

Naturwissenschaften 23, 807 (1935)

"*Thus one disposes provisionally (until the entanglement is resolved by actual observation) of only a* **common** *description of the two in that space of higher dimension. This is the reason that knowledge of the individual systems can decline to the scantiest, even to zero, while that of the combined system remains continually maximal. Best possible knowledge of a whole does* **not** *include best possible knowledge of its parts — and this is what keeps coming back to haunt us*"

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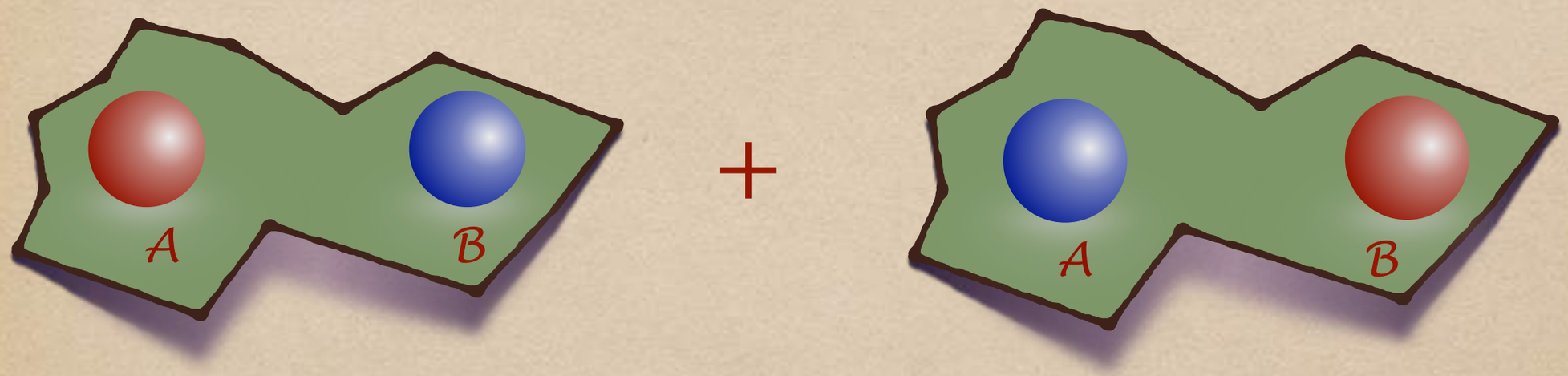
Entanglement



$$|\psi\rangle = \frac{|\text{Rosso}\rangle_A|\text{Blue}\rangle_B + |\text{Blue}\rangle_A|\text{Rosso}\rangle_B}{\sqrt{2}}$$

Entanglement is a resource for quantum technologies

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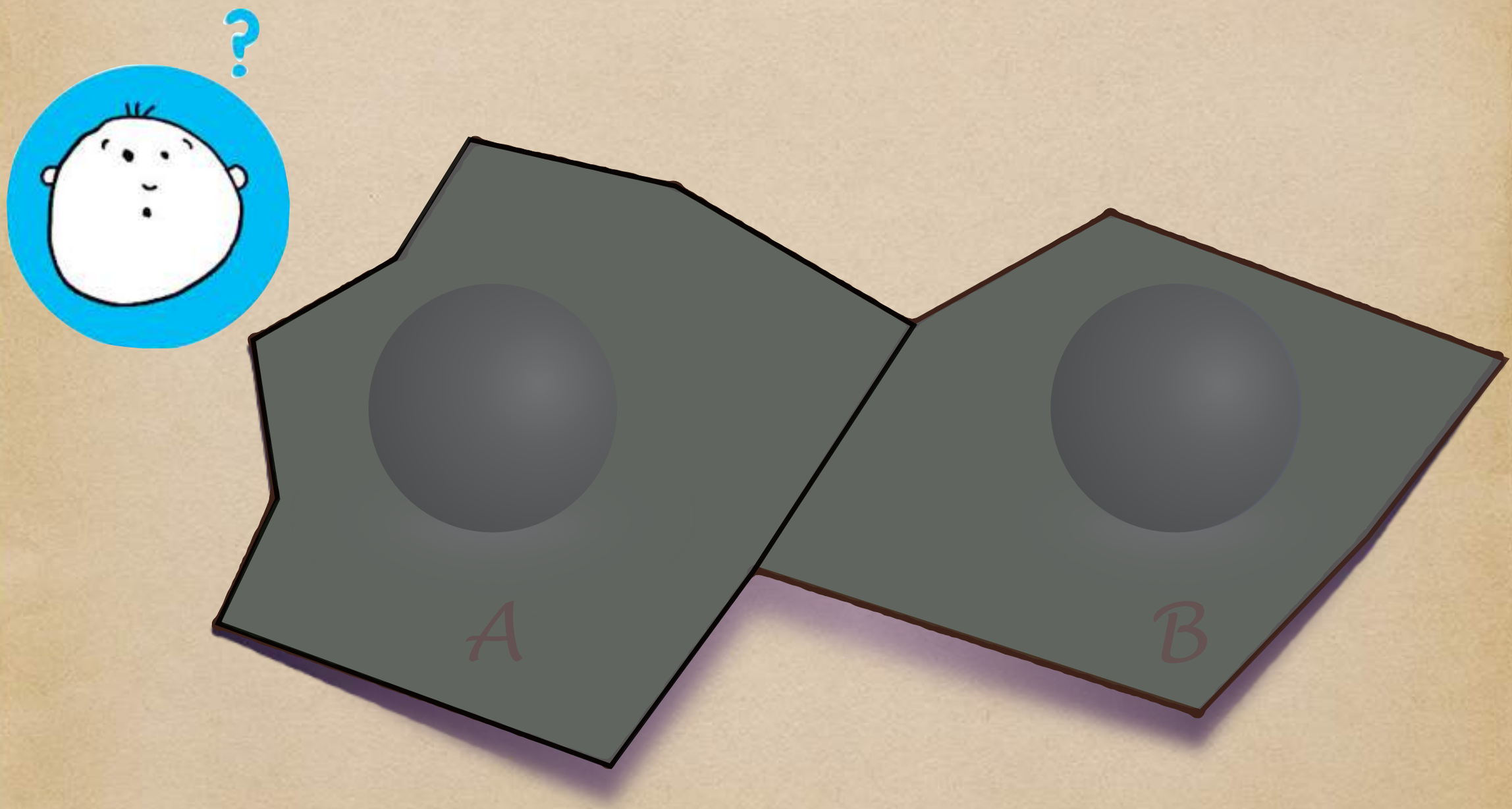
Entanglement



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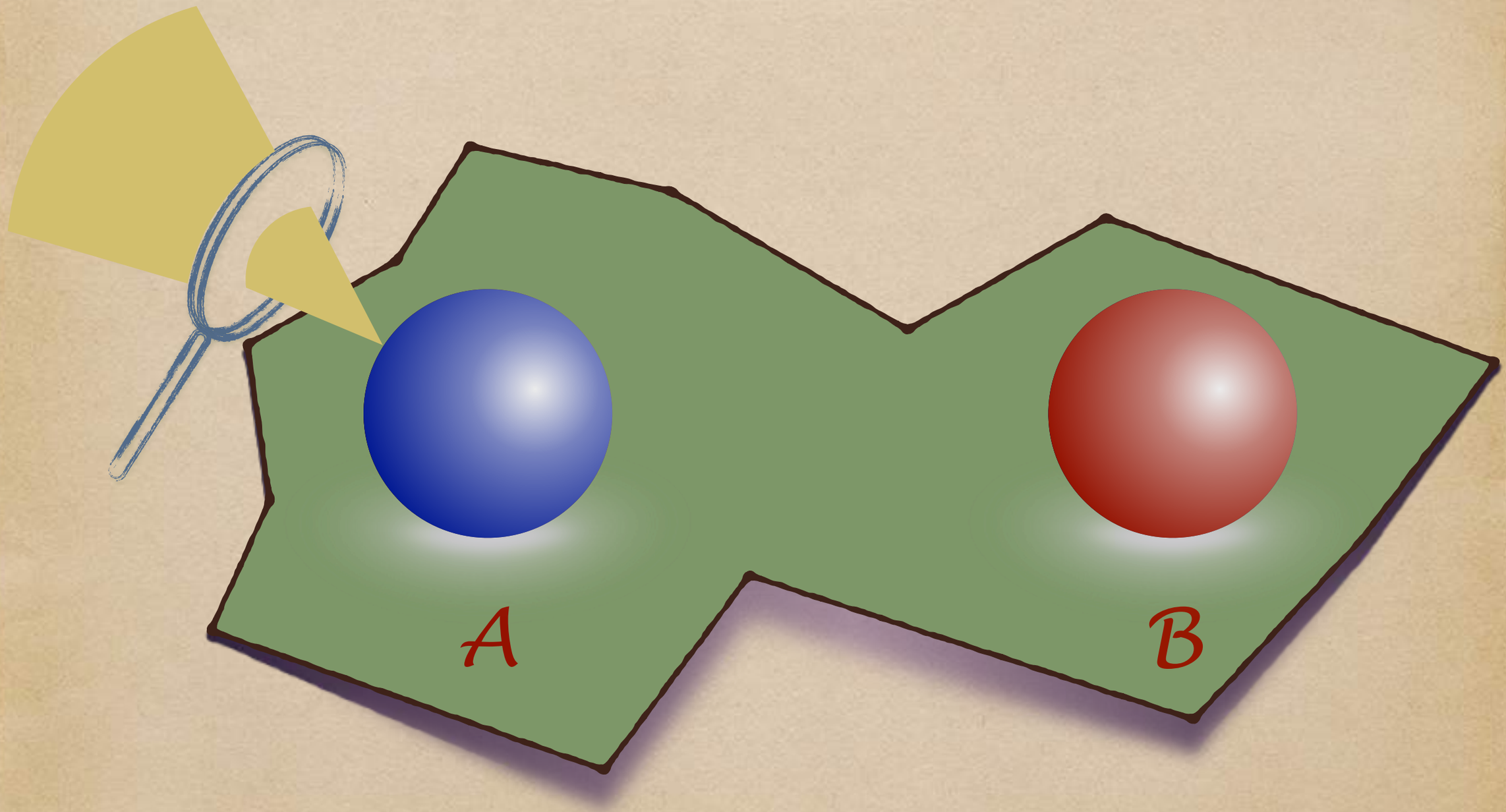
Entanglement



