When Science meets science-fiction

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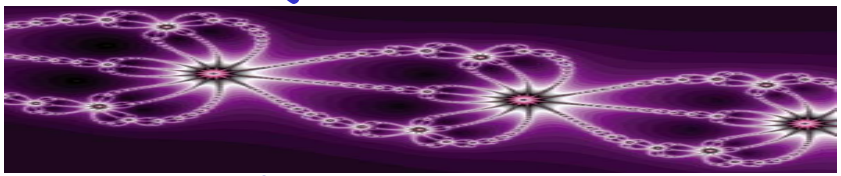
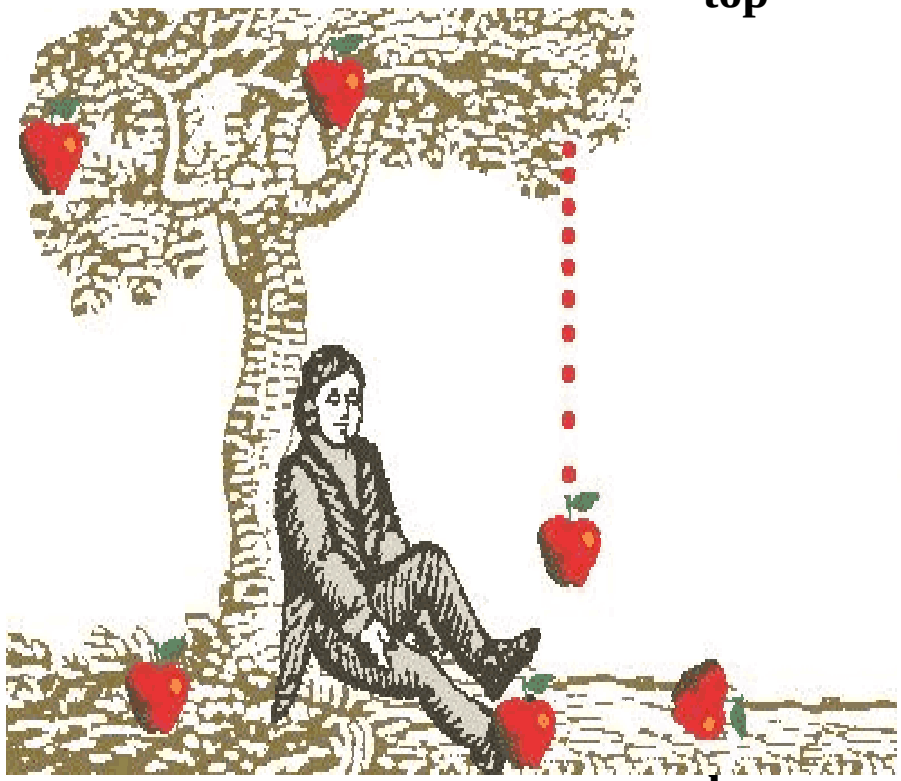
From Newton

to Quantum



Teleportation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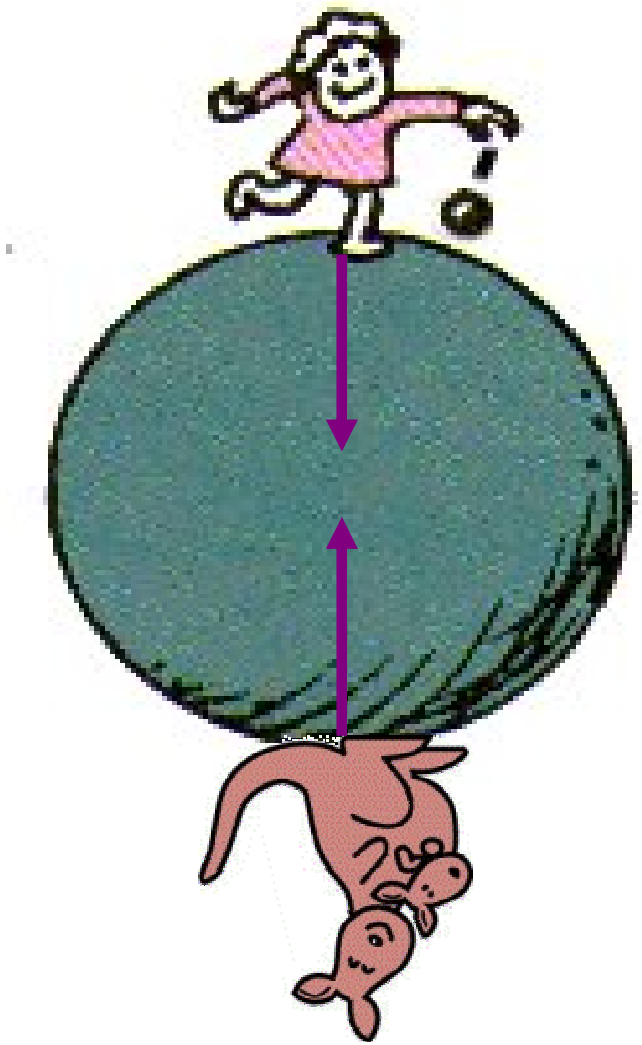
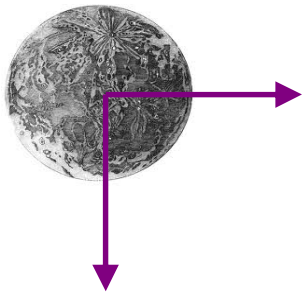
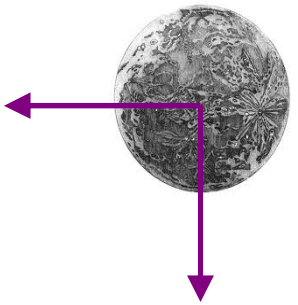




While falling down, the Moon moves forwards

$\Rightarrow$ the Moon misses Earth

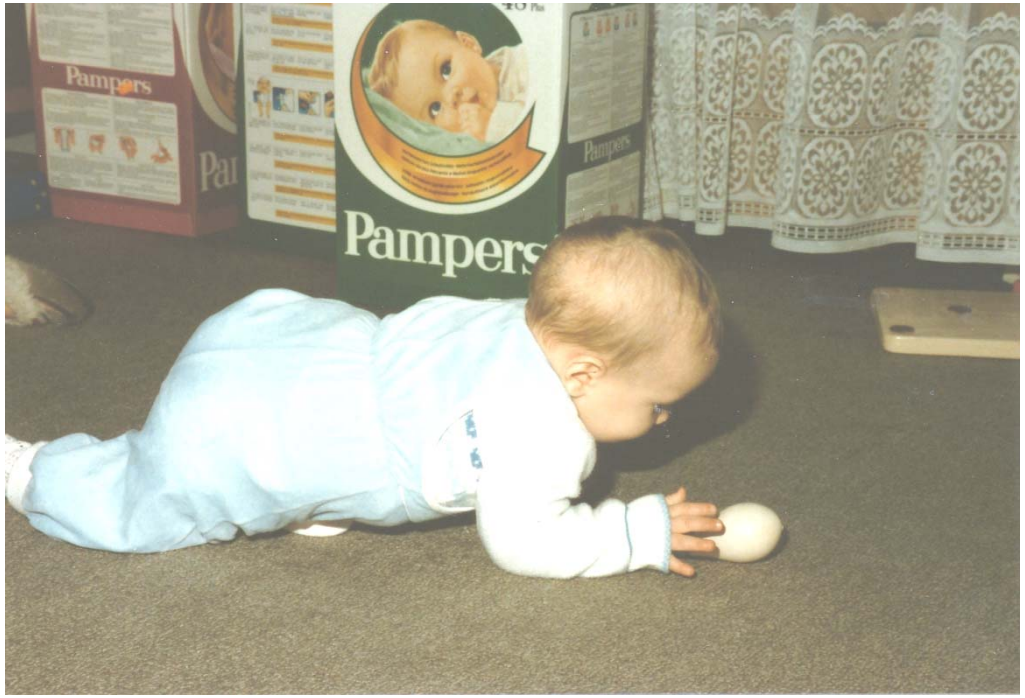


While falling down, the Moon moves forwards

$\Rightarrow$ the Moon misses Earth

$$F = G \cdot \frac{m \cdot M}{d^2}$$

My first physics experiments



In order to interact with an object, one has to crawl to it or to throw balls at it.

