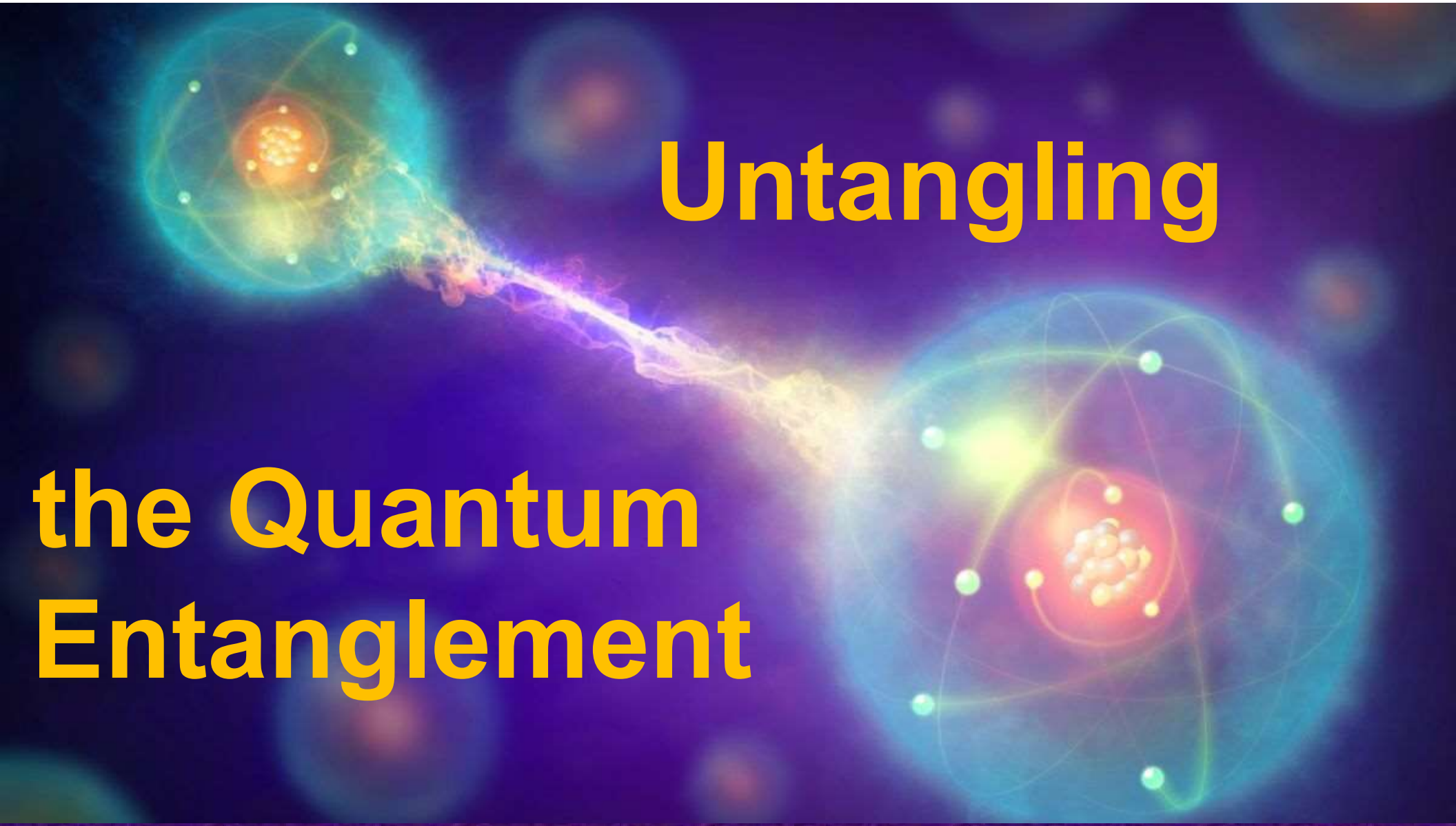
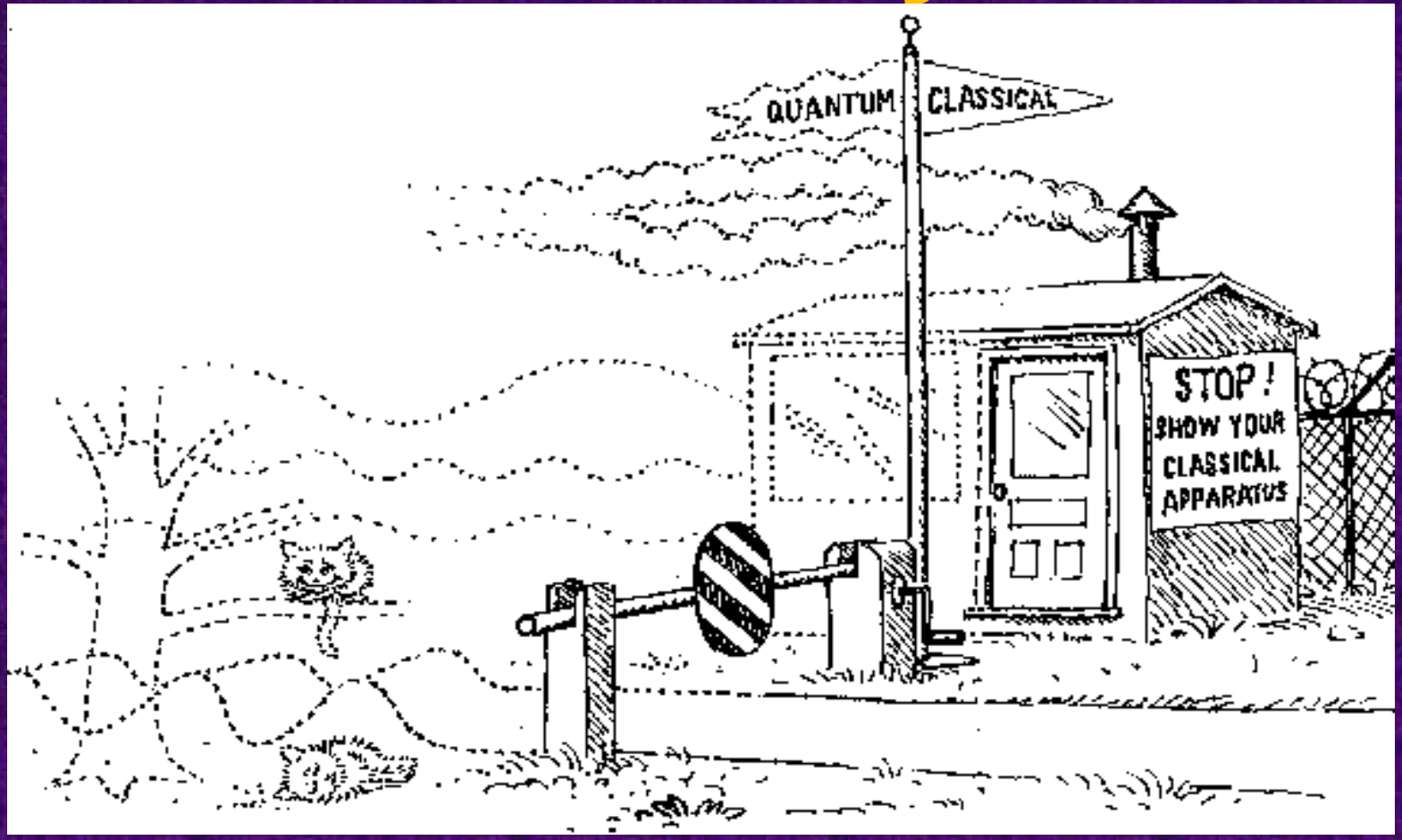