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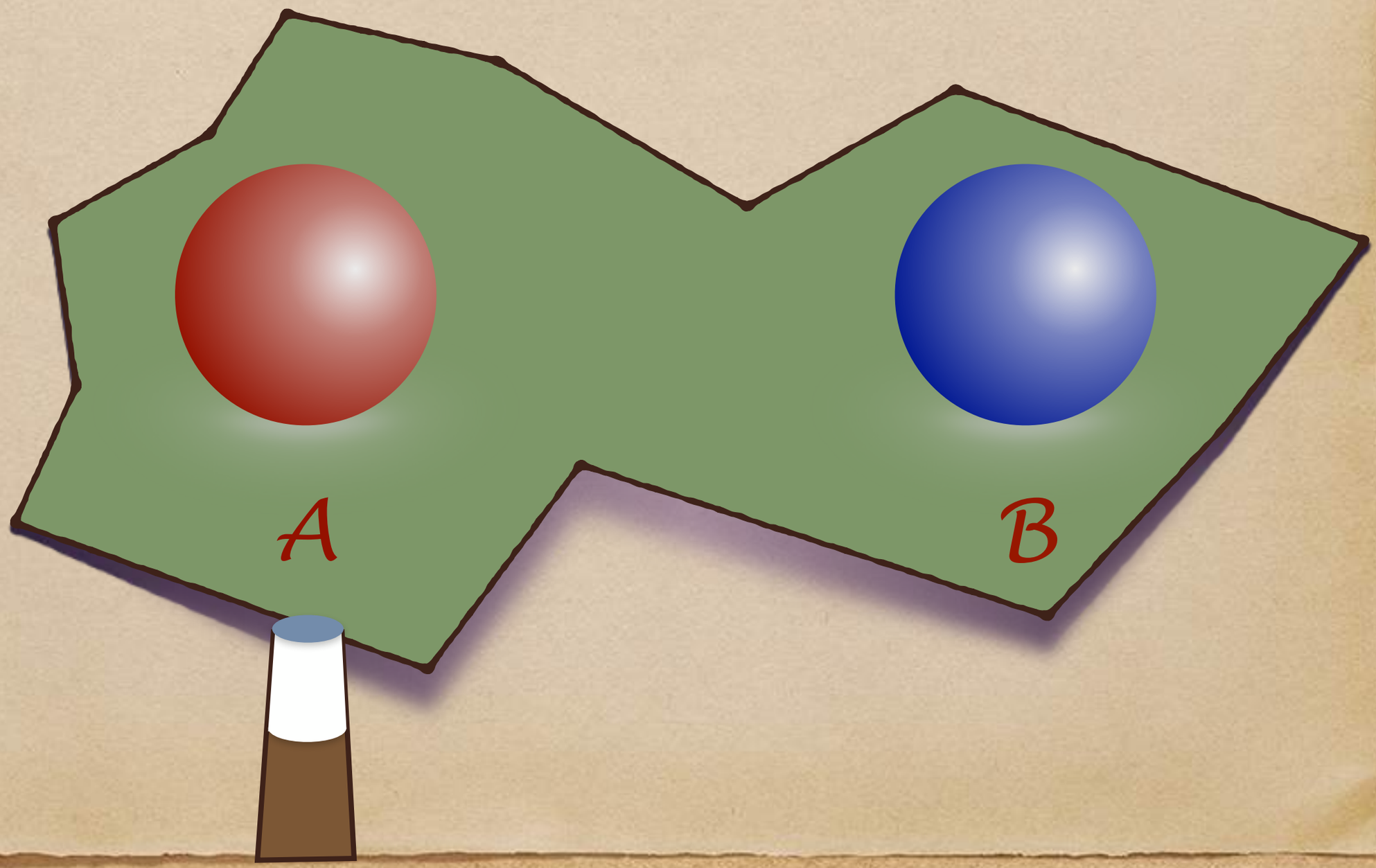
Entanglement



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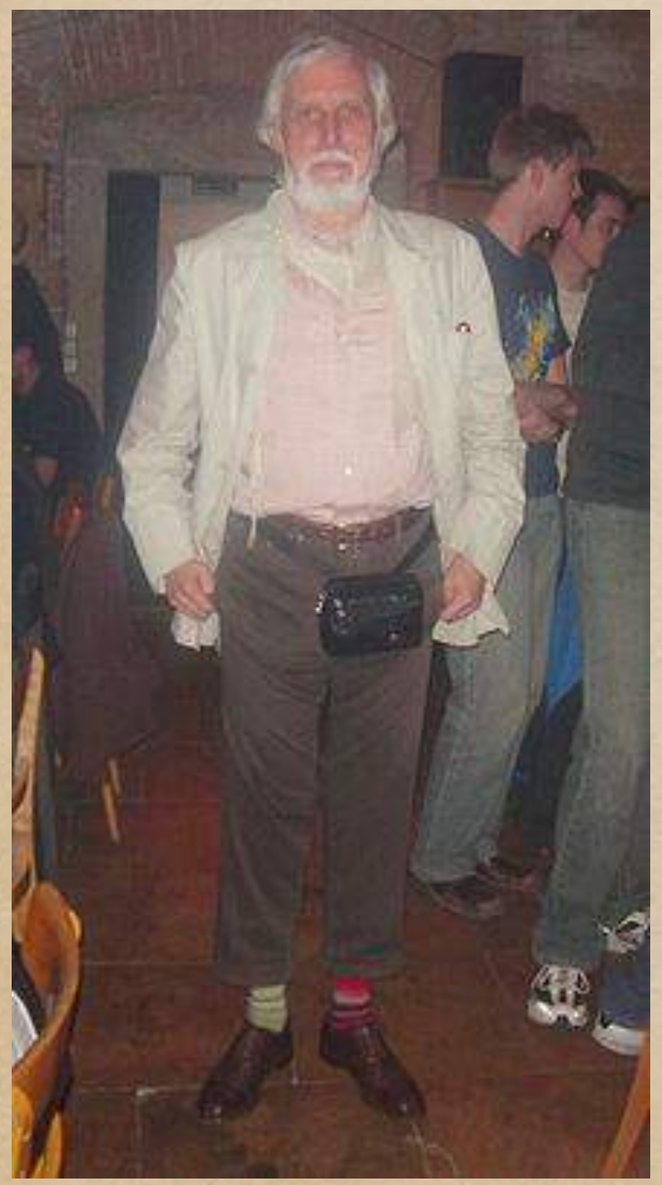
Quantum fashion

Reinhold Bertlmann

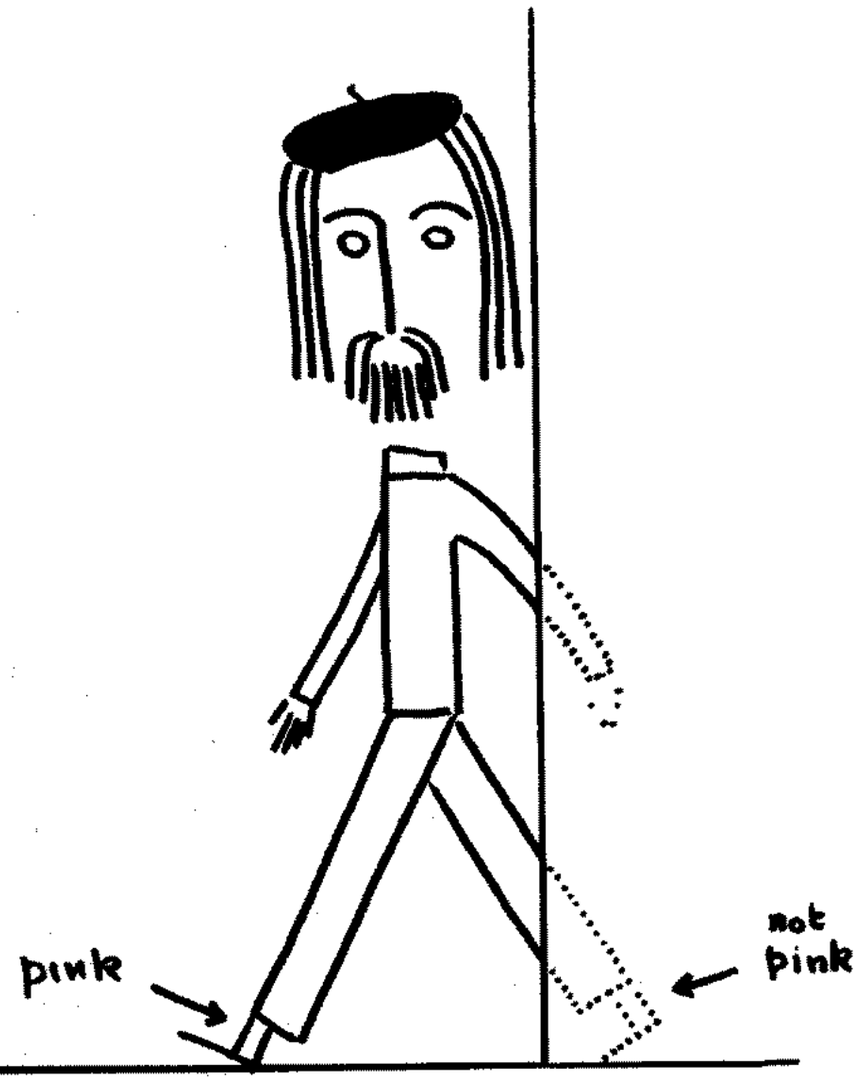


J. S. Bell, Bertlman's socks and the nature of reality,
Journal de Physique 42, 41 (1981)

Fig 1

Les chaussettes
de M. Bertlmann
et la nature
de la réalité

Fondation Hugot
juin 17 1980



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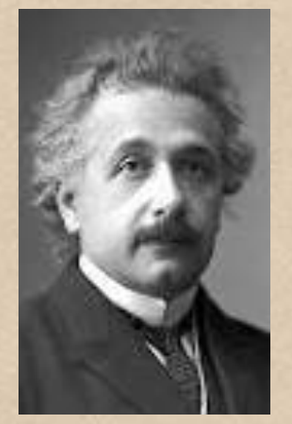
A battle of giants

Einstein



Bohr

Realism

Or against quantum randomness

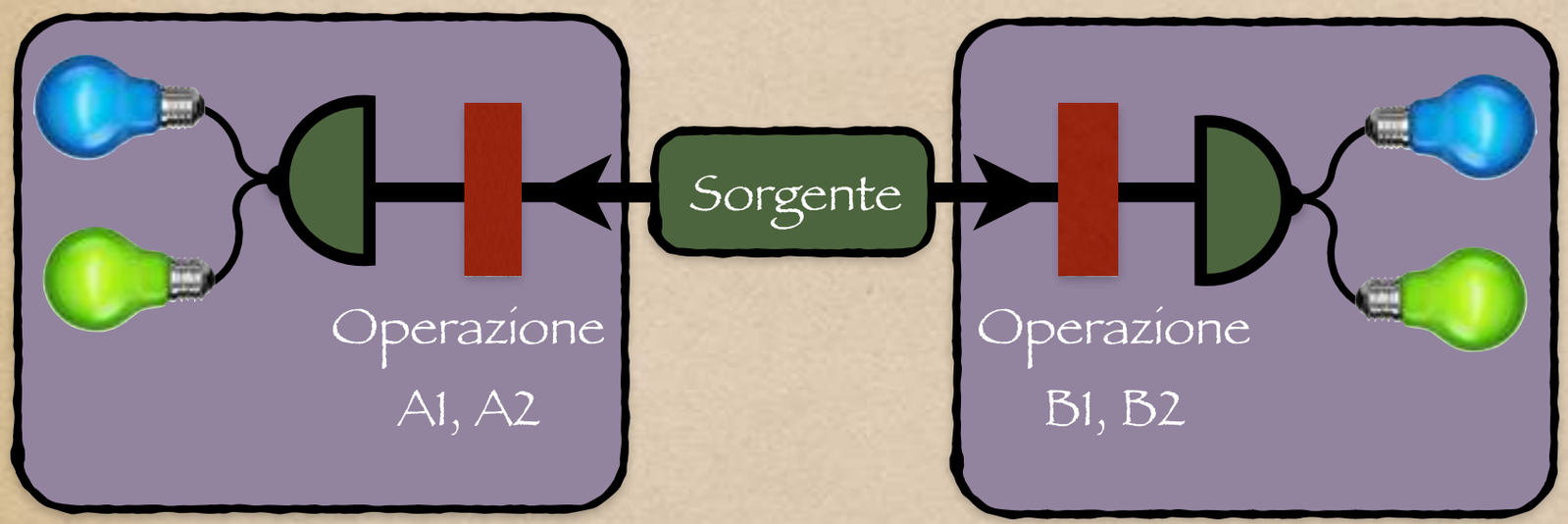
Locality

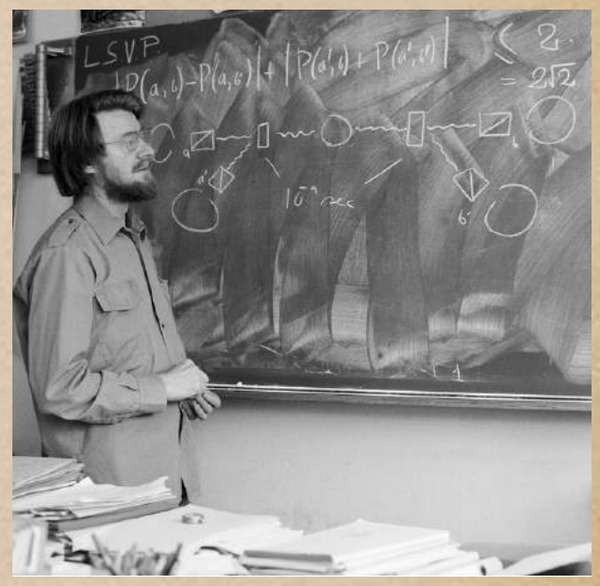
Or against spooky actions at distance

These assumptions define classical reality
and bound the degree of correlation among events
spatially separated and disjoint
Bell theorem)

Entangled systems violate such bound!!