Telekinesis: that doesn't work !

Likewise, telepathy doesn't work: no information can go from one location to a distant location without some physical support carrying this information.

A good question

Hey, Dad/mom, how does the Moon know in which direction she is supposed to fall ?

Does the Moon (and your body) use a sort of stick to feel the presence of Earth ? Or does she send her some sorts of balls ?

That's an excellent question, we are now in position to do some real Physics !

Newton asked himself this deep question

That Gravity should be innate, inherent and essential to Matter, so that one Body may act upon another at a Distance thro' a Vacuum, without the mediation of any thing else, by and through which their Action and Force may be conveyed from one to another, is to me so great an Absurdity, that I believe no Man who has in philosophical Matters a competent Faculty of thinking, can ever fall into it.

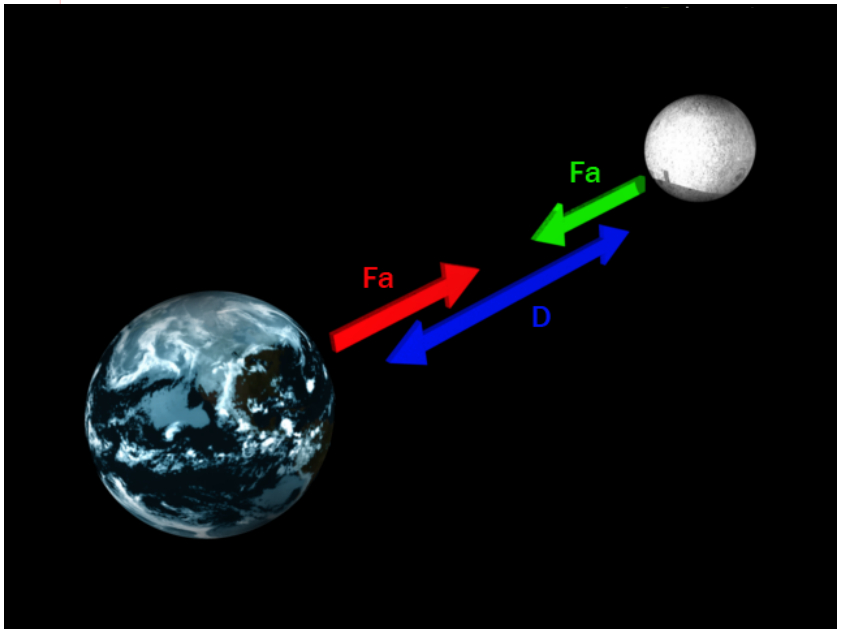
Isaac Newton
Papers & Letters on Natural Philosophy and related documents
Edited by Bernard Cohen, assisted by Robert E. Schofield
Harvard University Press, Cambridge, Massachusetts, 1958

Newton

One should be mad to believe in my theory of Universal Gravity !

Nevertheless, this theory dominated Science during more than three centuries and one still teaches it today.

Newton's non-locality allows for telepathy



According to Newton, if one would move a rock on the Moon, this would have an immediate effect on our weight on Earth.

That would be telepathy !

Had someone done the experiment, he would:

1. Have falsified Newton's theory, and
2. Have found that gravity propagates at the speed of light.

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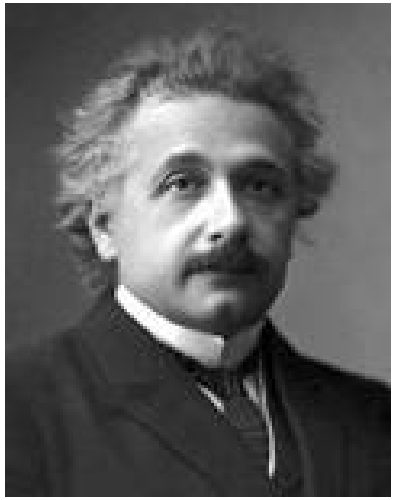
Einstein

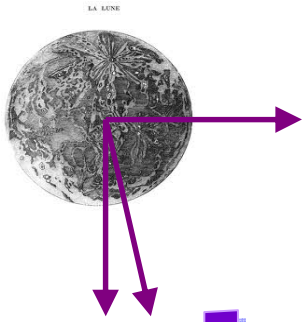


The childish question "how does the Moon know in which direction to fall" has been resolved only by Einstein's general relativity theory.

Roughly, Earth, Moon and all objects continuously send out in all directions little balls.

These little balls are called gravitons.

They have no mass, as particles of light (photons), and propagate at the speed of light.



Isn't Physics beautiful ?

Because of the slight propagation delay of the gravitons, the Moon "falls" slightly next to the centre of Earth.

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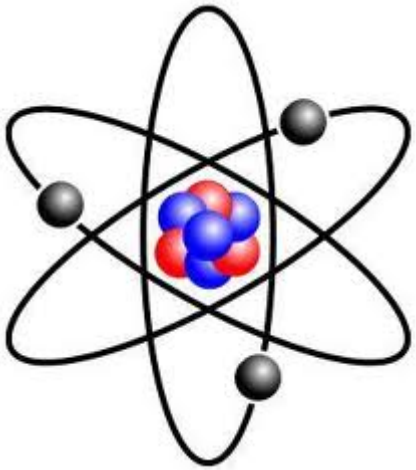
Isn't Physics beautiful ?

But that's not the end. About 10 years after general relativity, here comes quantum theory, the theory that describes the world of atoms and photons (particles of light).

Schrödinger

$$\dot{\Psi} = -i \cdot H \cdot \Psi$$



Discovered in Arosa, Switzerland

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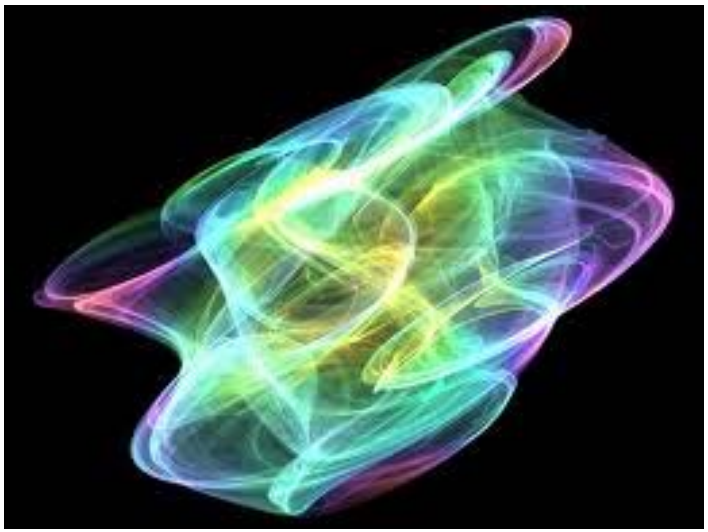
Schrödinger

Hey, Dad/Mom, how do the electrons know where the nucleous is ?