Untangling the Quantum Entanglement

Irina Novikova
Department of Physics
College of William and Mary

Classical Physics vs Quantum Physics



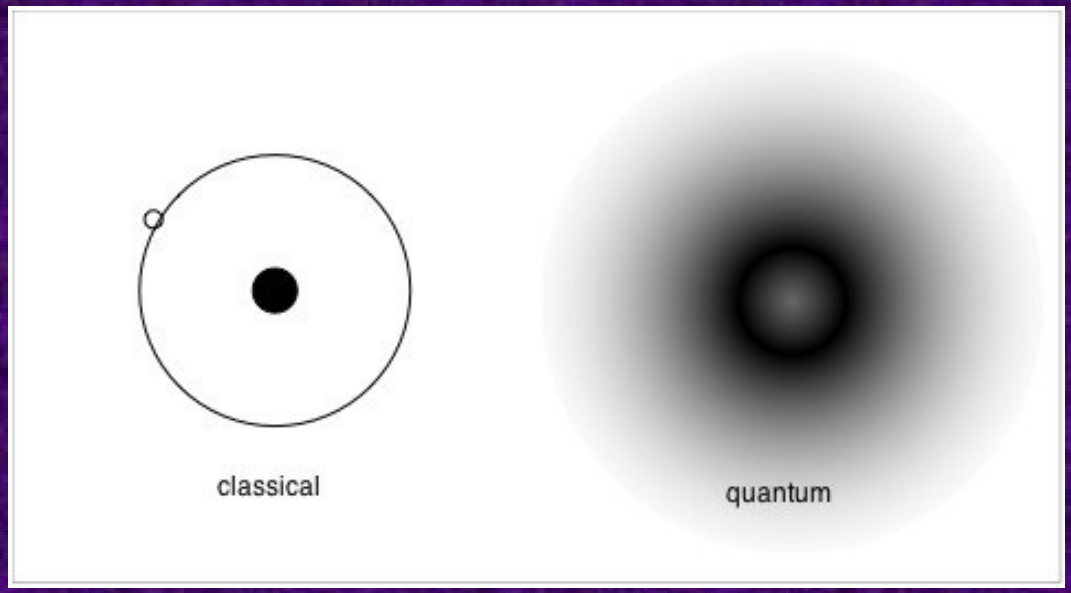
Quantum world is fuzzy…

Uncertainty principle

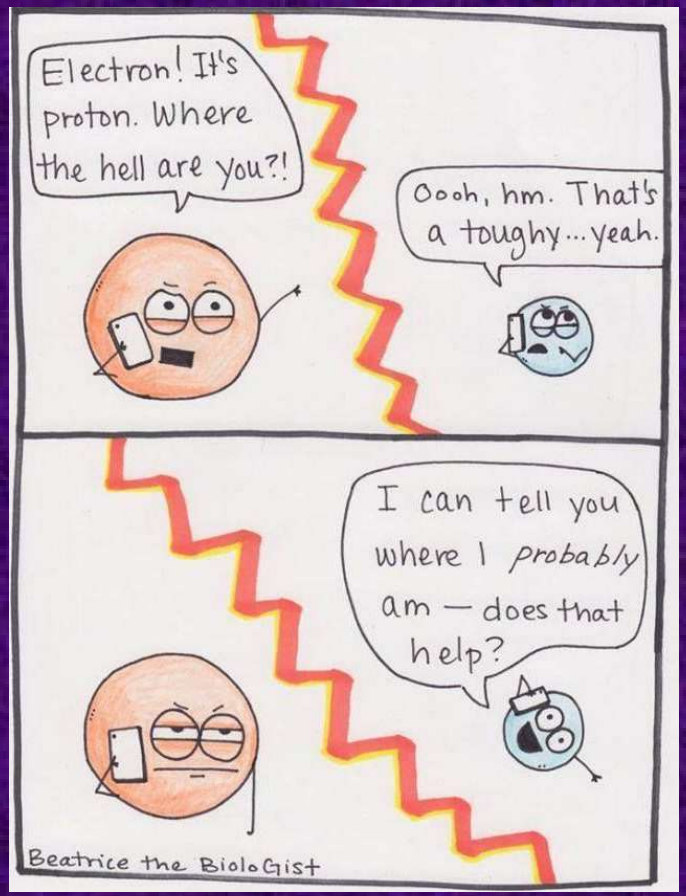
Heisenberg uncertainty principle



One cannot measure position and momentum (velocity) of a quantum object simultaneously with arbitrary precision

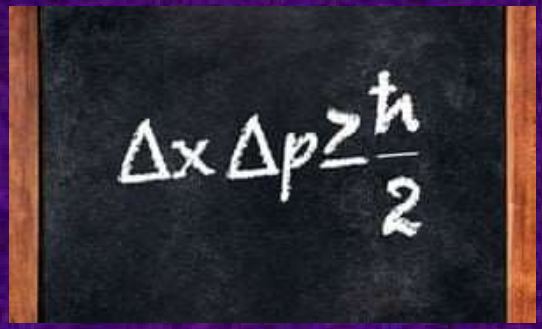


Very pronounced at atomic level

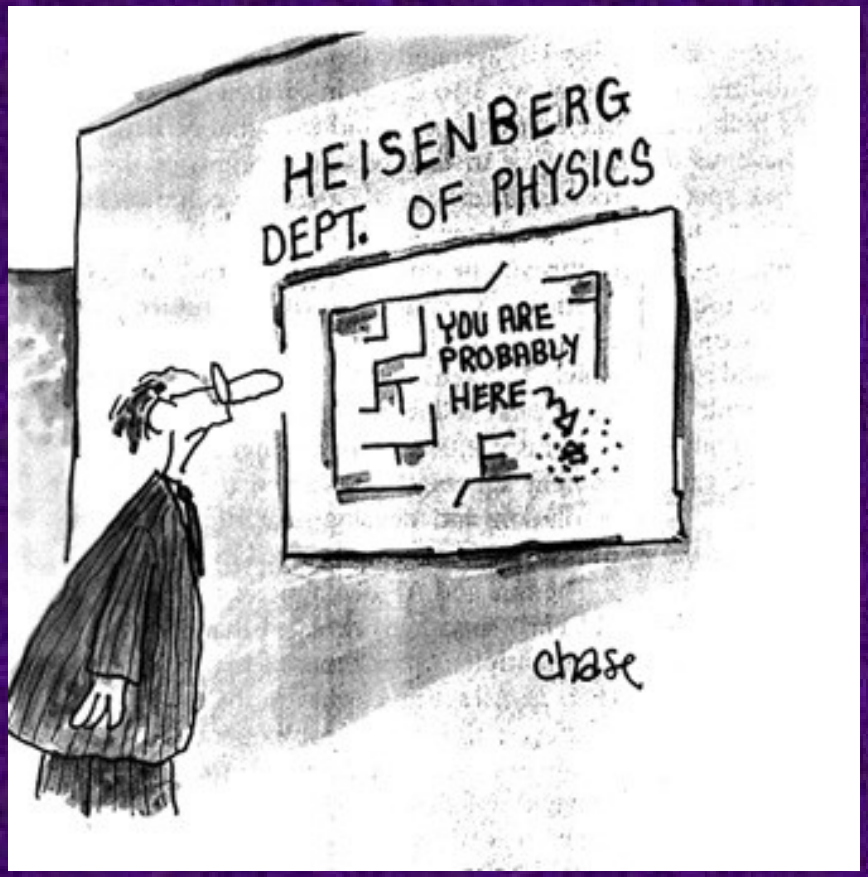


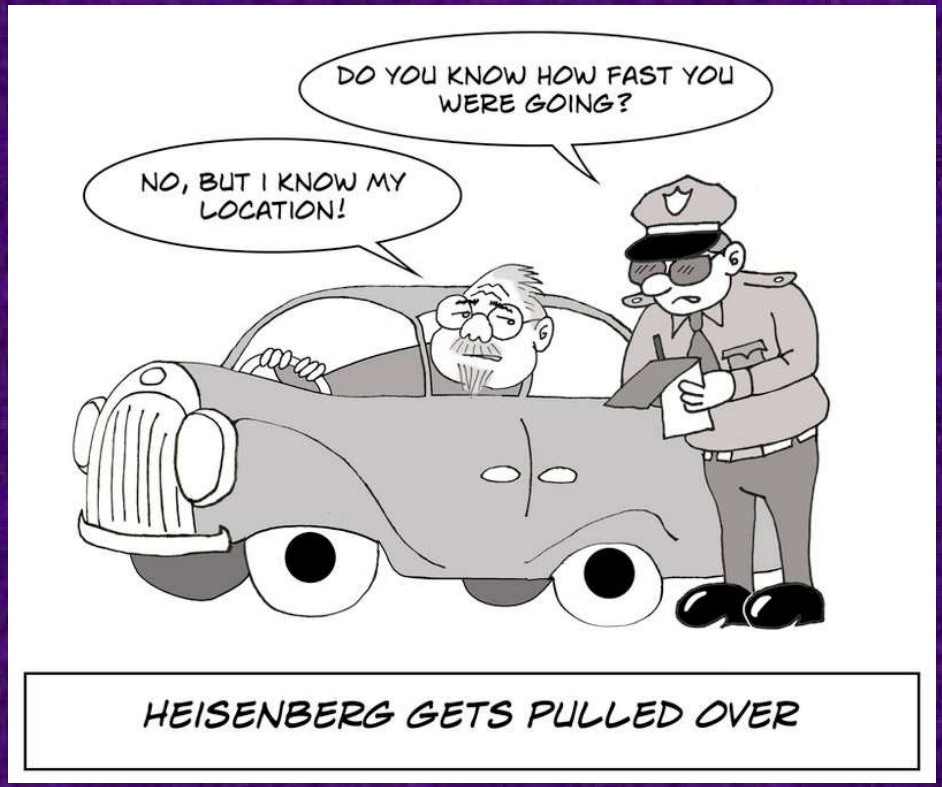
Uncertainty principle

Heisenberg uncertainty principle



One cannot measure position and momentum (velocity) of a quantum object simultaneously with arbitrary precision