Bell's test





Classically

$$\mathcal{B} = |C(A1, B1) + C(A1, B2) + C(A2, B1) - C(A2, B2)| \leq 2$$

± 1

Quantumly

$$2 < \mathcal{B} \leq 2\sqrt{2}$$

The second coming

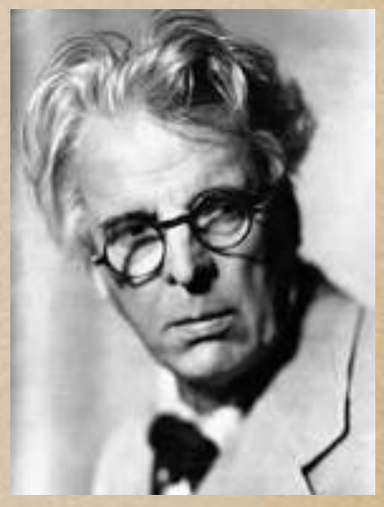
"The second coming"

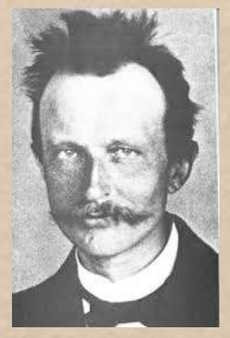
Russian icon

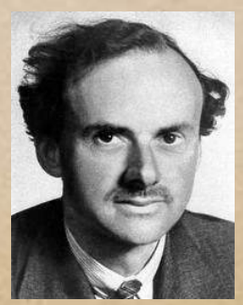
c. 1700.

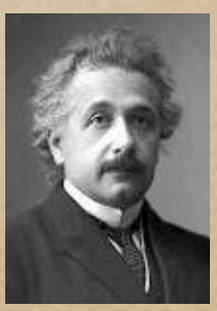
"The second coming"

(W. B. Yeats, 1919)









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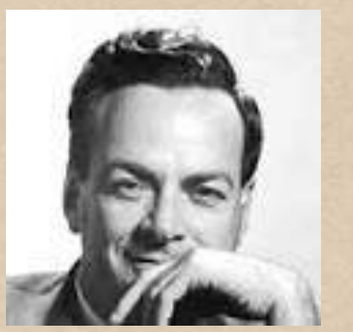
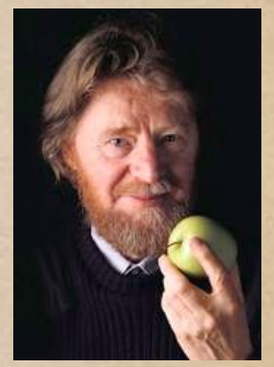
The second coming


Feynman

Deutsch

Grover


Bell

Bennett

Shor

Ekert

Zeilinger

The second quantum resolution:
we can control the quantum world

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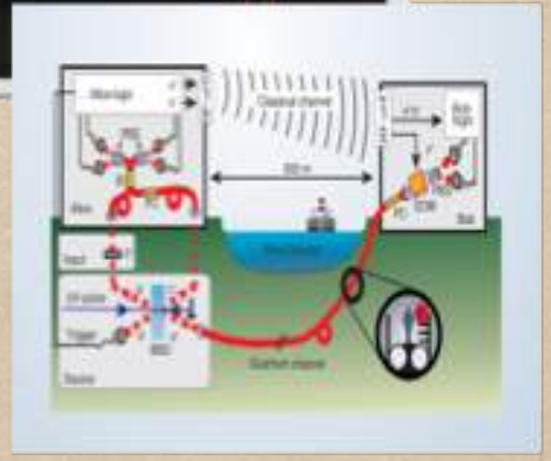
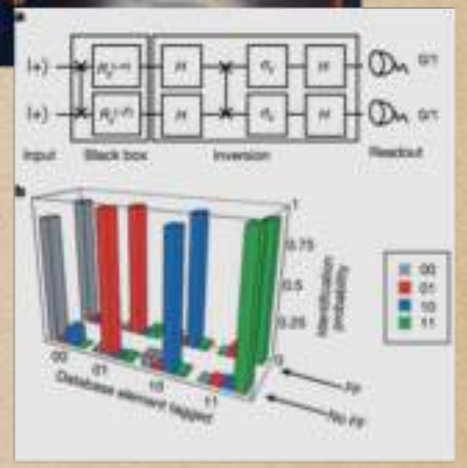
Quantum realities

Quantum cryptography



Quantum teleportation



Quantum computation

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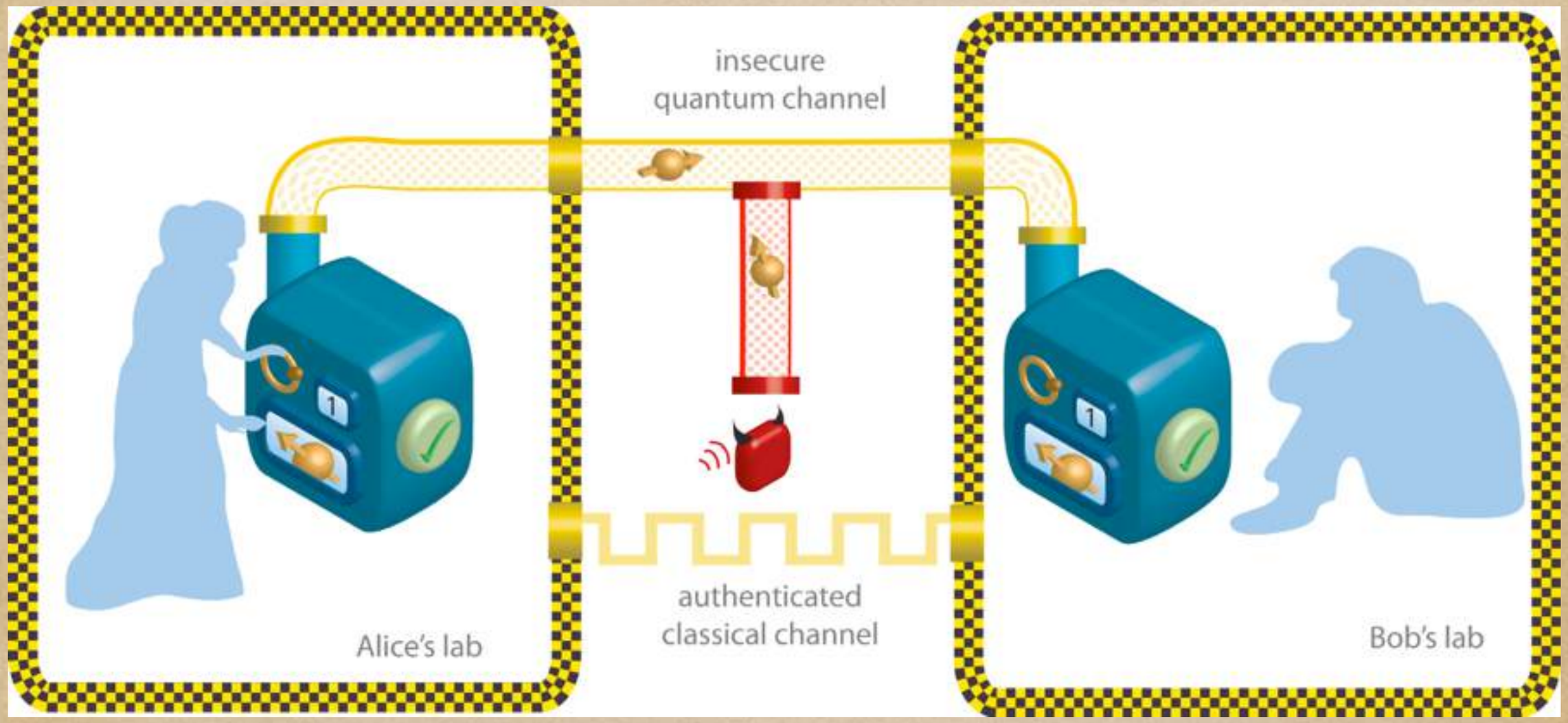
Criptography



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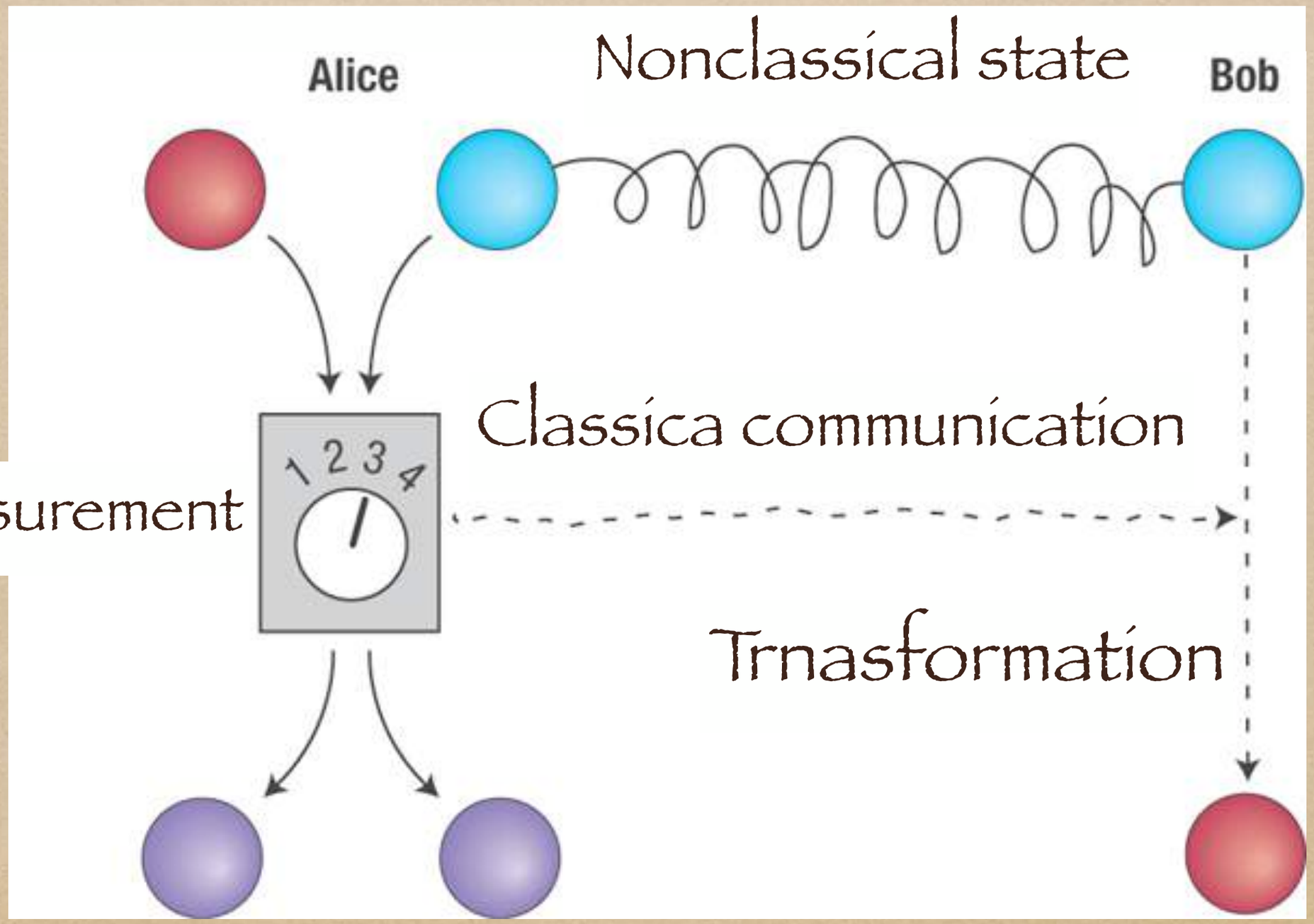
Teleportation