One is tempted to search for the "qravitons"



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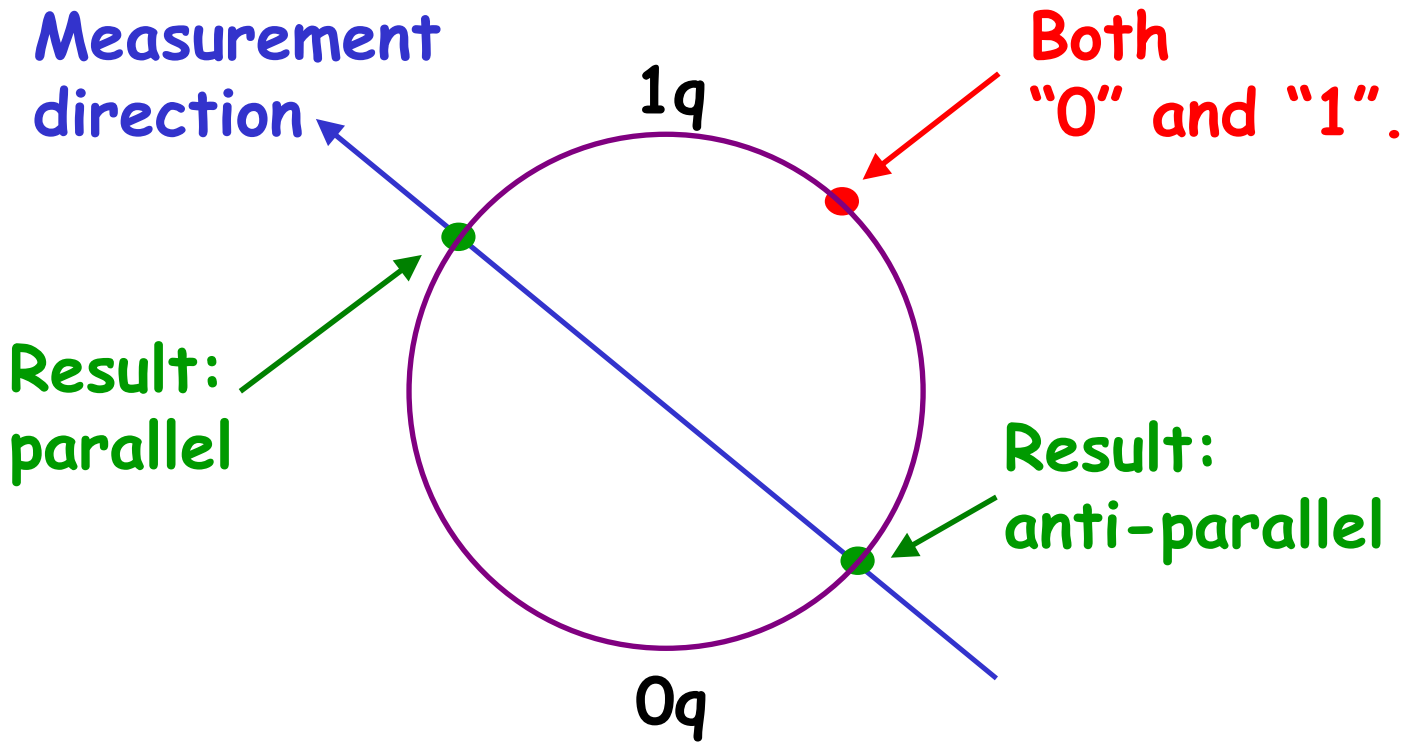
Qubit = Quantum Bit



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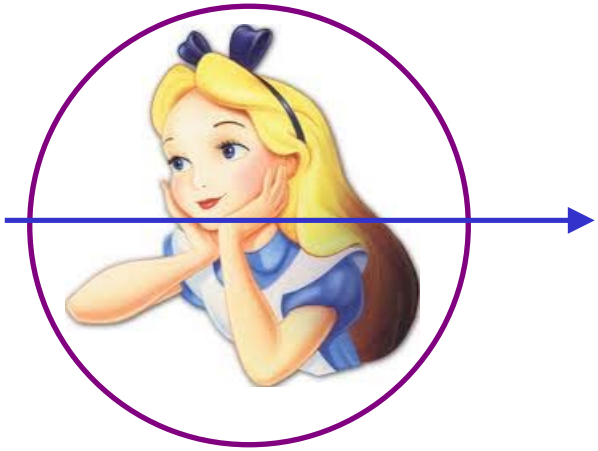
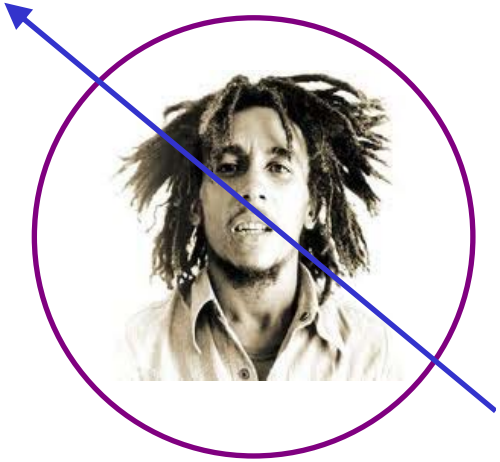
2 qubits

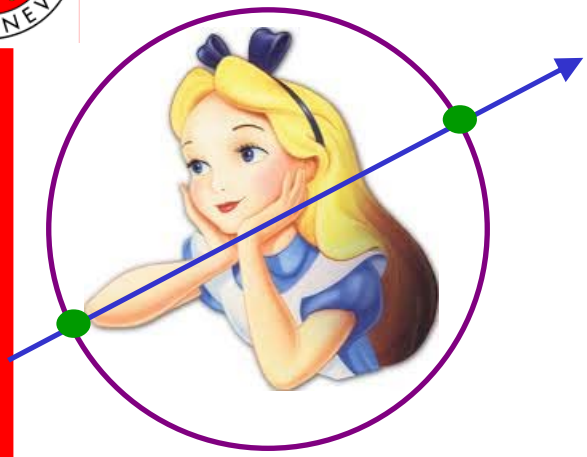
Alice large distance ***Bob***

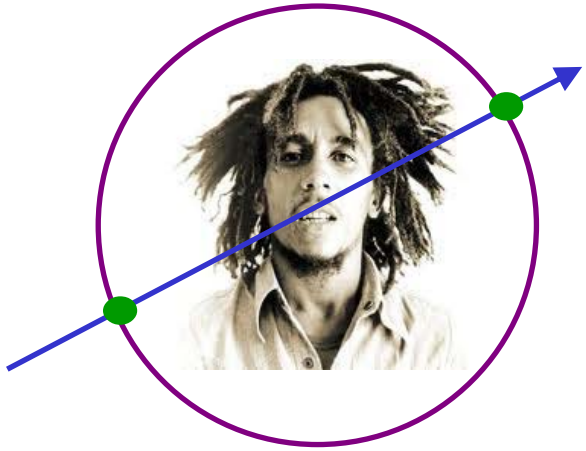
measurement a ***measurement b***





Entanglement of 2 qubits





Entanglement: 1. same measurement ⇒ same results

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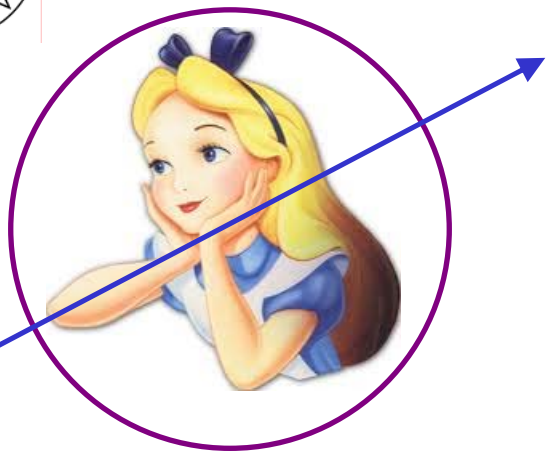
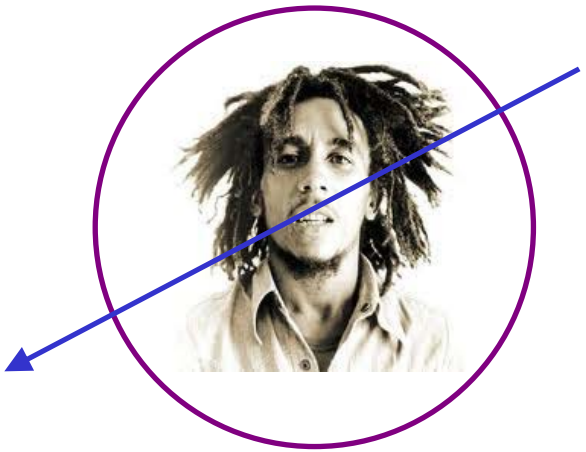
Entanglement of 2 qubits