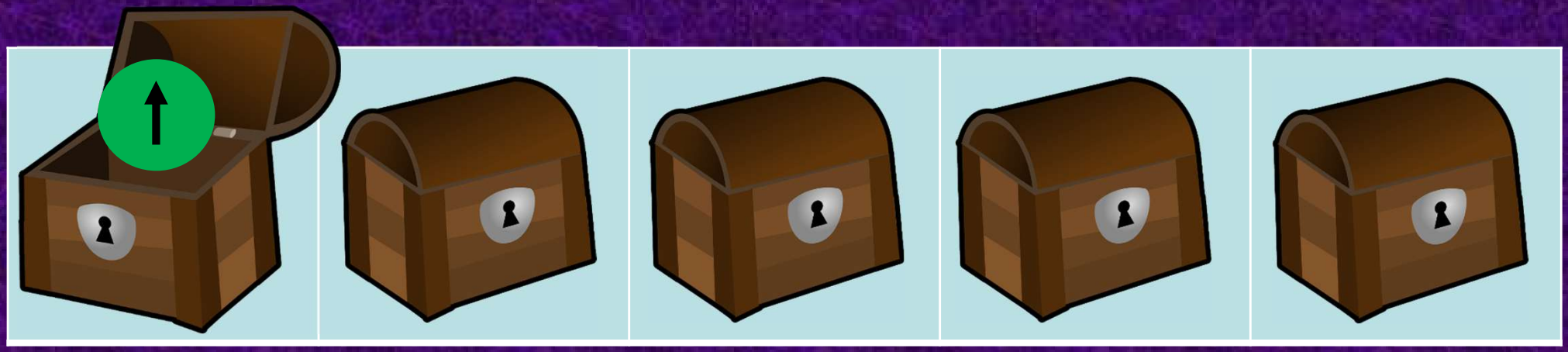


Weirdness of quantum measurements



Identical boxes (right from a certified quantum distributor)

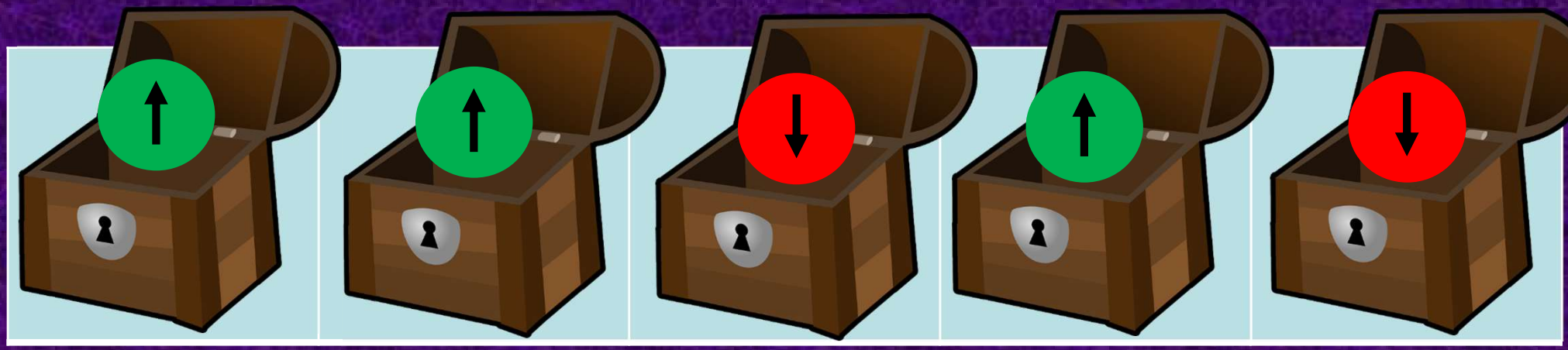
Weirdness of quantum measurements



First box measured: green (up). So the rest of identical boxes will show the same result, right?!



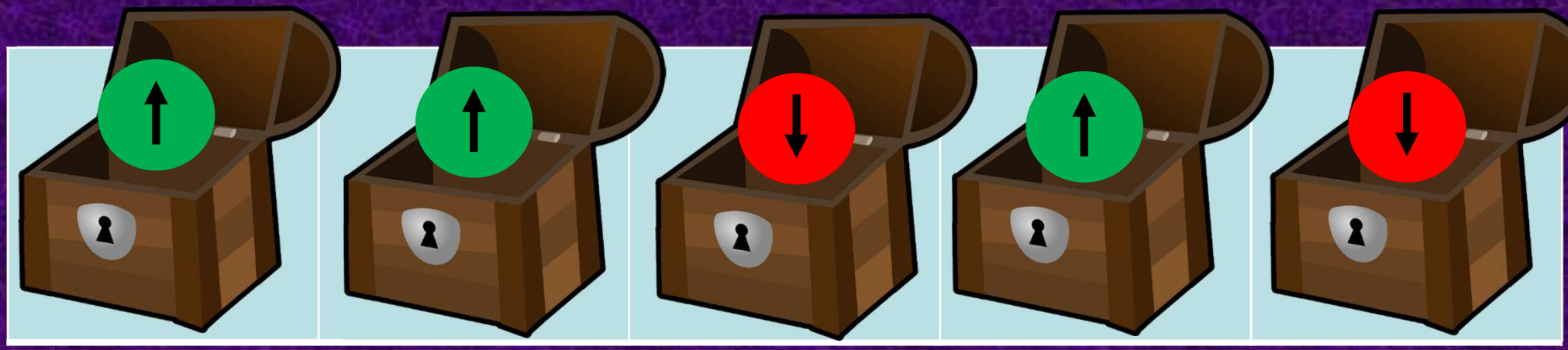
Weirdness of quantum measurements



Identical boxes, identical measurements – different results?!



Weirdness of quantum measurements

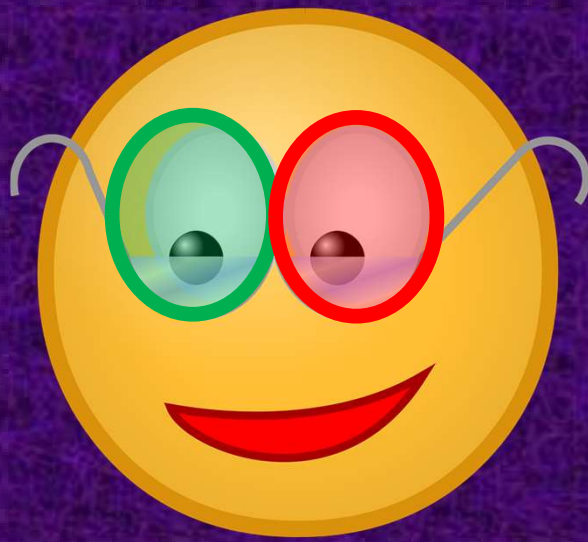


Identical boxes, identical measurements – different results?!



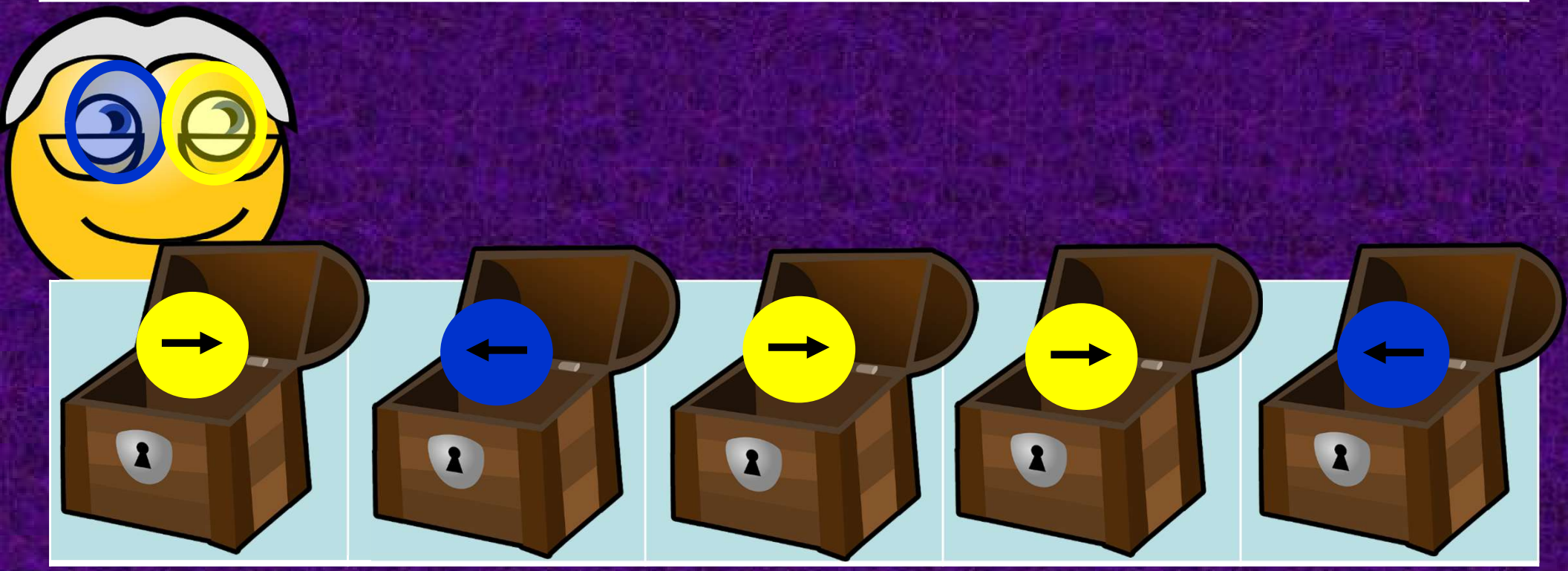
Do you see GGRGR?