Teleportation



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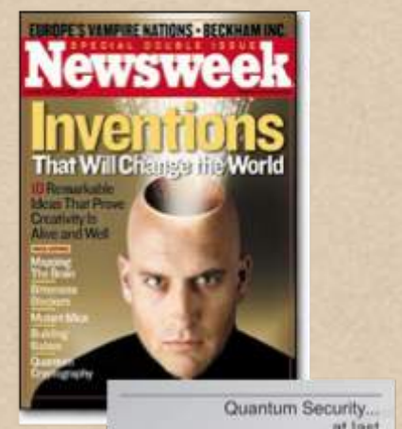
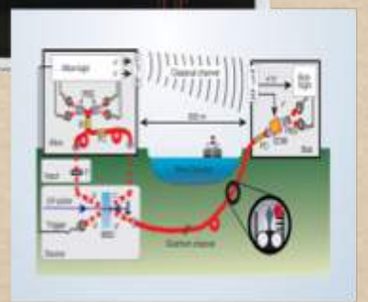
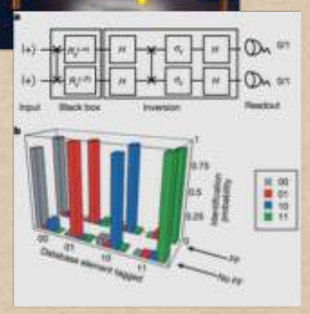
Uhmm....



Quantum cryptography



Quantum teleportation



Quantum computation

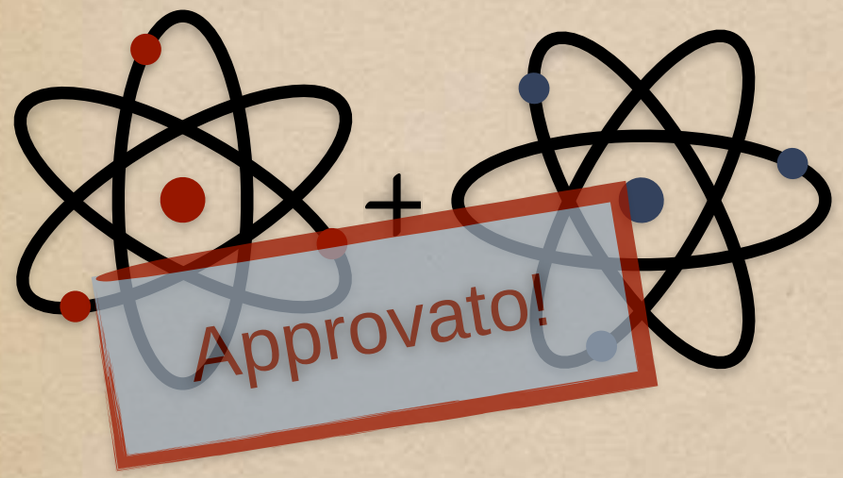
We need microscopic systems

All should be isolated

The control should be perfect!

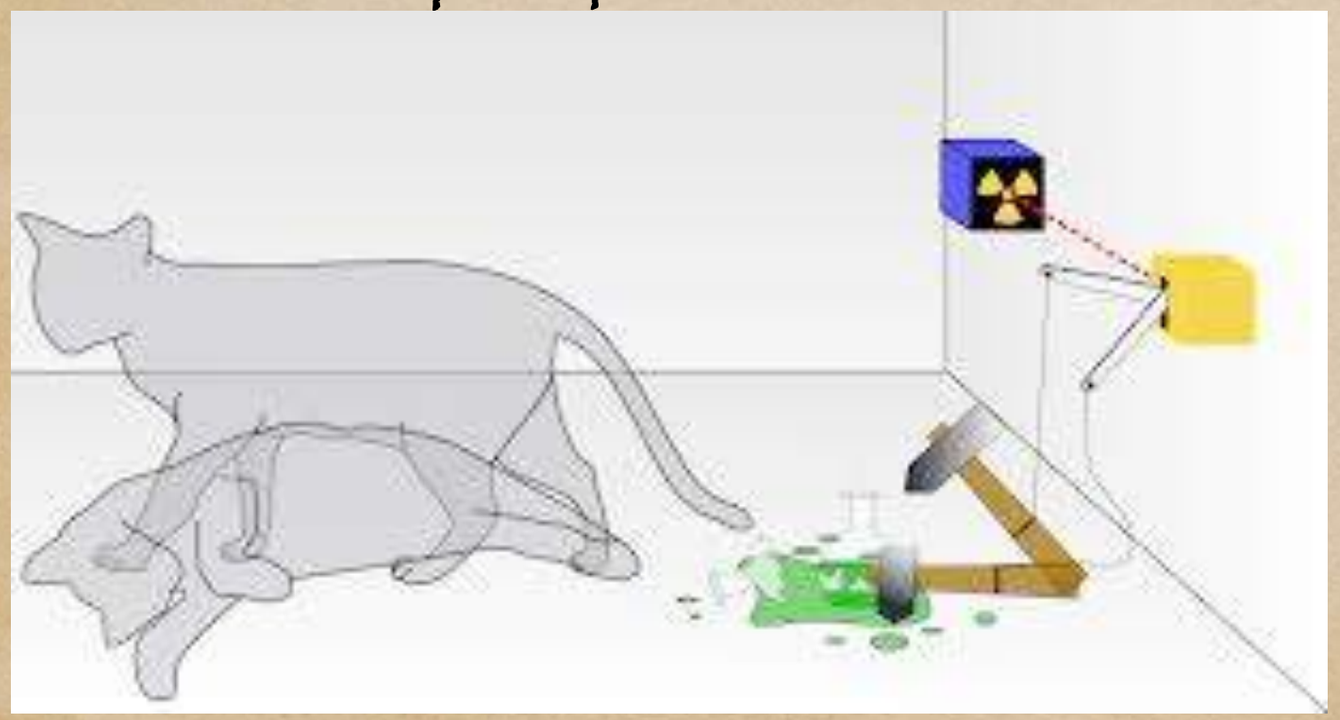
Are just microscopic systems under special conditions to be 'favoured'?

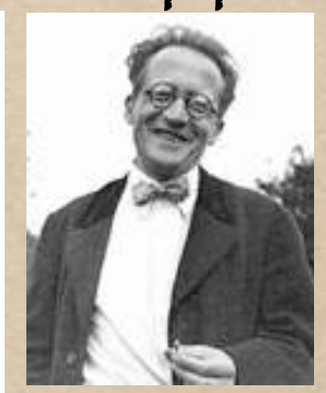
Broadening the context



Quantum effects are certified in our best labs!

Macroscopic quantum effects do not appear to be evident





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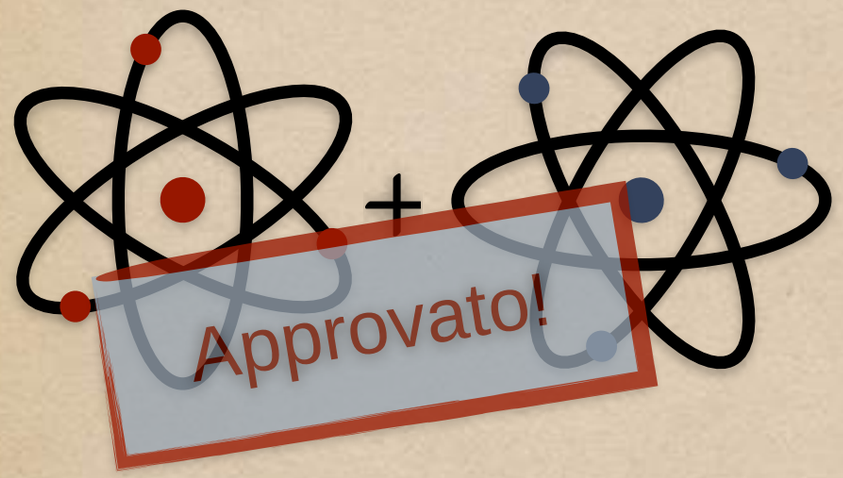
Broadening the context

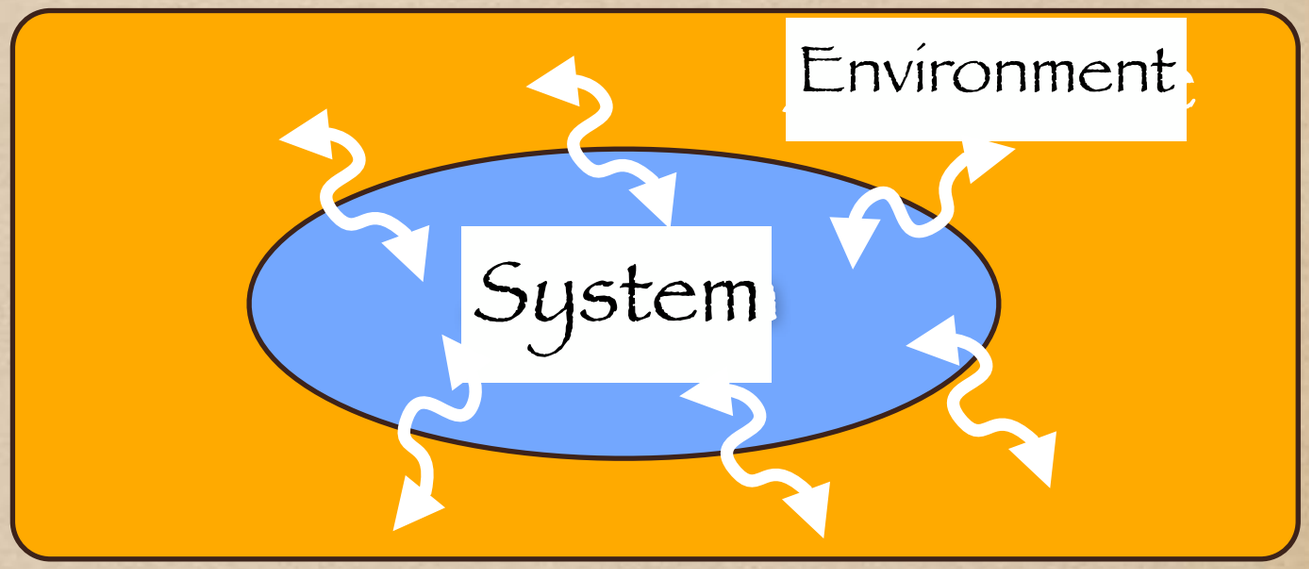


Quantum effects are certified in our best quantum labs

Macroscopic quantum effects do not appear to be evident

Decoherence

Wociej Zurek, LANL



Environment:=what is not 'system'