Entanglement: 1. same measurement ⇒ same results

2. opposite measurements ⇒ opposite results

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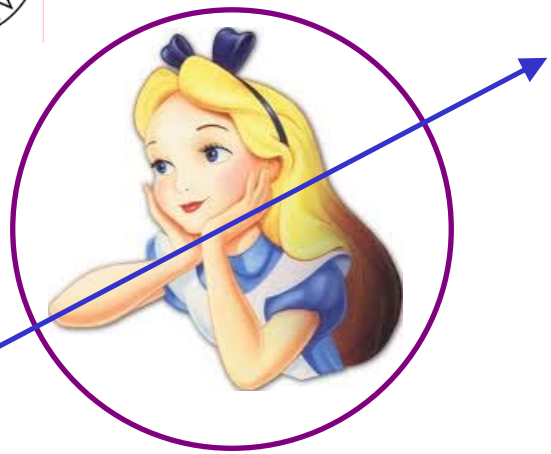
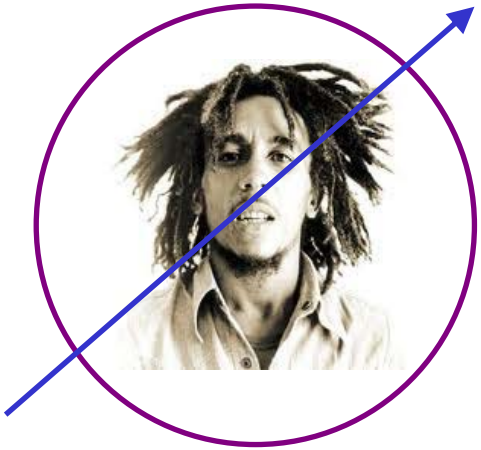
Entanglement of 2 qubits





Entanglement: 1. same measurement ⇒ same results

2. opposite measurements ⇒ opposite results

3. nearby measurements ⇒ high probability to collect same results

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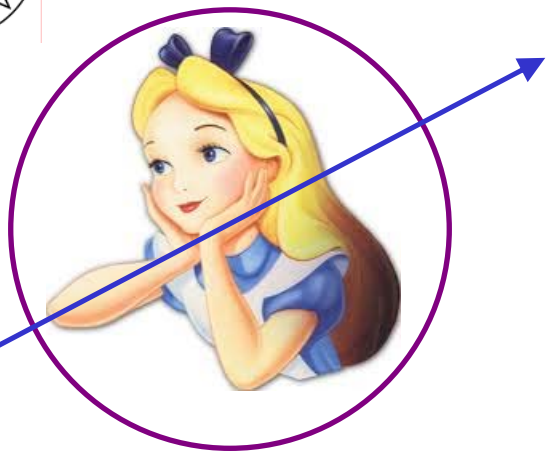
Entanglement of 2 qubits



As for gravitation, there is full correlation between Alice (on the Moon) and Bob (on Earth).

As for Newton's theory, quantum theory predicts that the effect is immediate.

Let's look for "gravitons"

Satigny – Geneva – Jussy

The "gravitons" should propagate at at least 100'000 times the speed of light !

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Salart et al., Nature 454, 861, 2008
Cocciaro et al., PLA 375, 379, 2011
J-W Pan et al., PRL 110, 260407, 2013

Nature 454, 861, 2008

There are no "graviton".

History doesn't repeat itself.

Hey Dad/Mom, how do the quantum bits manage to always give the same answer when asked the same question ?

Hypothesis: they do as good students do, they learn one answer per possible question.

The Bell game

Measurement direction *a*

Measurement direction *b*

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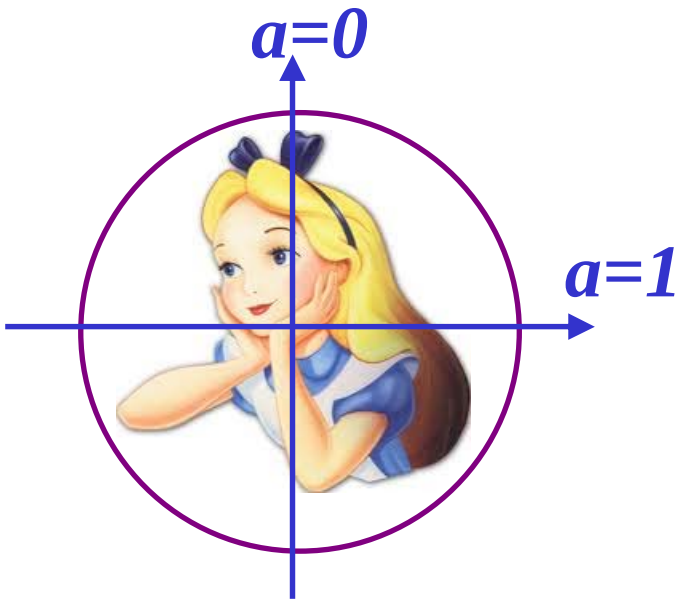
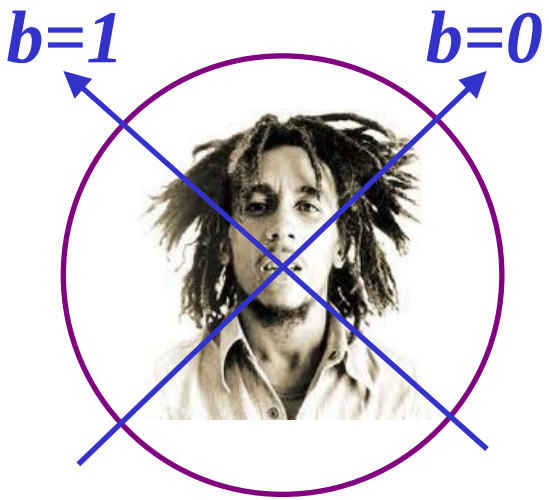
Rules of the Bell game:

If $a \times b = 0$, Alice and Bob get one point each time they give the same answer.

If $a \times b = 1$, Alice and Bob get one point each time they give opposite answers.

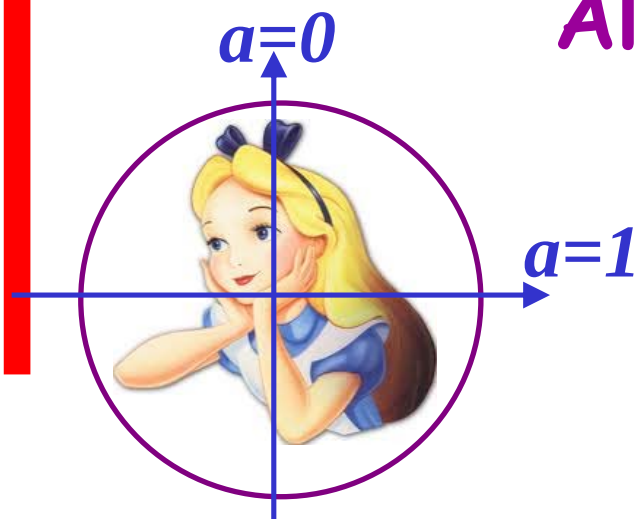


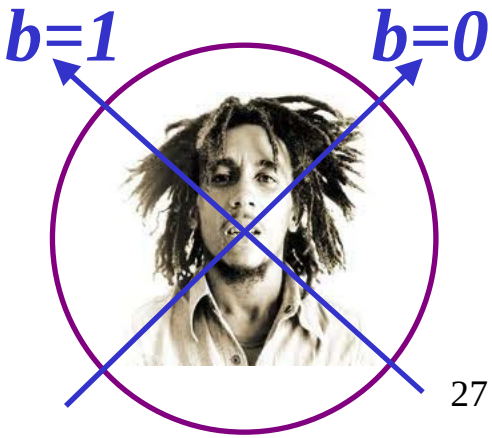


A little calculation

a	b	$a \times b$	
0	0	$0 \times 0 = 0$	**The goal of Bell's game**
0	1	$0 \times 1 = 0$	*Identical answers*
1	0	$1 \times 0 = 0$	
1	1	$1 \times 1 = 1$ $\Rightarrow$	*Opposite answers*

It looks easy, isn't it?
… except that
Alice knows only *a*
and Bob
only *b*.