Yep, exactly that!

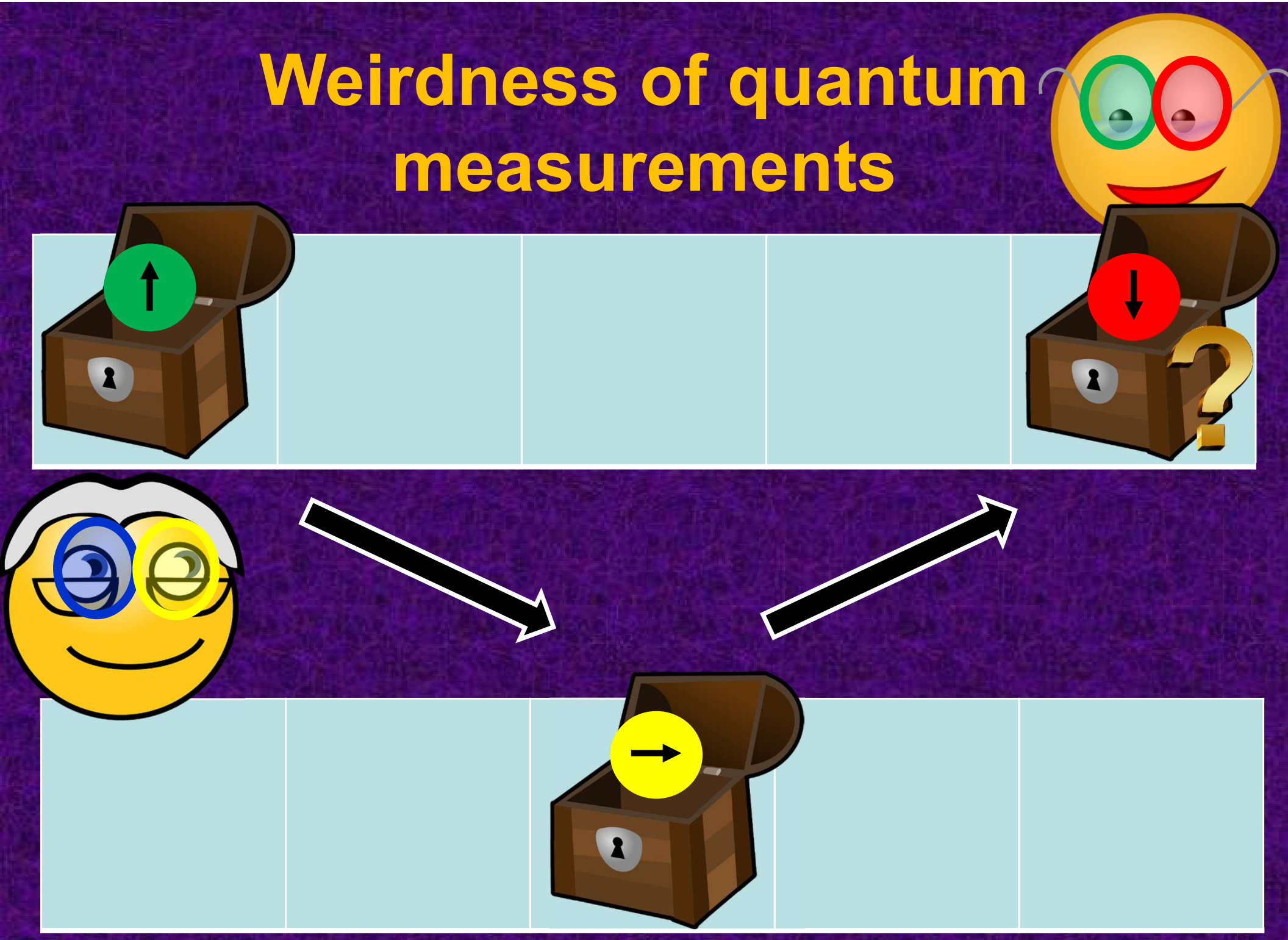


Weirdness of quantum measurements





Weirdness of quantum measurements



Weirdness of quantum measurements









What we learn so far:

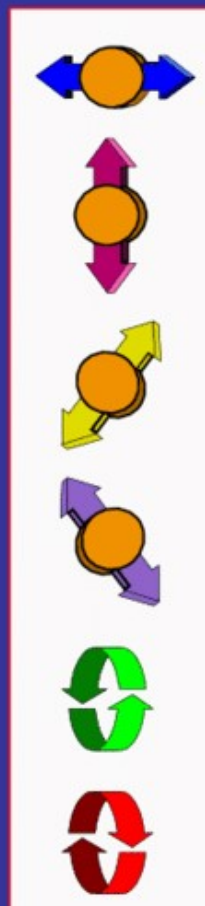
1. Identical measurement of identical particles can lead to different results (can predict probability, but not individual outcome)

2. If we make a different measurement in between two identical ones, that can chance the outcome!

We cannot measure two different properties (up-down) or (left-right) at the same time!!!

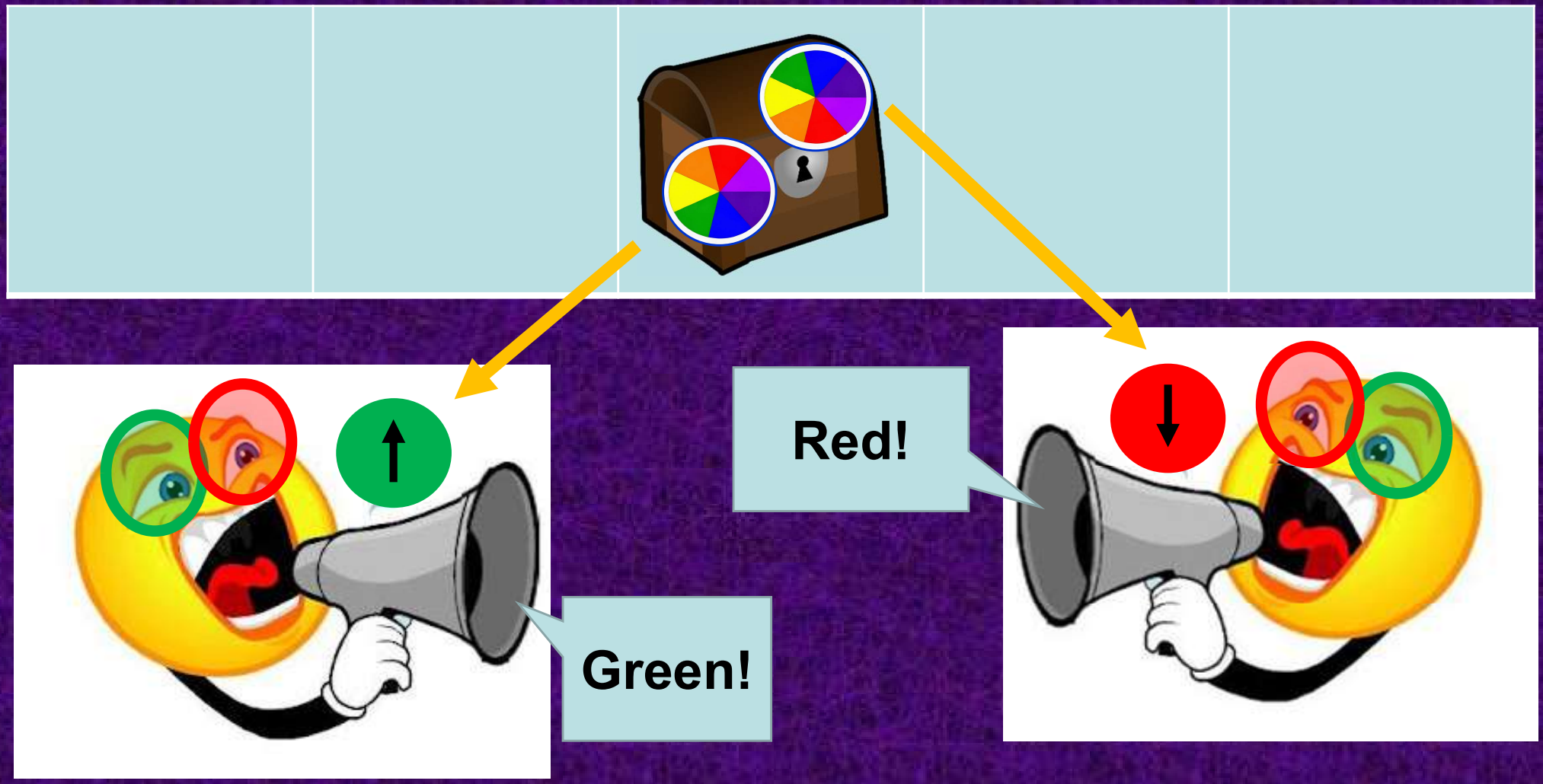
Optical qubits: polarized photons

We can realise a qubit as the state of single-photon polarisation



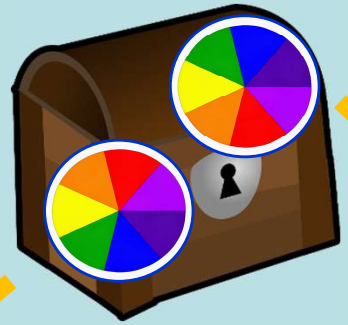
Horizontal	$\|0\rangle$
Vertical	$\|1\rangle$
Diagonal up	$\frac{1}{\sqrt{2}}(\|0\rangle+\|1\rangle)$
Diagonal down	$\frac{1}{\sqrt{2}}(\|0\rangle-\|1\rangle)$
Left circular	$\frac{1}{\sqrt{2}}(\|0\rangle+i\|1\rangle)$
Right circular	$\frac{1}{\sqrt{2}}(\|0\rangle-i\|1\rangle)$