$$i\hbar\partial_t|\psi\rangle = \hat{E}|\psi\rangle$$

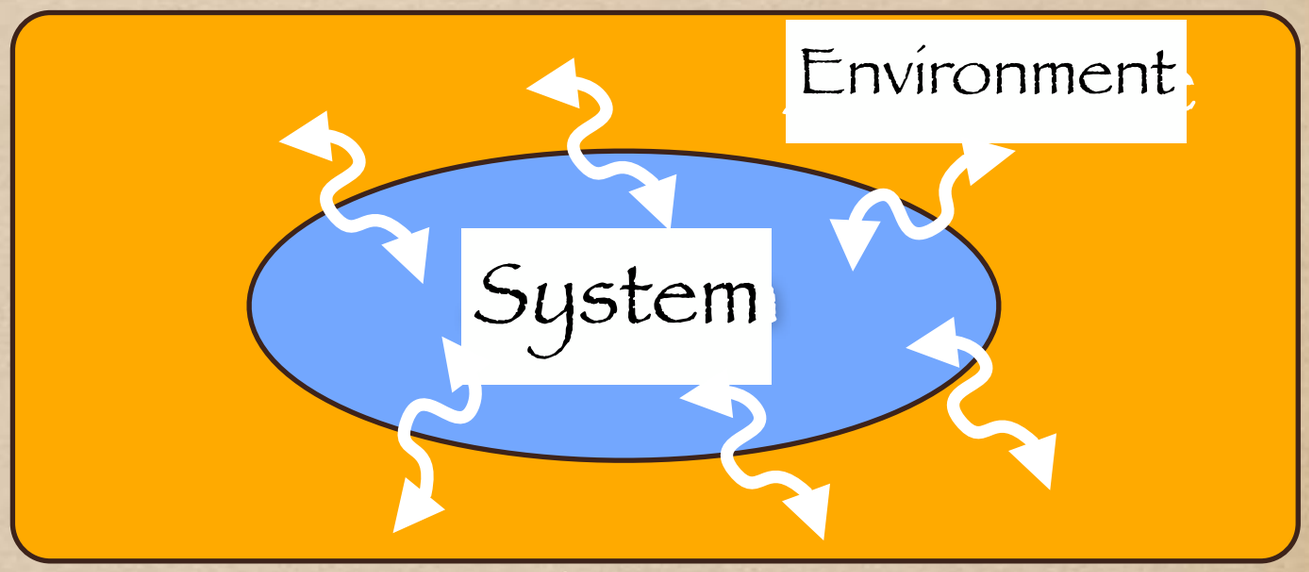
Eq. di Schroedinger:
no environment

$$\partial_t\rho = \mathcal{L}(\rho)$$

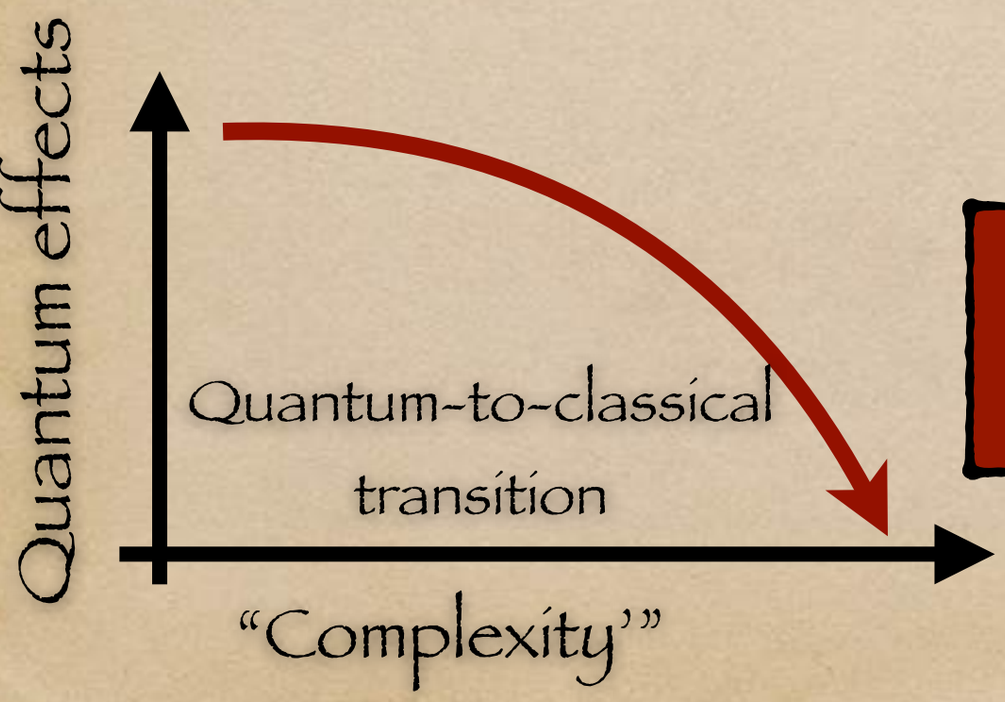
Master Equation:
environment is there

Decoherence

Wociej Zurek, LANL



Environment:=what is not system



Is it possible to observe quantum effects at a macro scale?

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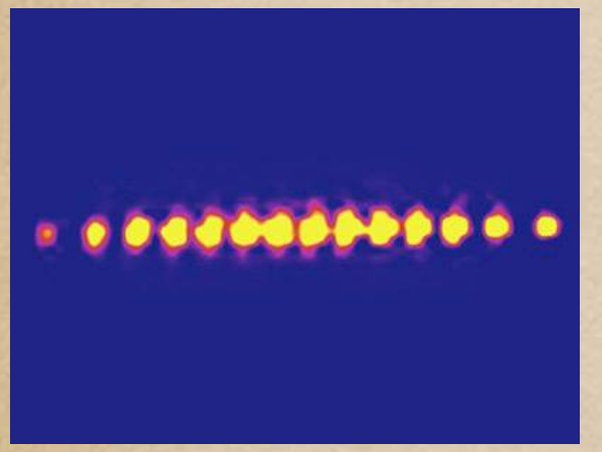
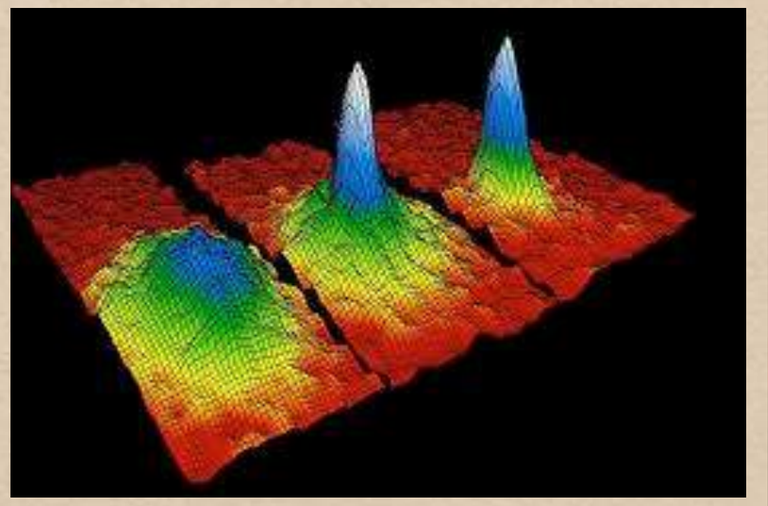
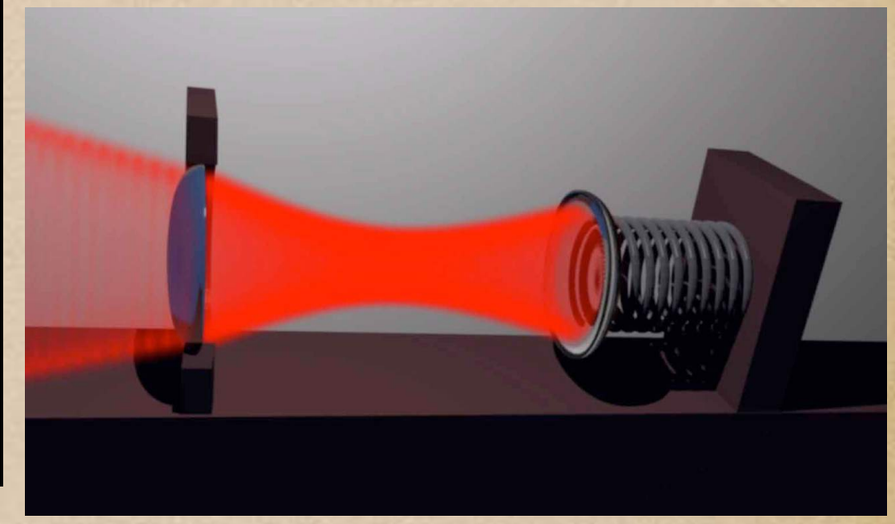
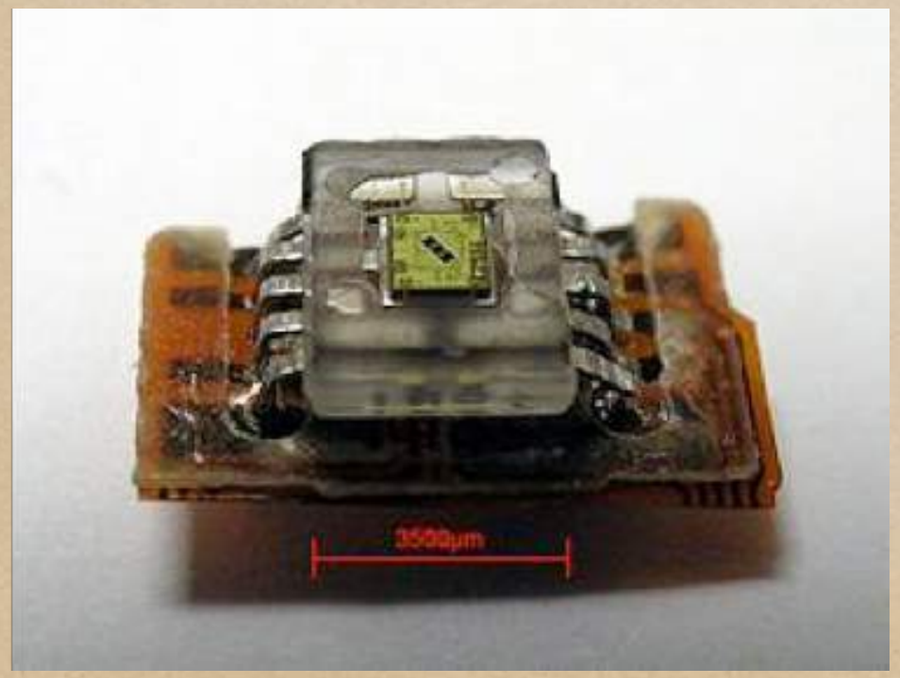
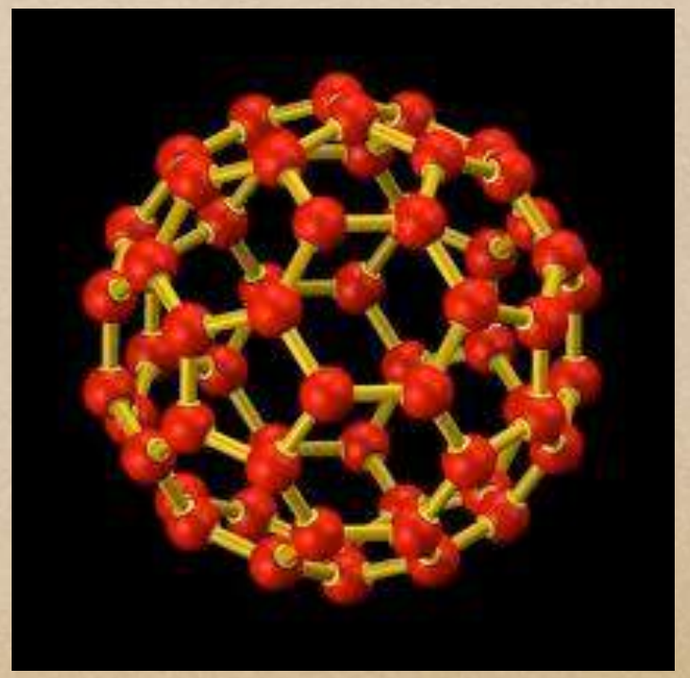
No, no, no!