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A little calculation

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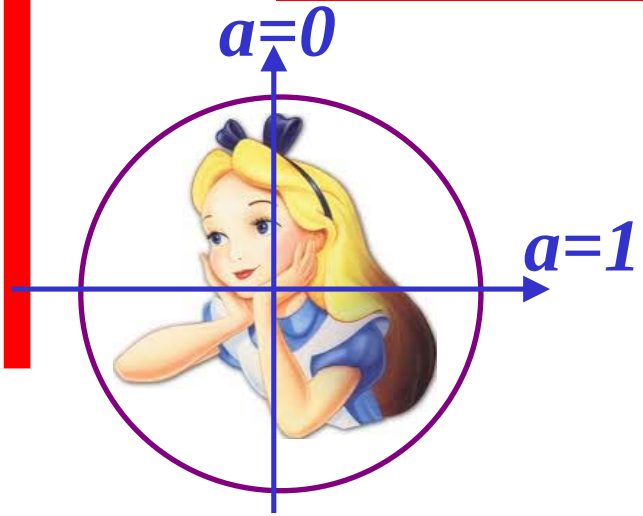
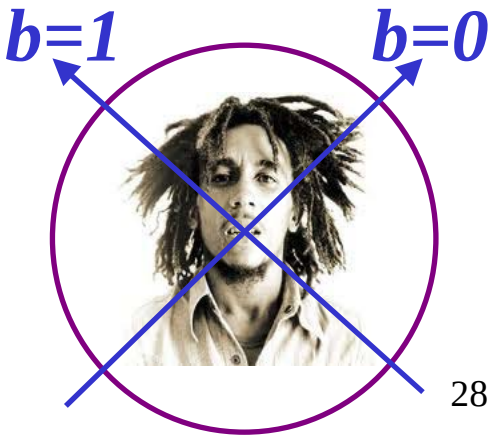
a	b	$a \times b$	
0	0	$0 \times 0 = 0$	Identical answers
0	1	$0 \times 1 = 0$	
1	0	$1 \times 0 = 0$	
1	1	$1 \times 1 = 1$	$\Rightarrow$ Opposite answers

The goal of Bell's game

Hey Dad/Mom, how can they calculate $a \times b$ if no one knows both a and b ?





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Hey Dad/Mom, how can they calculate $a \times b$ if no one knows both a and b ?

As $a \times b$ equals zero 3 times out of 4, Alice and Bob can bet on $a \times b = 0$ and arrange to always give identical answers.
Thus they win 3 times out of 4.

Home work:

Convince yourself that Alice and Bob can't win more frequently than 3 times out of 4,
(nor lose more frequently than 3 times out of 4).

Alice and Bob can't win more frequently than 3 times out of 4

It's pretty intuitive, remember that Alice doesn't know b and Bob doesn't know a.

To do better, Alice should sneak over to Bob, or should throw him some kinds of balls with her question written on.

Alice and Bob can't win more frequently than 3 times out of 4

It's pretty intuitive, remember that Alice doesn't know b and Bob doesn't know a.

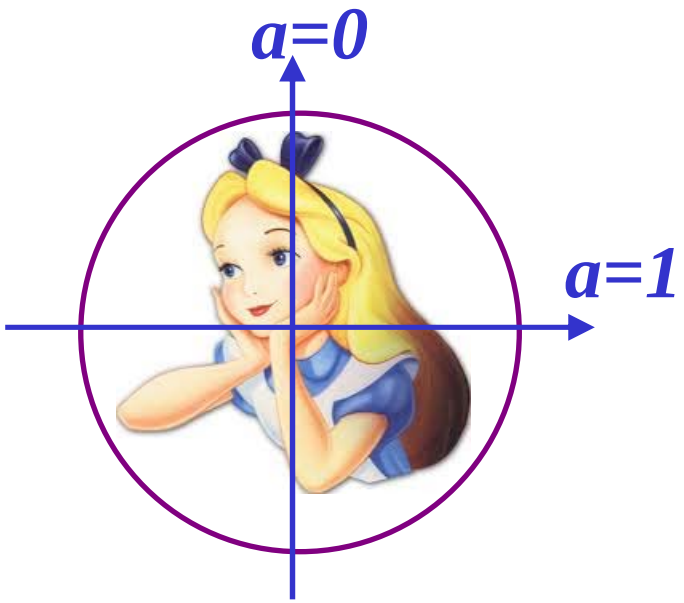
No student can win more frequently than 3 times out of 4.

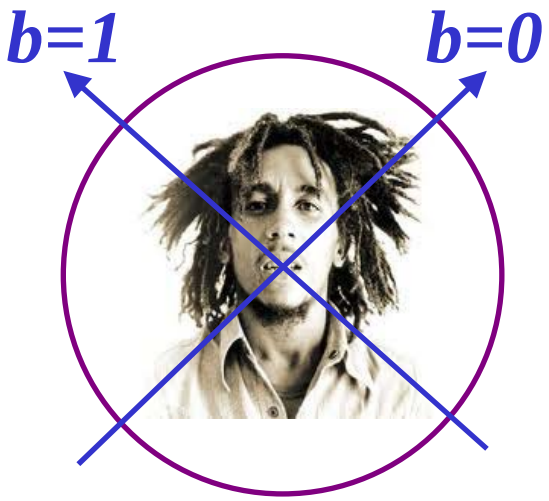
Except if the students are quantum !

Indeed …
quantum theory predicts it's possible to win at Bell's game more frequently than 3 times out of 4 !

Hey Dad/Mom, how does Nature calculate $a \times b$ when *a* and *b exist nowhere* together ?

Quantum prediction: one can win more frequently than 3 times out of 4, i.e. do nonlocal calculations !





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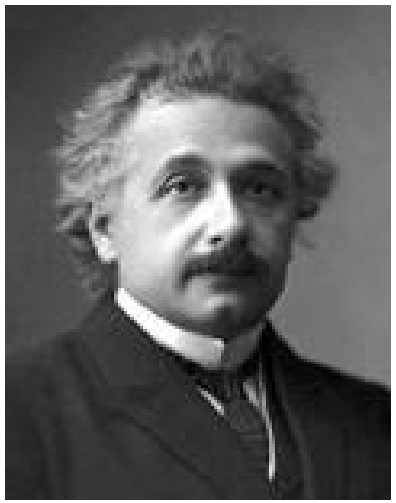
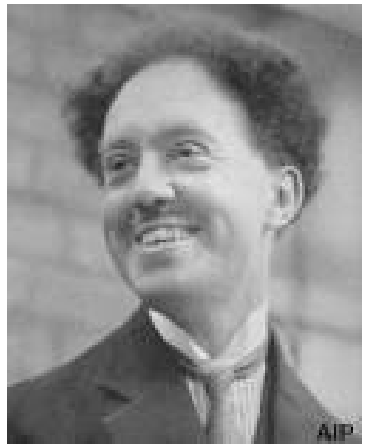
Those who didn't believe it possible to win more frequently than 3 times out of 4:

Einstein



Schrödinger

de Broglie



And the one who said it's obviously possible:

Bohr: « it suffices to take into account the very conditions of the entire experiment. »

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And all the others who believed this was nothing but a minor curiosity.

Geneva played a significant role in the history of quantum non-locality:

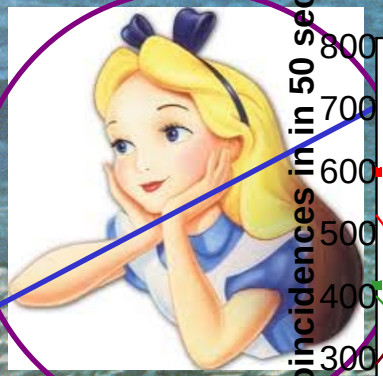
1964: John Stewart Bell, a physicist at CERN, near Geneva, invented the Bell game.