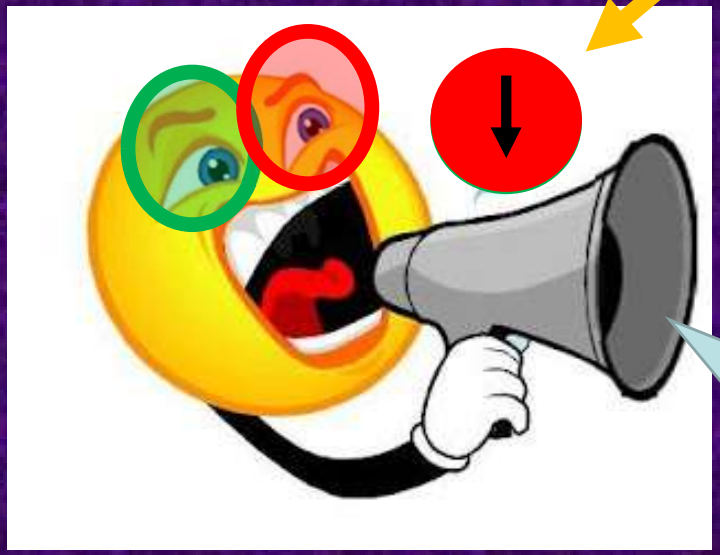
It’s getting weirder and weirder: two particles are entangled



It's getting weirder and weirder: two particles are entangled

But equally possible…





Red!

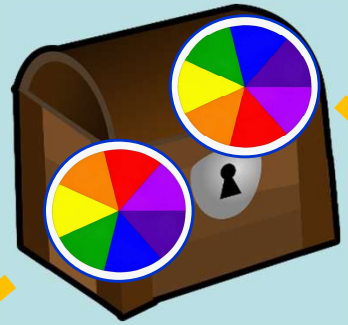
Green!

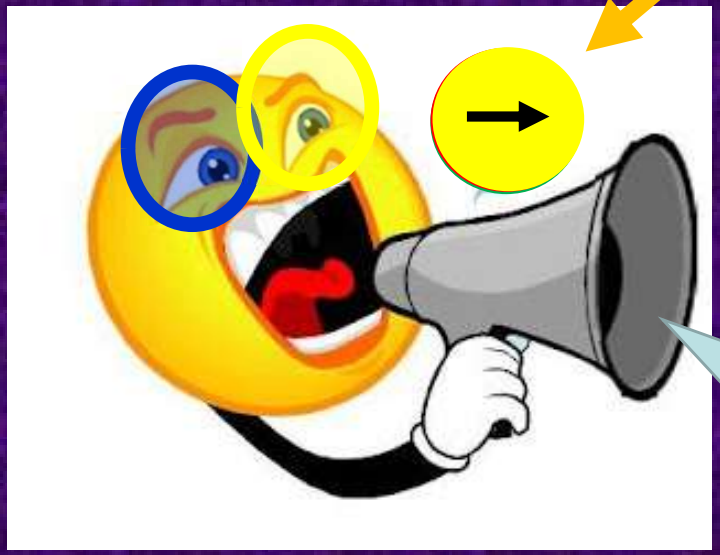


Random results, but always opposite to each other!

It's getting weirder and weirder: two particles are entangled

And even with a different measurement…





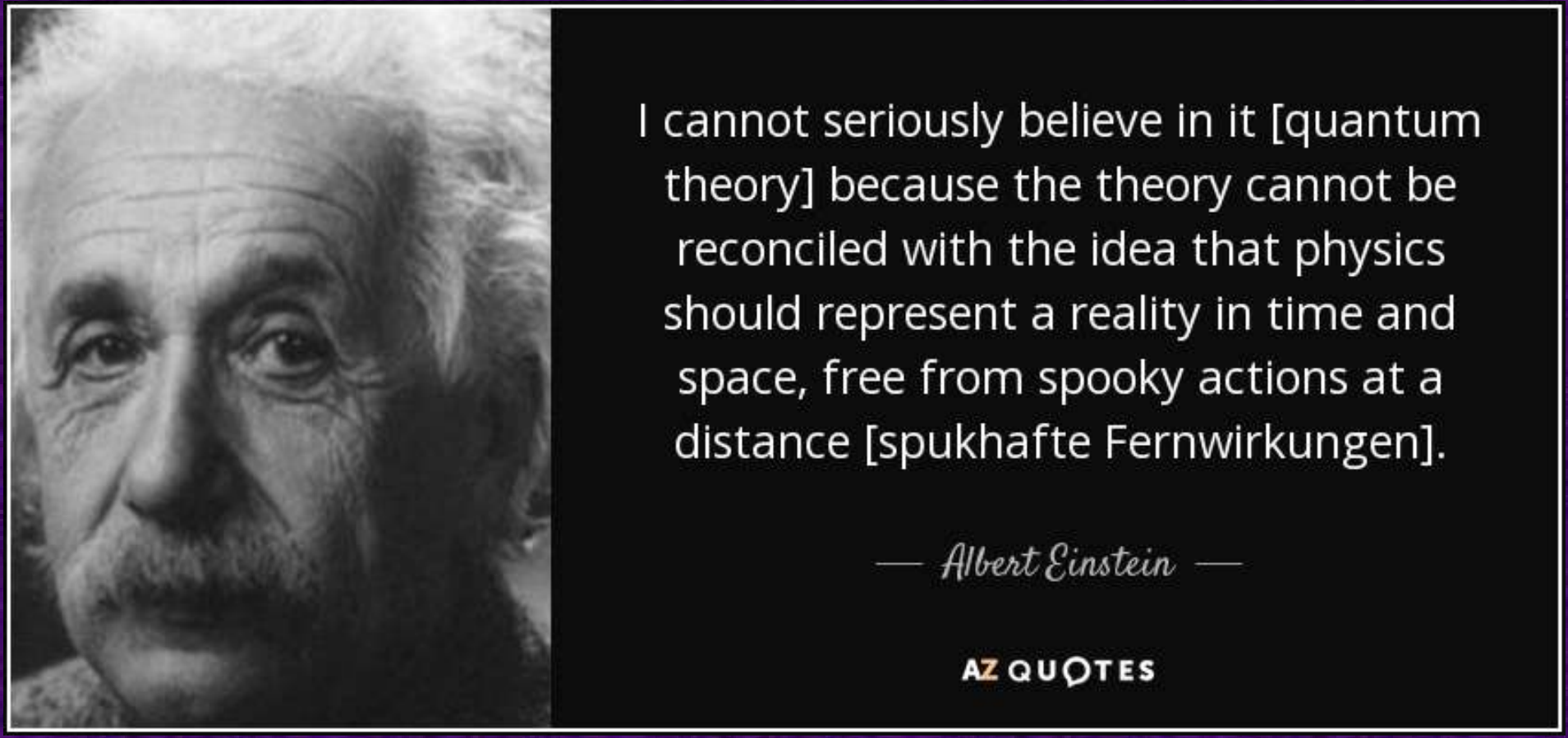
Yellow!

Blue!



Random results, but always opposite to each other!

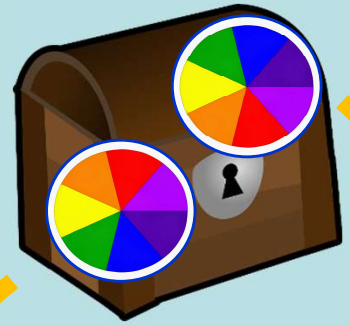
It's getting weirder and weirder: two particles are entangled

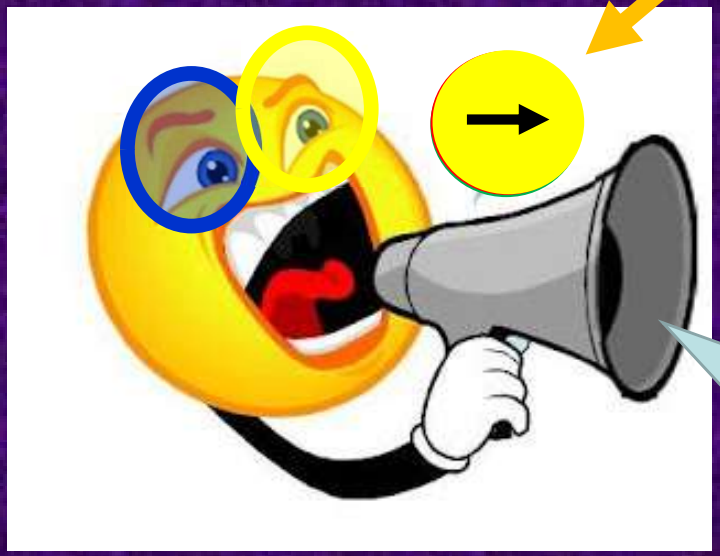


In short: Einstein did not like Quantum Mechanics

Einstein-Podolsky-Rosen (EPR) paradox

Can we use entangled particles to carry out two incompatible measurements?