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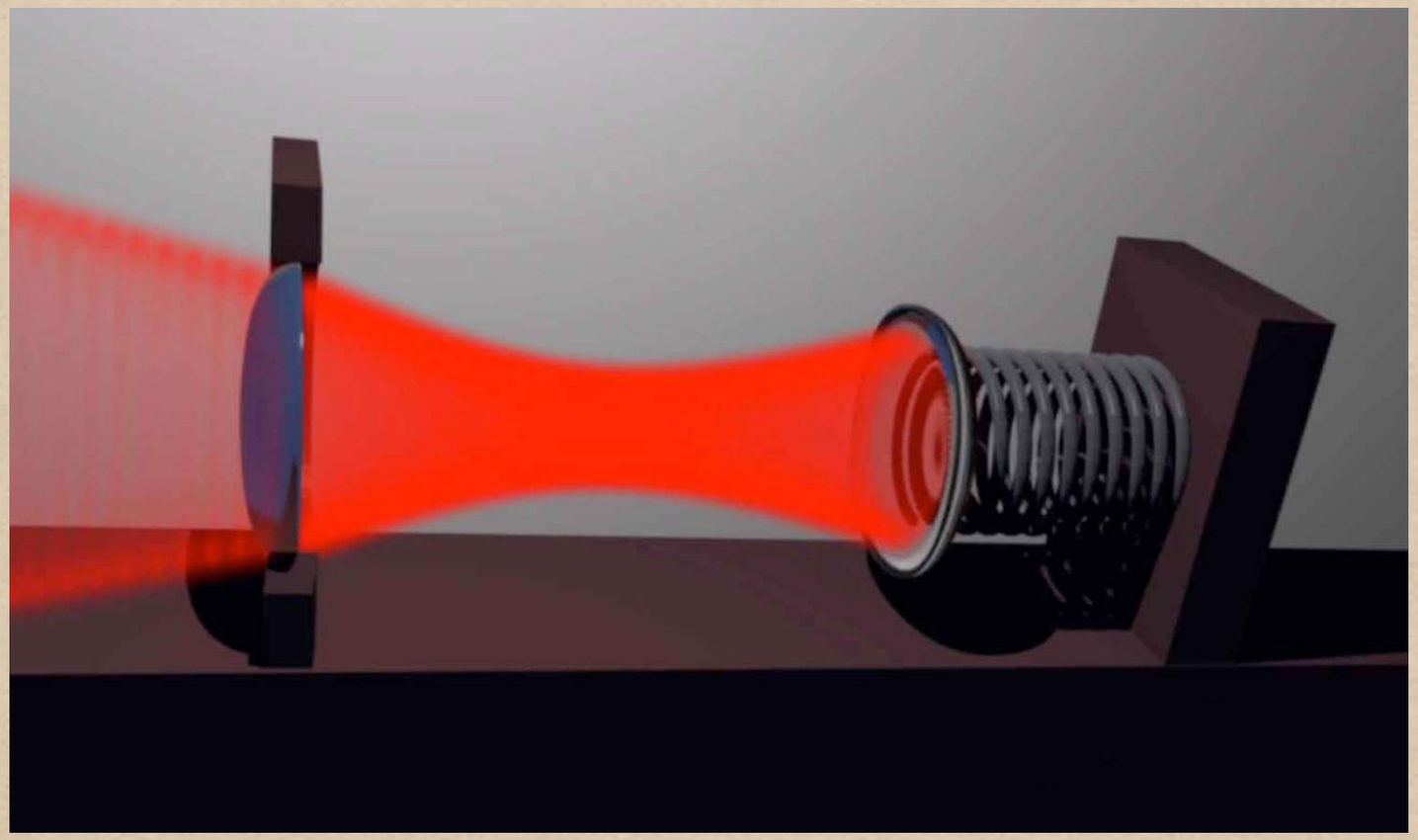
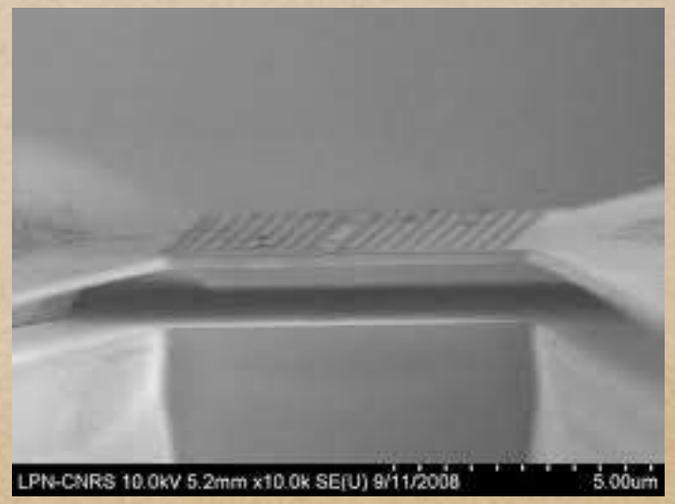
Lux fiat!

and a mirror, vibrating





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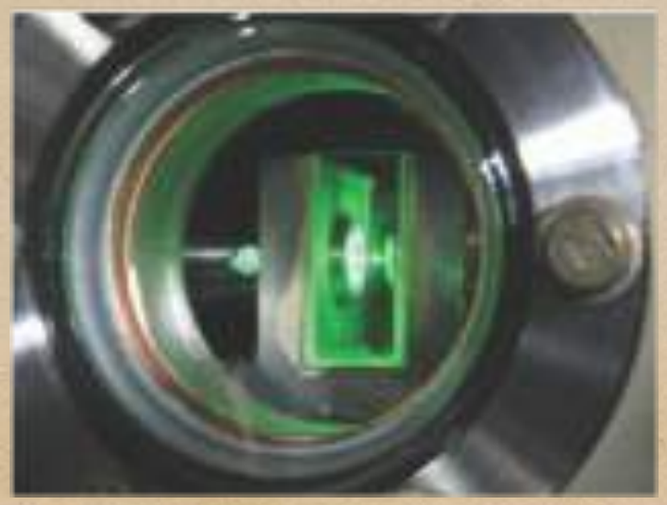
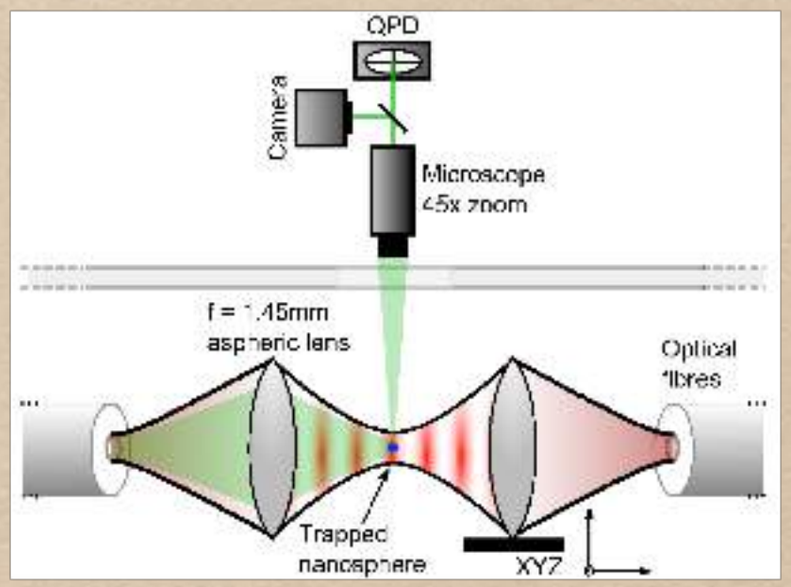
Lux fiat!

and a mirror, vibrating

Levitated nanospheres





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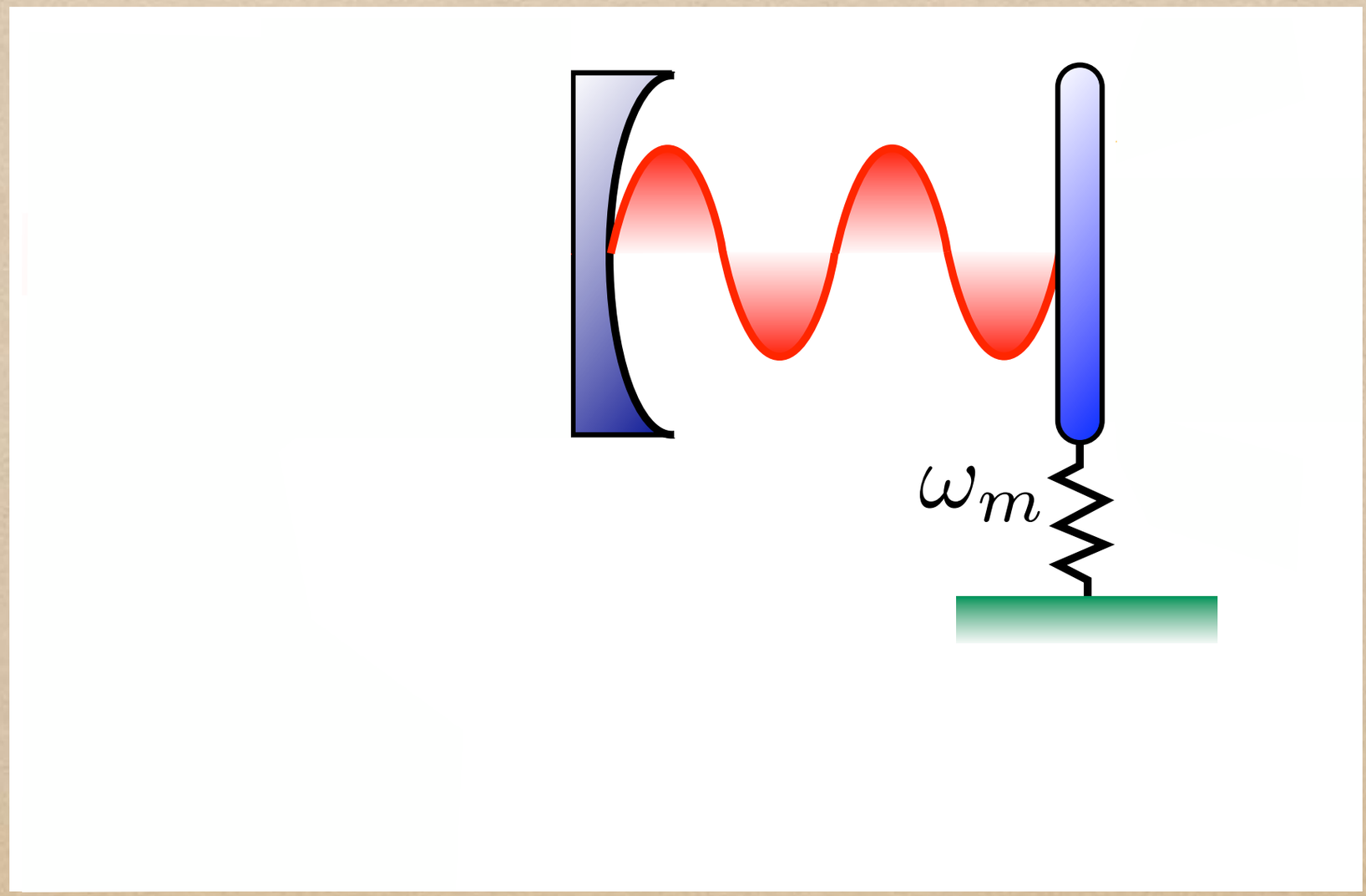
Lux fiat!

and a mirror, vibrating



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Lux fiat!