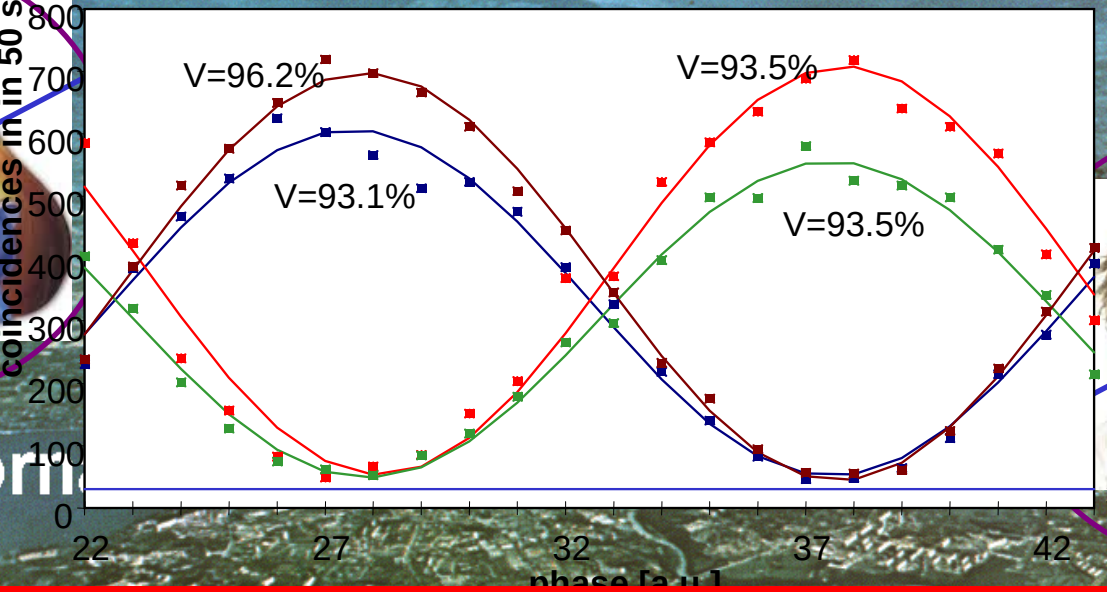
1991: I could prove that essentially all quantum states Ψ allow one to win at Bell's game more frequently than 3 times out of 4.

1997: My team demonstrated the first Bell game outside laboratories between the villages of Bernex and Bellevue, near Geneva.

Bell inequality violation over 10 km, Geneva, 1997

Isn't Physics beautiful ?





Bellevue

Corfi

Consequently, the qubits didn't learn an answer for each possible question.

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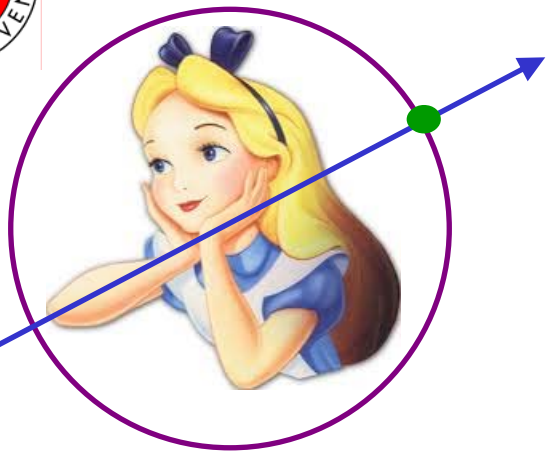
Hey Dad/Mom, but then, one can use quantum entanglement for telepathy ?

Non local Randomness



If Alice's result would be predetermined,
then Bob could know it.

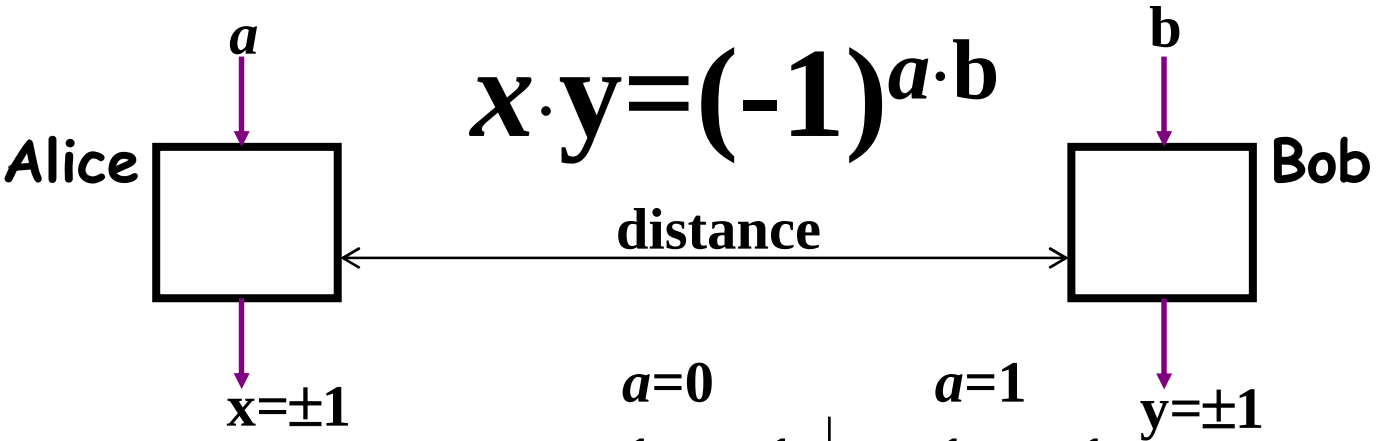
But then, Bob could deduce from his measurement setting and result the choice made by Alice.

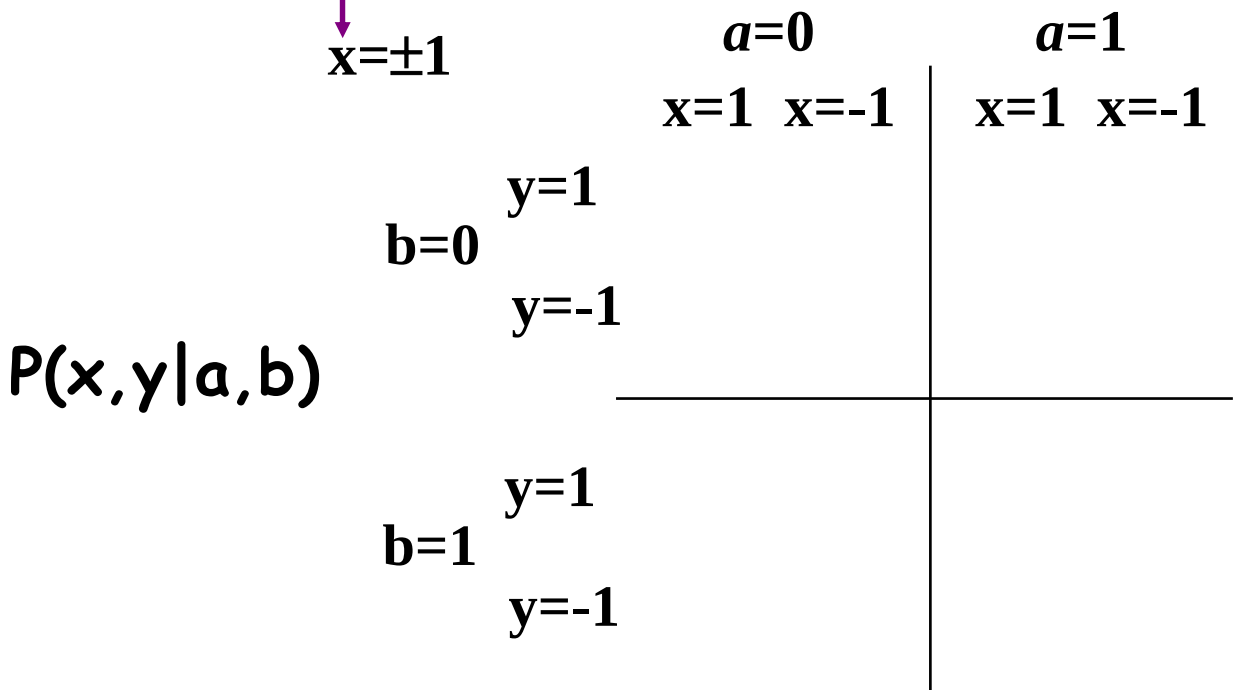
This would be telepathy (telekinesis of information) !

Since telepathy is impossible,
Alice's result can't be predetermined:
it has to be produced at random.

Non local Randomness

- Assume that distances really exist.
- Assume there is no hyper-determinism conspiracy.