Blue!

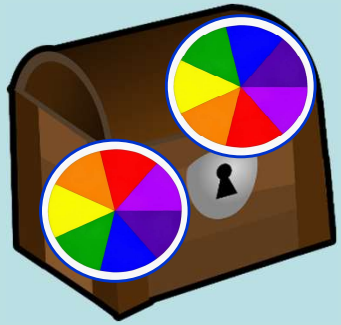
Green!



Did we beat the uncertainty principle? Nice try, but no!

Saving local realism: hidden variables

What if the two particles made prior arrangements?



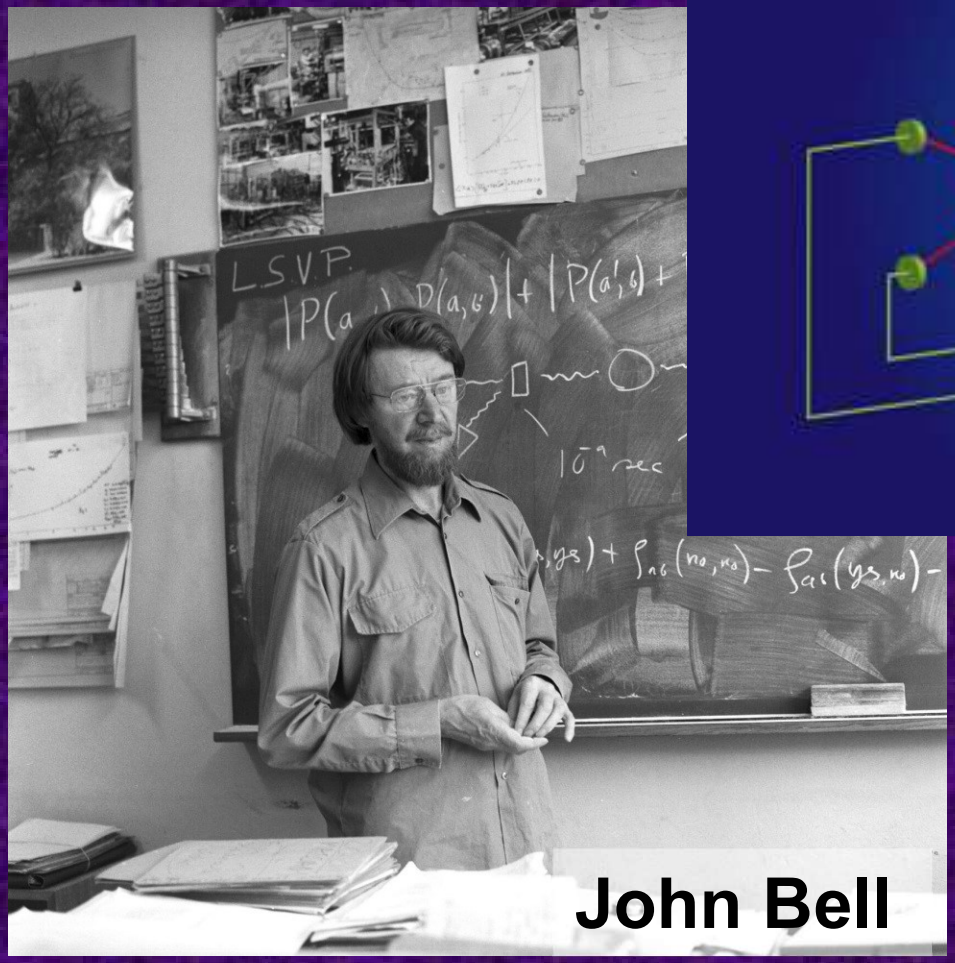


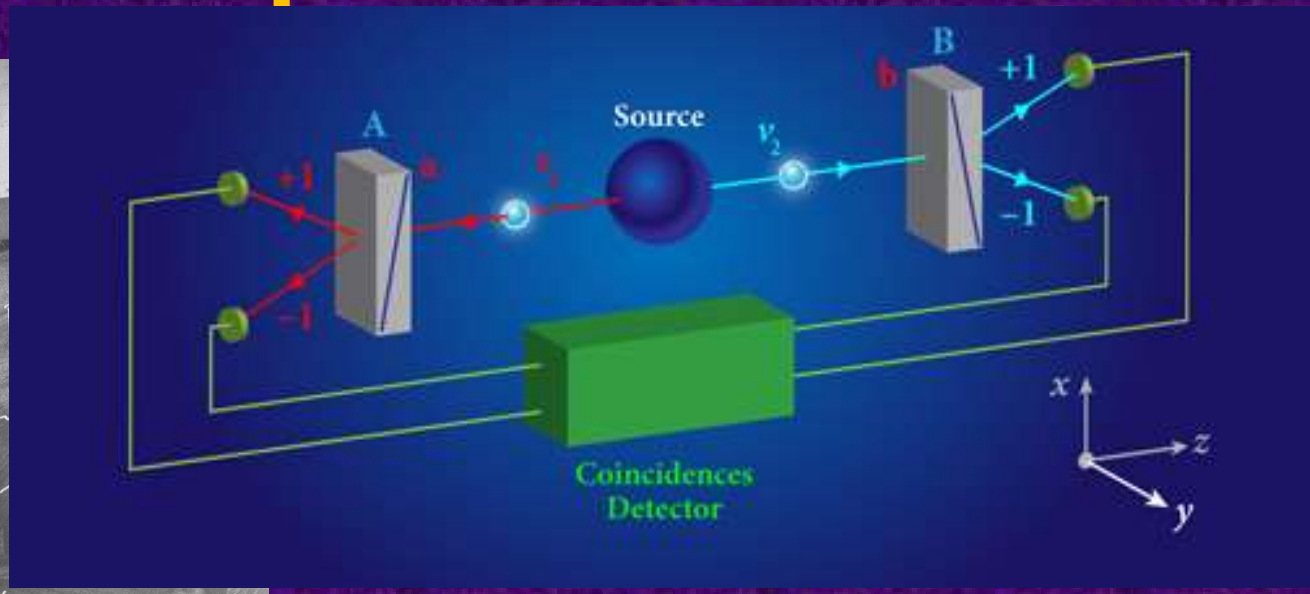
You'll be	I'll be
up	down
left	right
in	out



For 30 years physicists debated which treatment of reality (hidden variables vs non-locality) is real… without any possibility to test it!

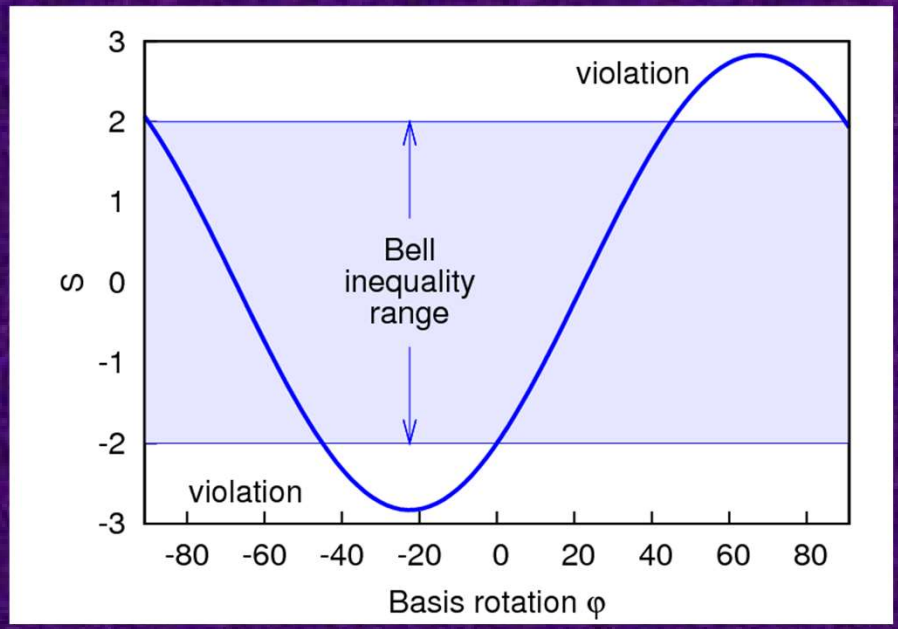
From philosophy to experiments: Bell inequalities





Coincidence count

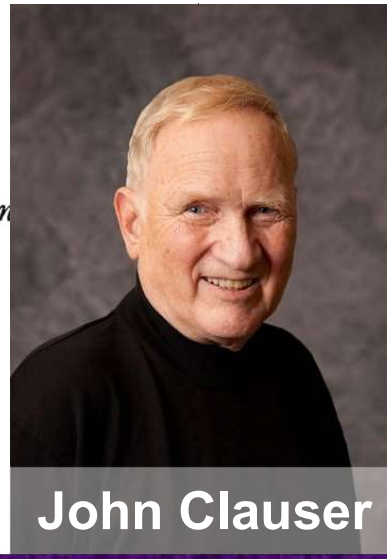
$S := E_{a,b} - E_{a',b} + E_{a,b'} + E_{a,b'}$