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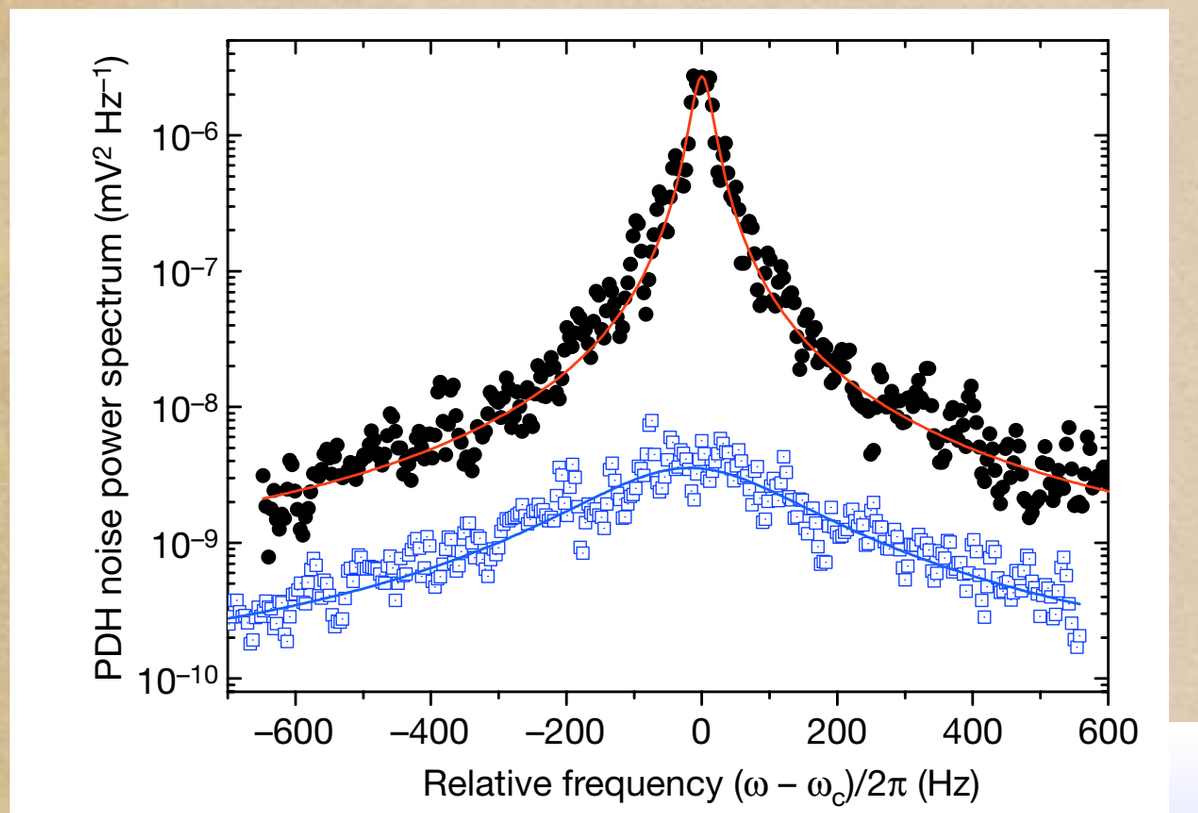
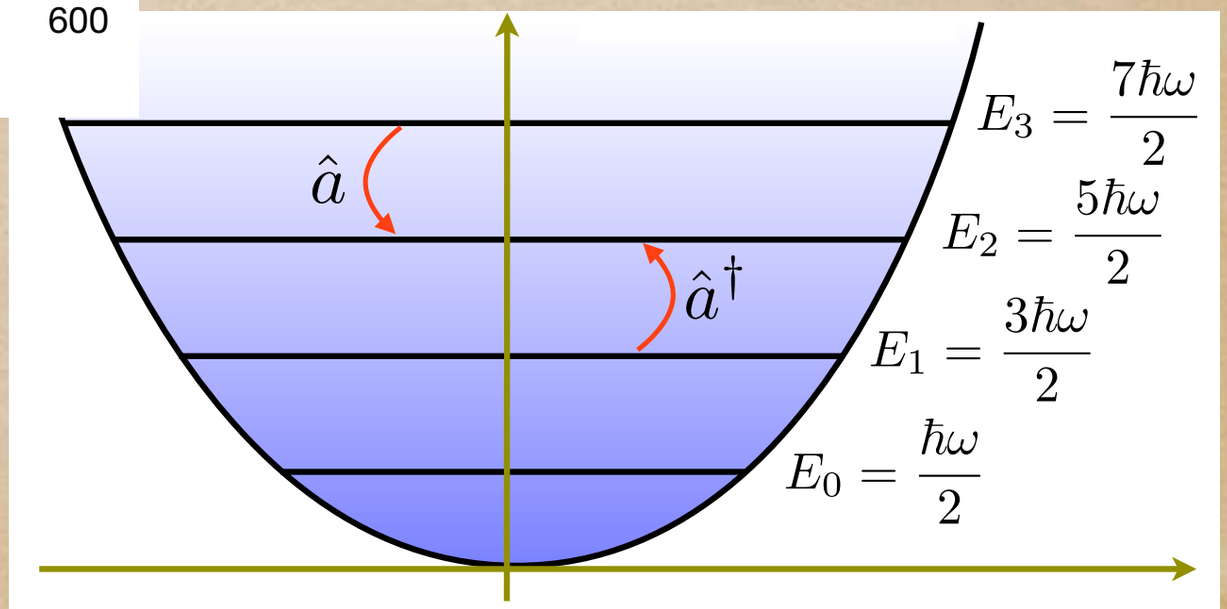


Classically

$$E = \frac{p^2}{2m} + \frac{1}{2}m\omega^2 x^2$$

Quantumly

$$E = \hbar\omega(n + 1/2)$$



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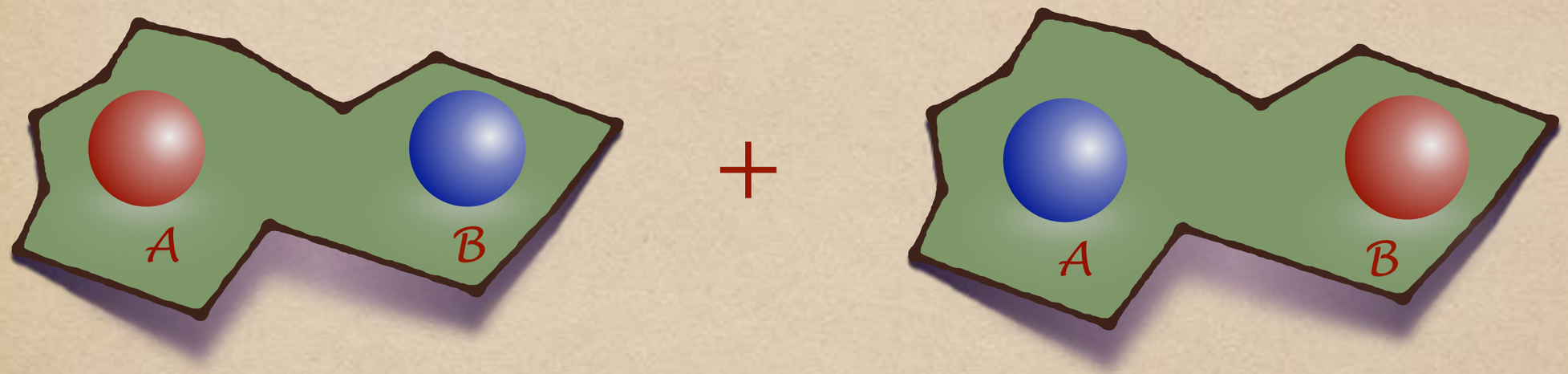
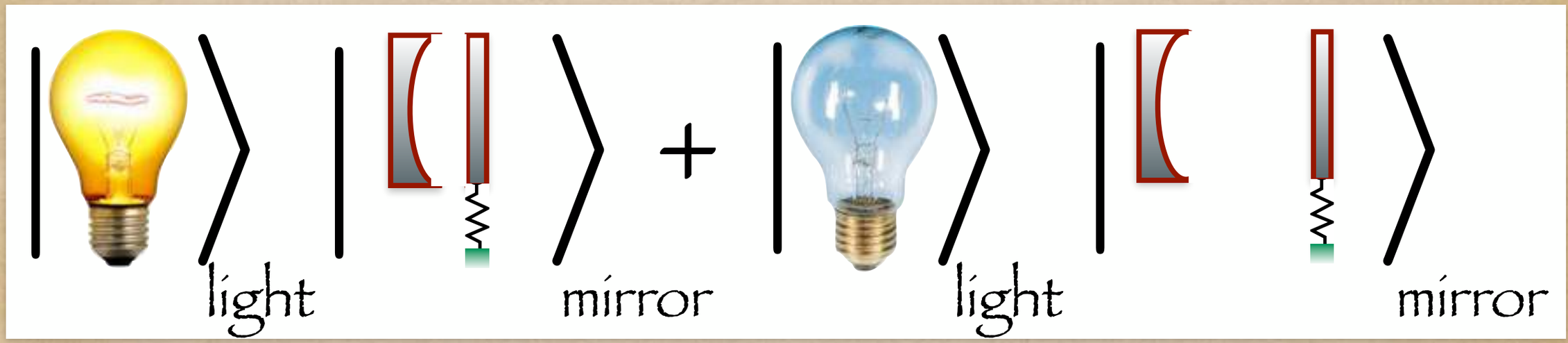
Entanglement in optomechanics