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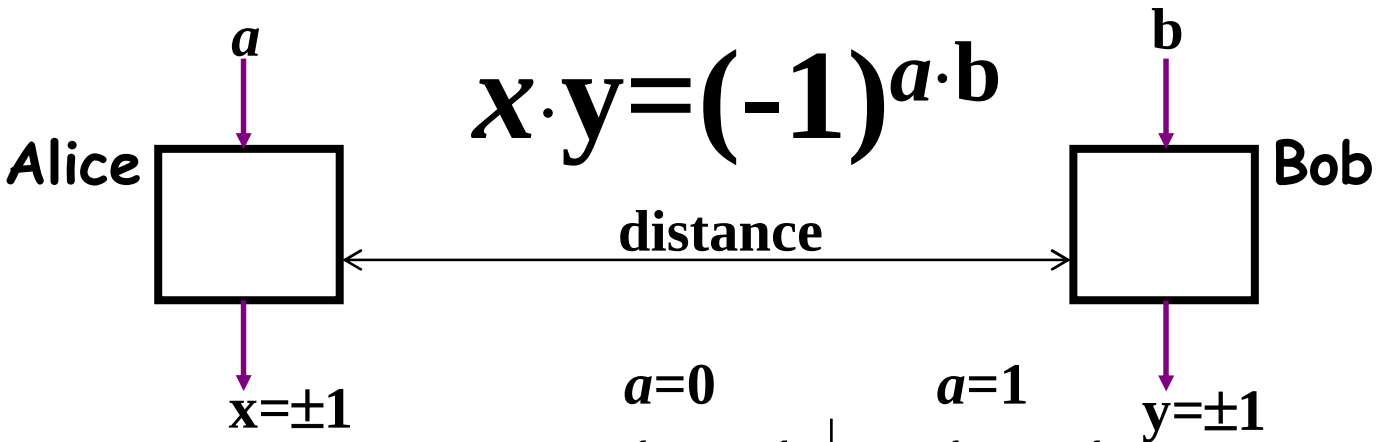

$P(x,y|a,b)$

		$a=0$		$a=1$	
		$x=1$	$x=-1$	$x=1$	$x=-1$
$b=0$	$y=1$	p	0	p	0
	$y=-1$	0	p	0	
$b=1$	$y=1$		0	0	
	$y=-1$	0	p	p	0

Non local Randomness

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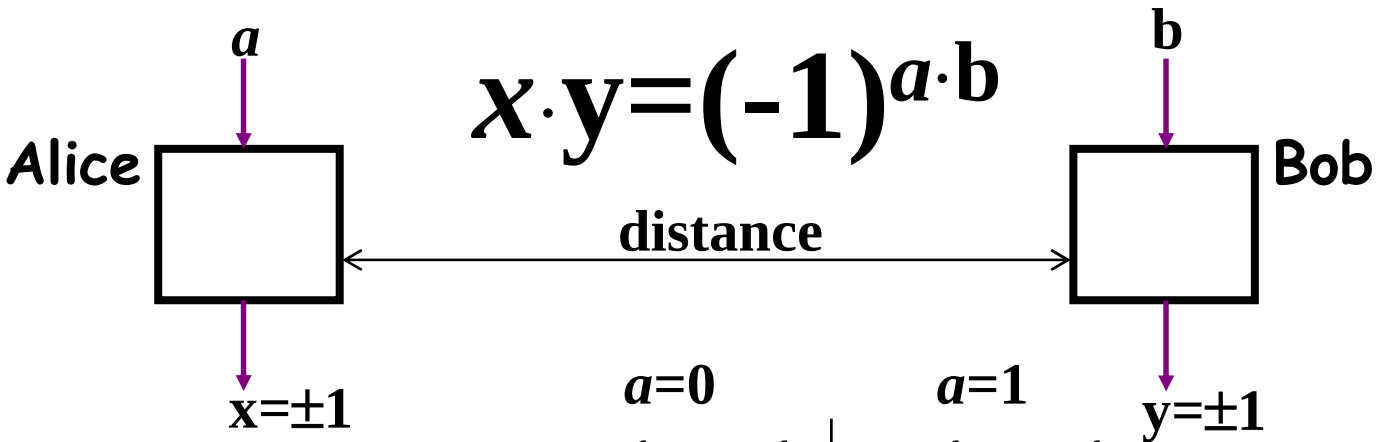
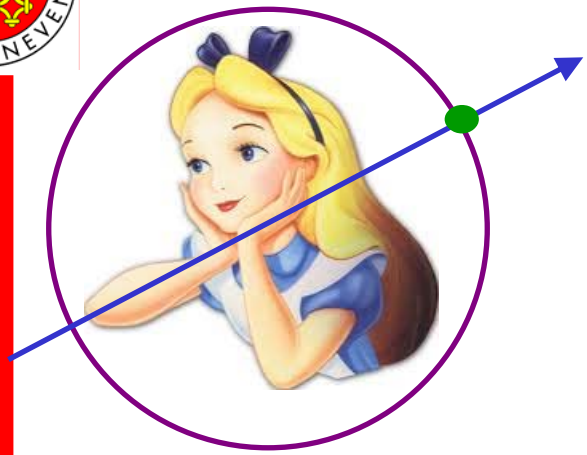
- Assume there is no hyper-determinism conspiracy.



$P(x,y|a,b)$

		a=0		a=1	
		x=1	x=-1	x=1	x=-1
b=0	y=1	1/2	0	1/2	0
	y=-1	0	1/2	0	1/2
b=1	y=1	1/2	0	0	1/2
	y=-1	0	1/2	1/2	0

Non local Randomness

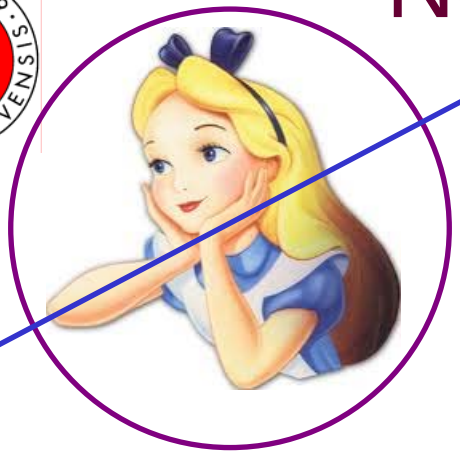


Hey Dad/Mom, what is a random event ?

It is an event intrinsically impossible to foresee: an act of pure creation.

Alice's result can't be predetermined: it has to be produced at random.

Non local Randomness



Randomness is what differentiates quantum non-locality from Newton's non-locality:
Randomness is what prevents quantum non-locality to allow for communications without any physical support:
Randomness prevents telepathy !

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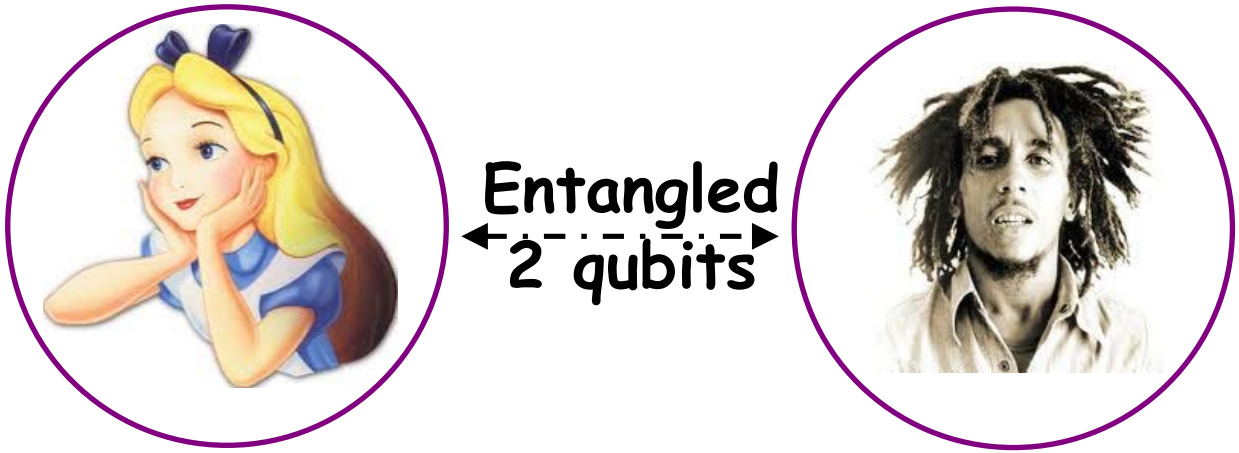
A bit of philosophy

- Entanglement - non local randomness – is a new form of causality. She causes correlations: identical question ⇒ identical answers.
- Once one admits that true randomness exists (acts of pure creation), nothing prevents this true randomness to manifest itself at several locations, as this doesn't allow for telepathy.
- True randomness, like non local randomness, arises, somehow, from outside space and time in the sense that no story taking place in space as time passes can tell how it happens.