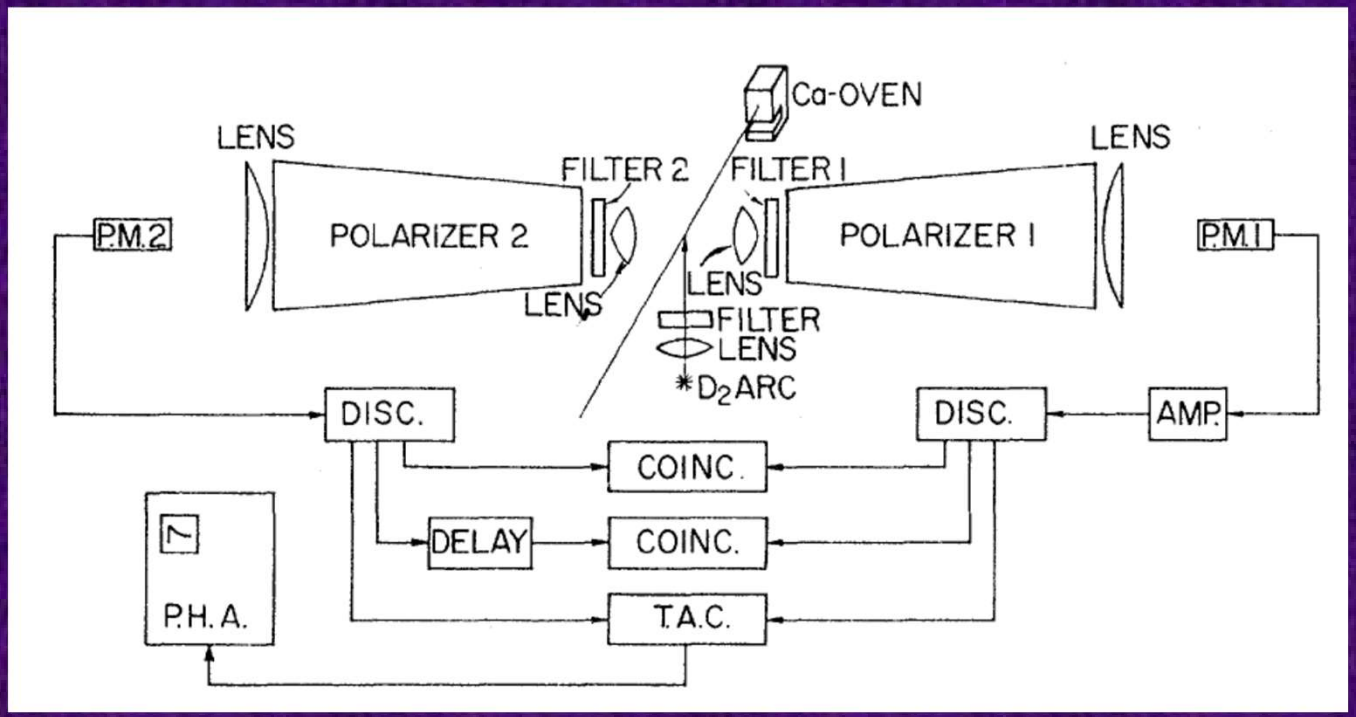
Experimental Test of Local Hidden-Variable Theories*

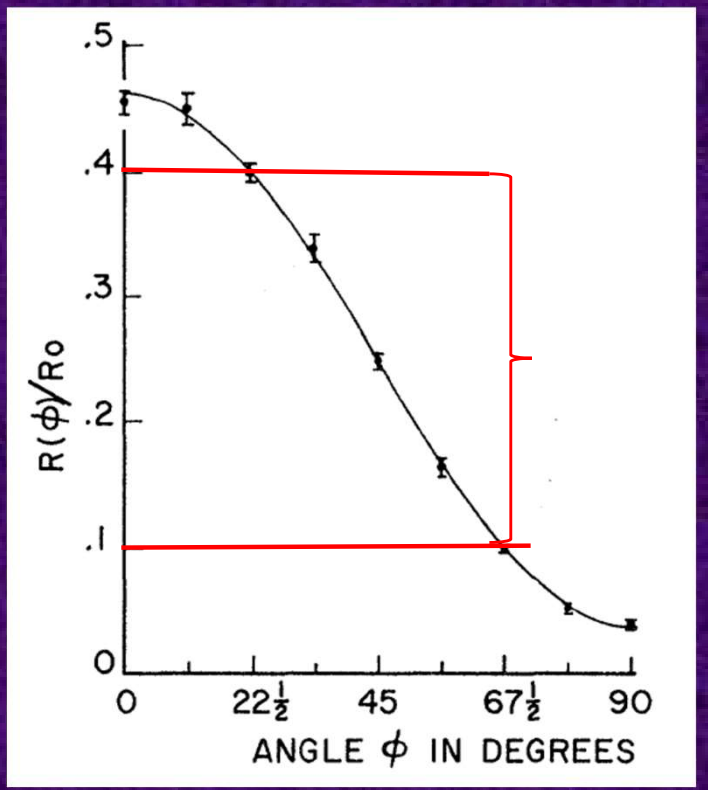
Stuart J. Freedman and John F. Clauser
Department of Physics and Lawrence Berkeley Laboratory, University of California, Berkeley, Californ
(Received 4 February 1972)

We have measured the linear polarization correlation of the photons emitted in an atomic cascade of calcium. It has been shown by a generalization of Bell's inequality that the existence of local hidden variables imposes restrictions on this correlation in conflict with the predictions of quantum mechanics. Our data, in agreement with quantum mechanics, violate these restrictions to high statistical accuracy, thus providing strong evidence against local hidden-variable theories.



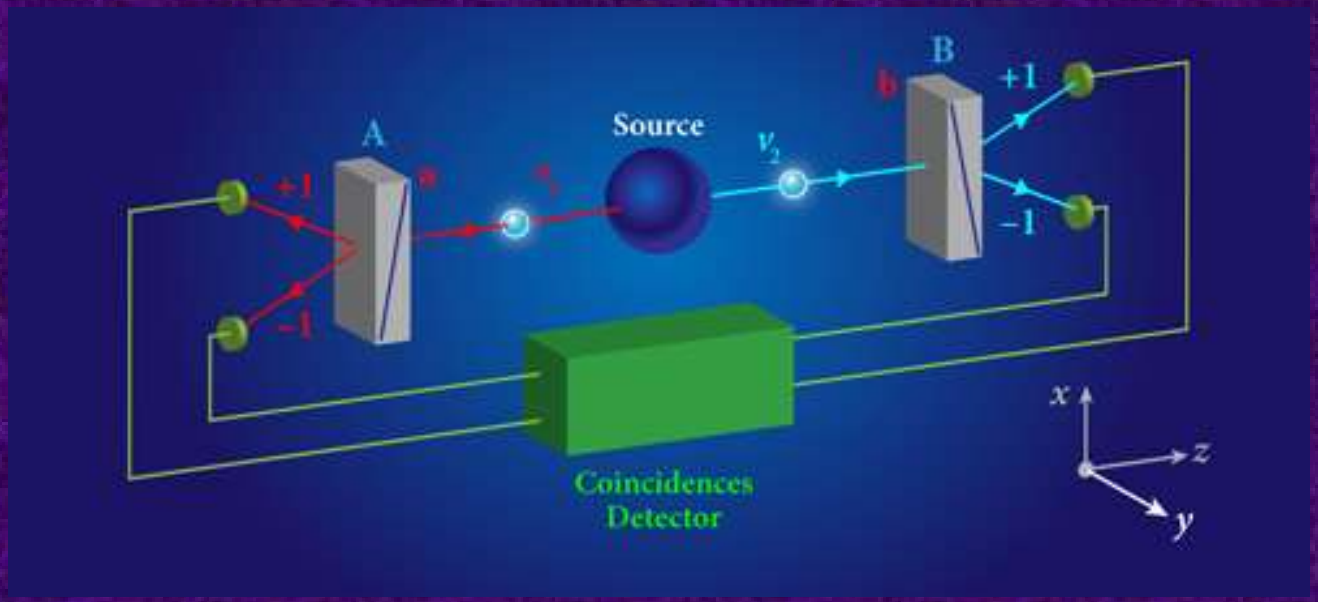
John Clauser





If the difference is more than 0.25 – no hidden variables

Troubles with experimental tests of Bell inequalities: loopholes



Locality loophope: what if the orientation of one detector somehow affect the outcome of the other?