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Quantum cats

Schroedinger

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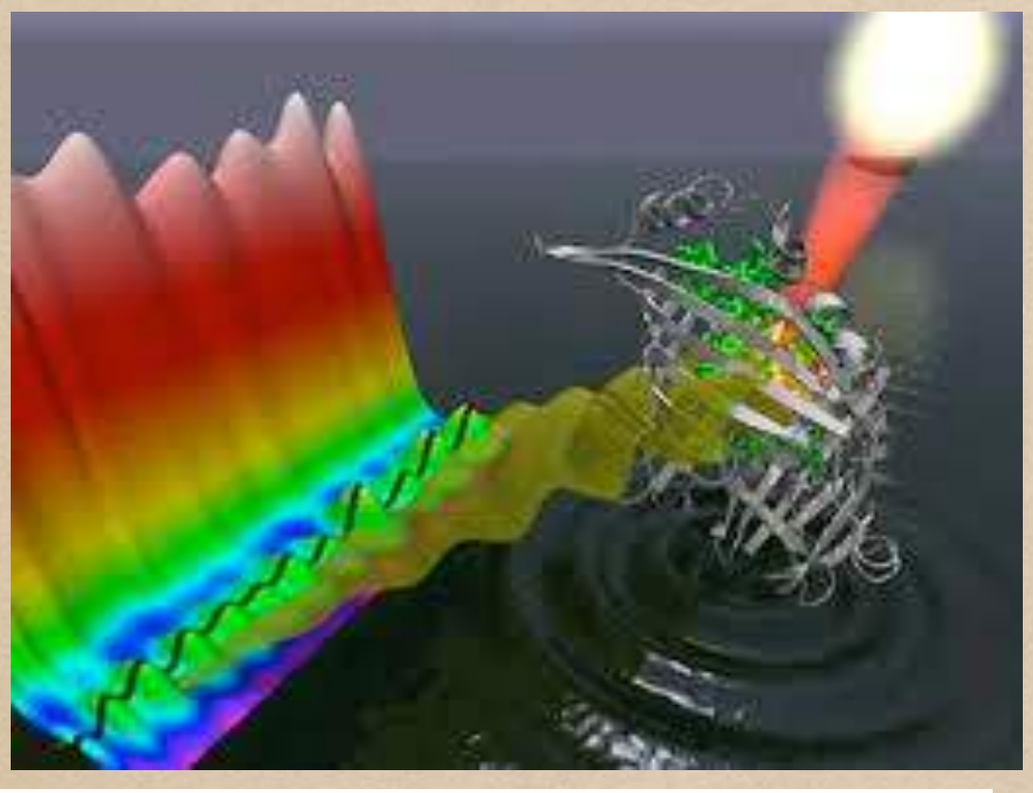
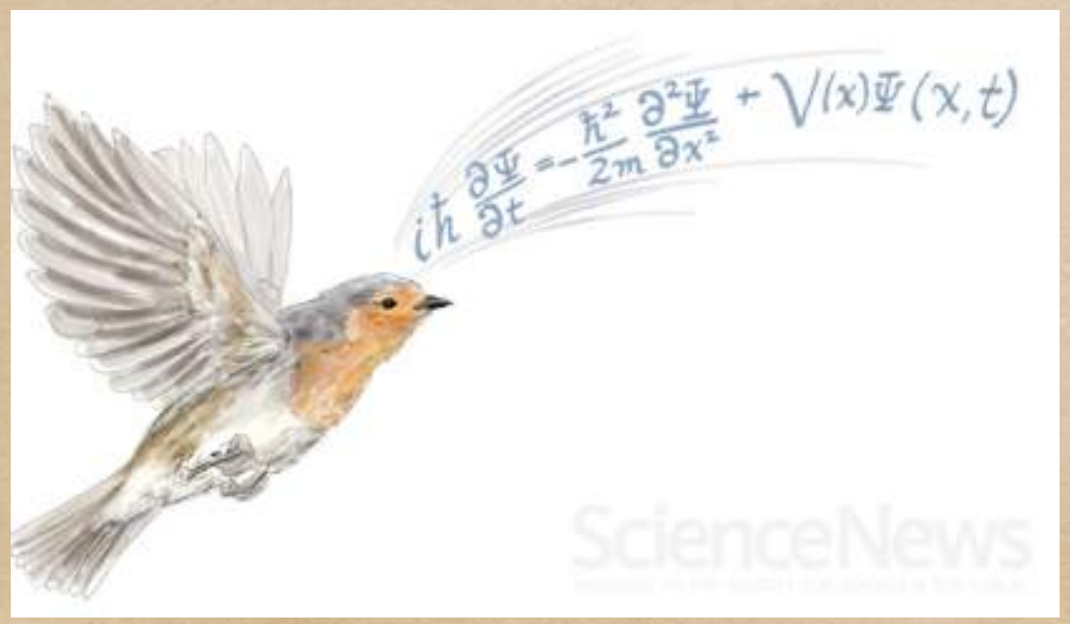
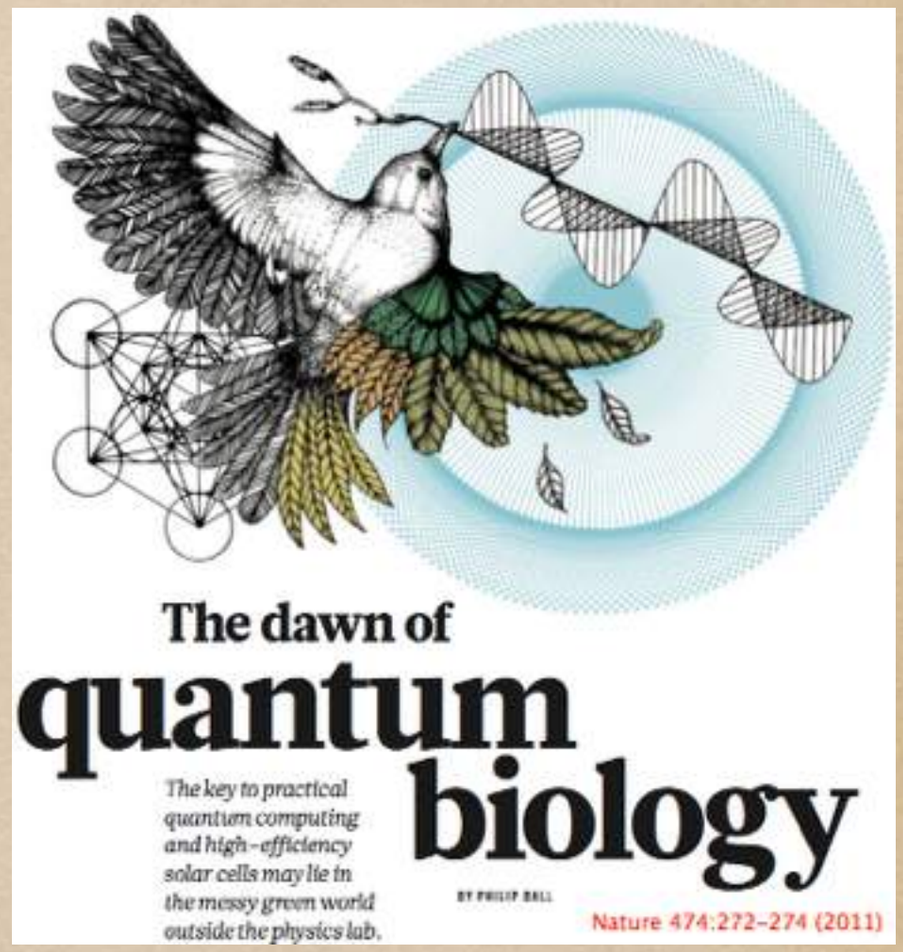
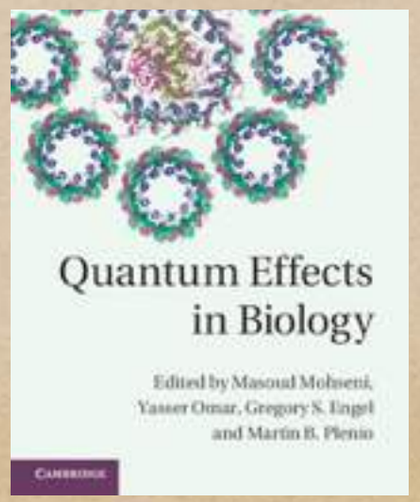




No, no, no!





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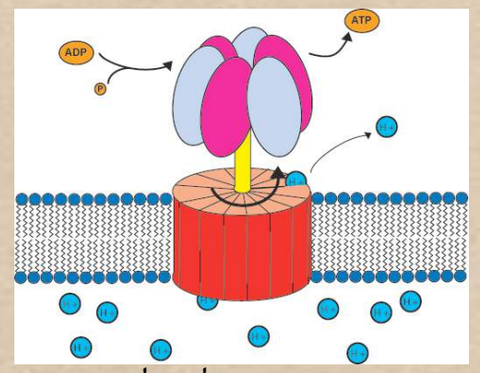
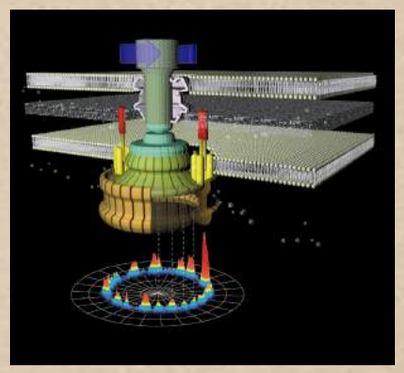
Another revolution

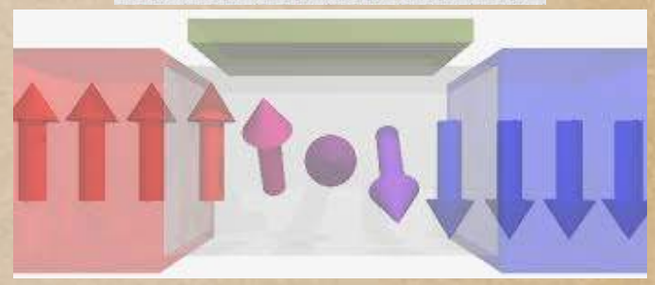
The third quantum revolution:
all is quantum!

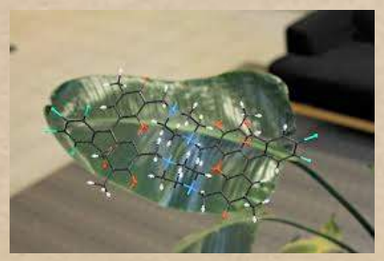


Molecular motors
Biomolecular/Biochemical networks



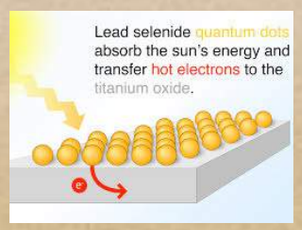
Spintronics/Magnetic memories

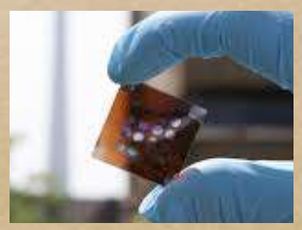




Quantum effects in
biological systems

‘Quantum-dot’
solar cells





The Belfast crew

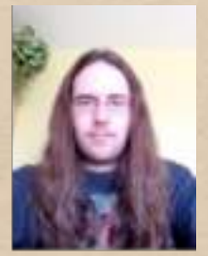
PhDs

Matteo Brunelli

Andrew Carlisle

Lorenzo Fusco

Ruari McCloskey



Darren Moore

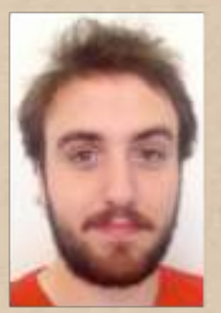
Matthew Power

Ben Rogers

Jader Pereira dos Santos

Brendan Reid

Kenneth McAlpine



Sam McMillen

Conor Gallagher

PostDocs

Mariona Moreno

Francesco Francica

Simon Pigeon

Fernando Nicacio

Steve Campbell

Staff

Gabriele De Chiara

Alessandro Ferraro

Jim McCann

MP

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