Quantum Teleportation



Identical questions ⇒ identical answers
(answers at random, but identical)

Quantum Teleportation

If I ask you identical questions, would you give me identical answers ?

!! The 2 qubits may answer "yes" and set themselves in an entangled state !!

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Quantum Teleportation

If I ask you identical questions, would you give me identical answers ?

If the answer is "yes", then any measurement on Bob's qubit would give the same answer as if the measurement would have been performed on the qubit to be teleported. This is QUANTUM TELEPORTATION !!!

Quantum Teleportation

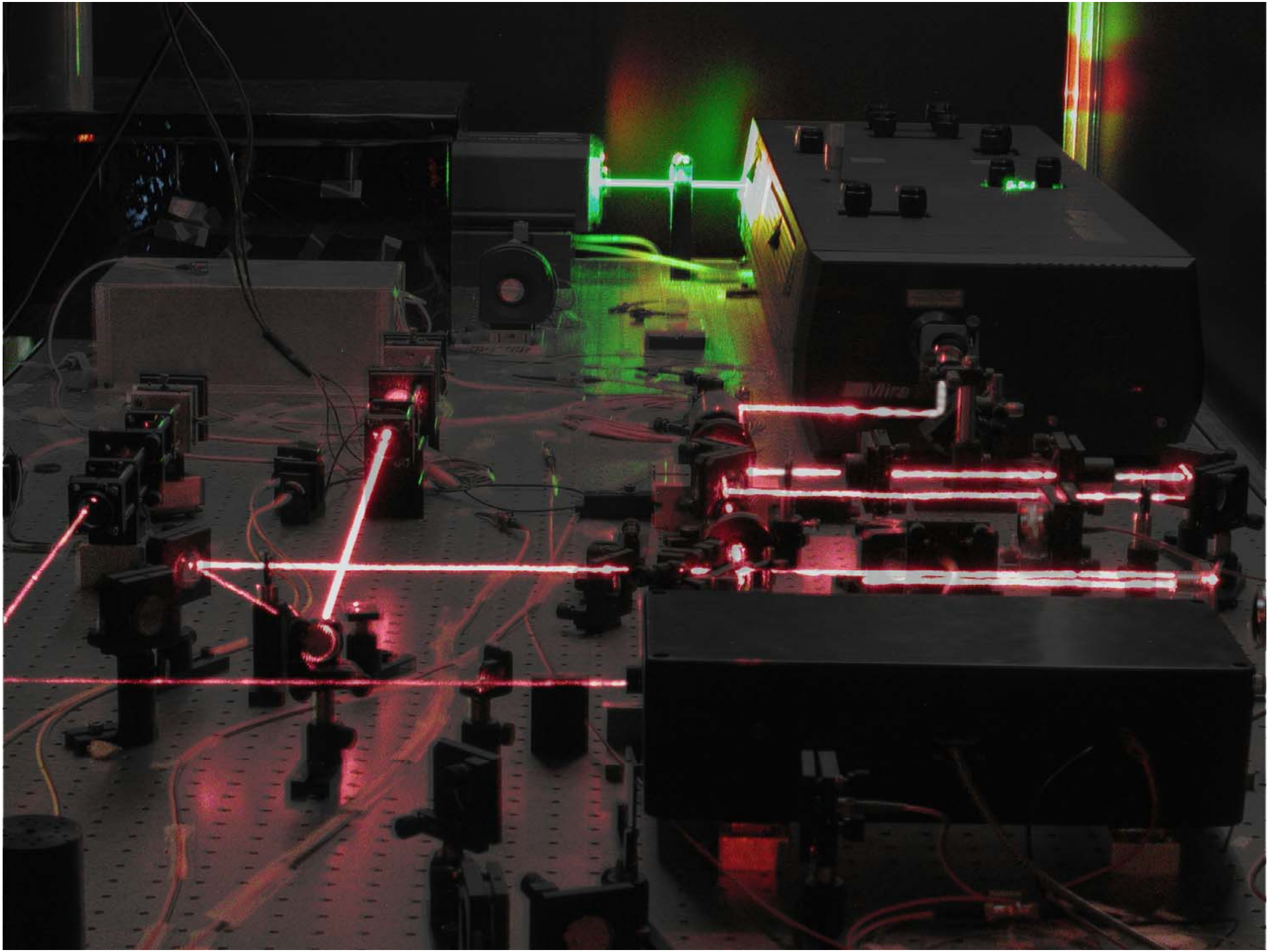
qubit to be teleported

Entangled
2 qubits

If I ask you identical questions, would you give me identical answers ?

yes/no

If the answer is "no", then Bob must «flip» his qubit. As Alice has to communicate the answer she got,
QUANTUM TELEPORTATION
doesn't go faster than the speed of light.



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Hey Dad/Mom, how does Nature produce non local Randomness?

The traditional answer of today's physics reads:

shut-up and calculate !

But the modern answer is:

Entanglement !

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Shall we understand it intuitively some day?

I'd bet "yes",
When quantum technologies will be all around us,
When Quantum Teleportation will be widespread,
Then, one will understand non local randomness
a bit as today one understands gravity

… maybe …

Application: quantum cryptography

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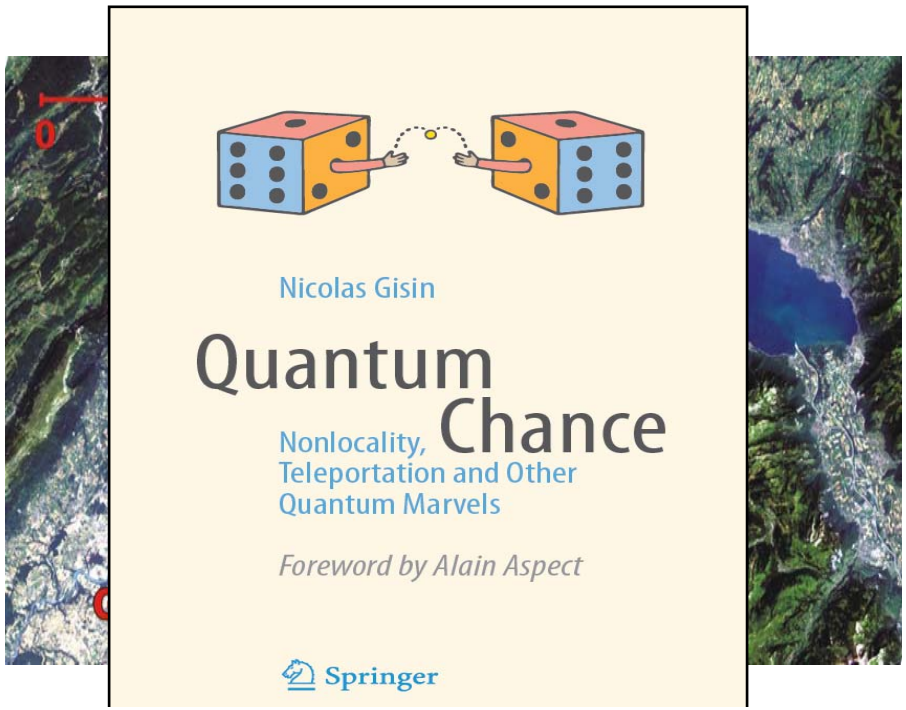
Lectures:

1. **The Age of Entanglement, par Louisa Gilder, Ed. Knopf 2008.**
2. ***Quantum Physics: a first encounter, by Valerio Scarani, Oxford University Press, 2006.***
3. **Quantum Chance, by Nicolas Gisin, Springer 2014.**



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