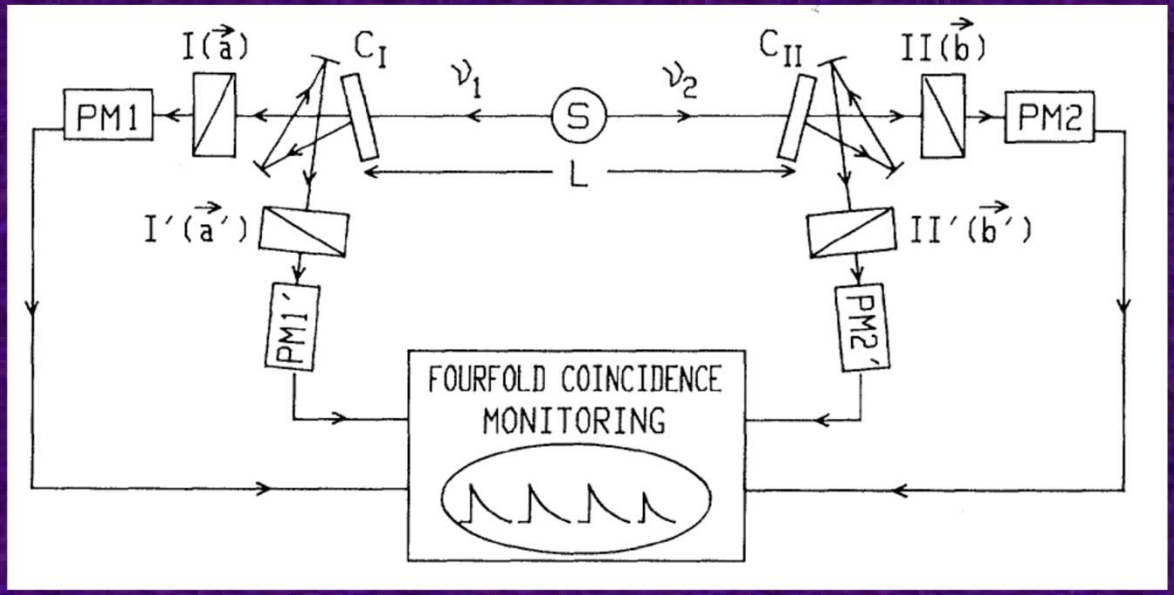
Experimental Test of Bell's Inequalities Using Time-Varying Analyzers

Alain Aspect, Jean Dalibard,[a] and Gérard Roger
Institut d'Optique Théorique et Appliquée, F-91406 Orsay Cédex, France

(Received 27 September 1982)

Correlations of linear polarizations of pairs of photons have been measured with time-varying analyzers. The analyzer in each leg of the apparatus is an acousto-optical switch followed by two linear polarizers. The switches operate at incommensurate frequencies near 50 MHz. Each analyzer amounts to a polarizer which jumps between two orientations in a time short compared with the photon transit time. The results are in good agreement with quantum mechanical predictions but violate Bell's inequalities by 5 standard deviations.



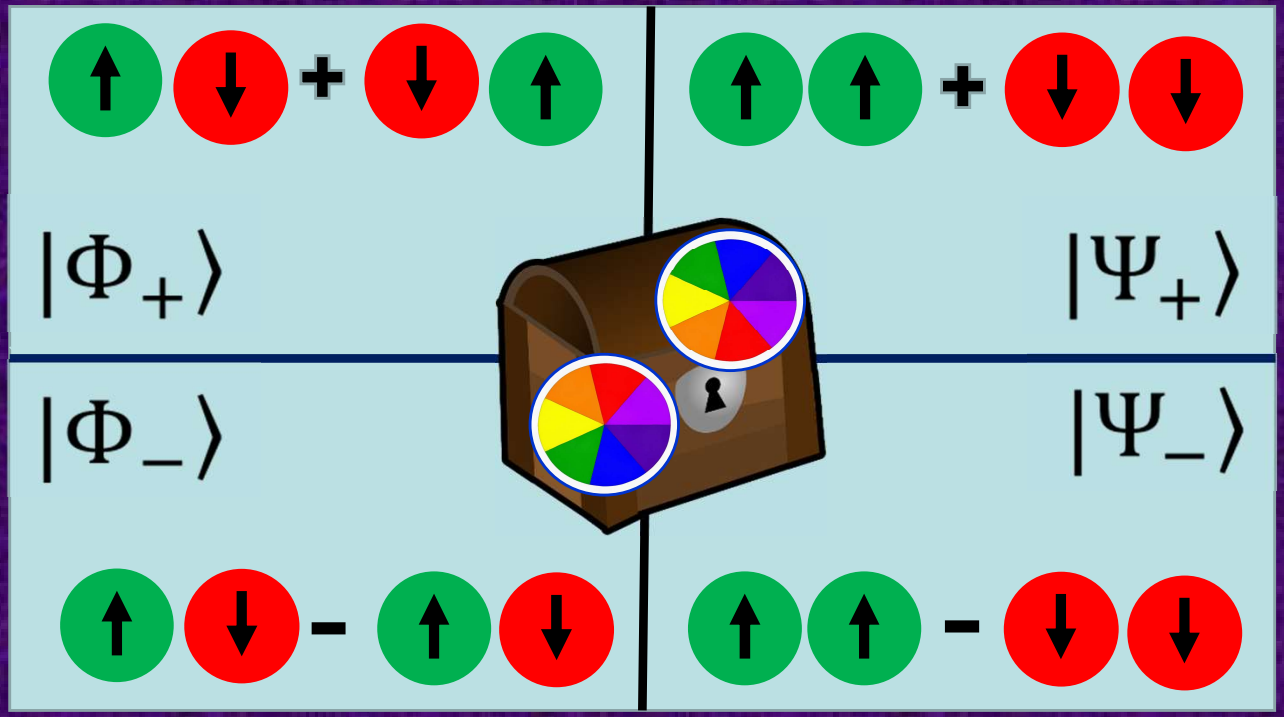


Key modification: they rapidly switched each detector orientation faster than light can travel from one detector to another

Even with locality loophole closed – no hidden variables!

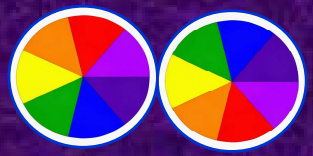
In fact, no violation of nonlocality being found so far!

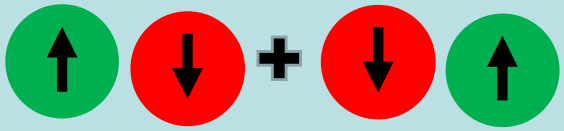
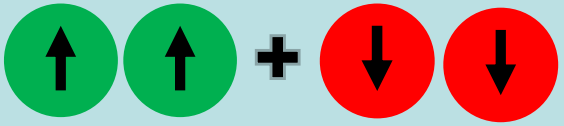
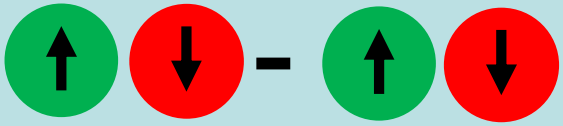
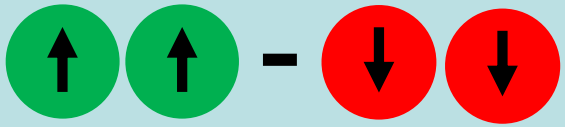
Bell states: entangled couple therapy



Quantum teleportation





 $\lvert\Phi_+\rangle$	 $\lvert\Psi_+\rangle$
$\lvert\Phi_-\rangle$ 	$\lvert\Psi_-\rangle$ 

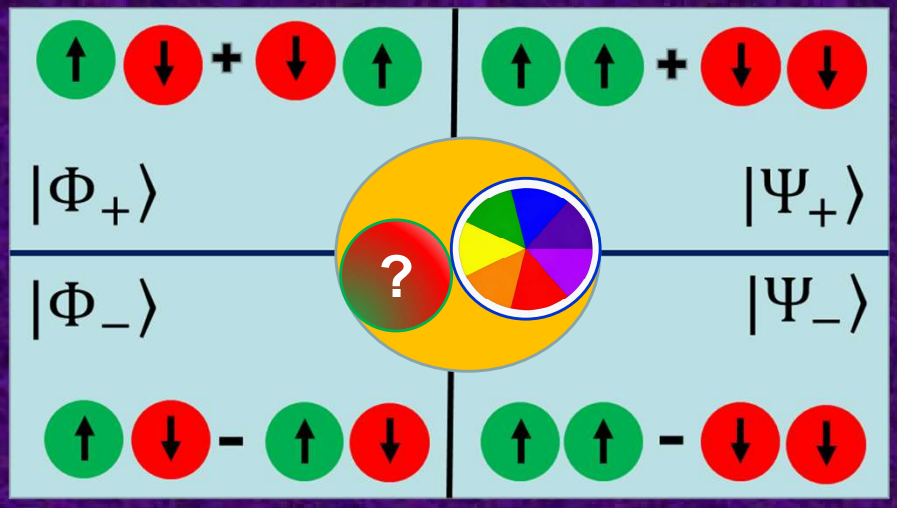
Quantum teleportation



Step 1: share entangled pair



Step 2: make Bell measurement

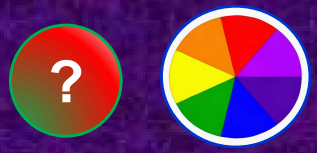


Quantum teleportation



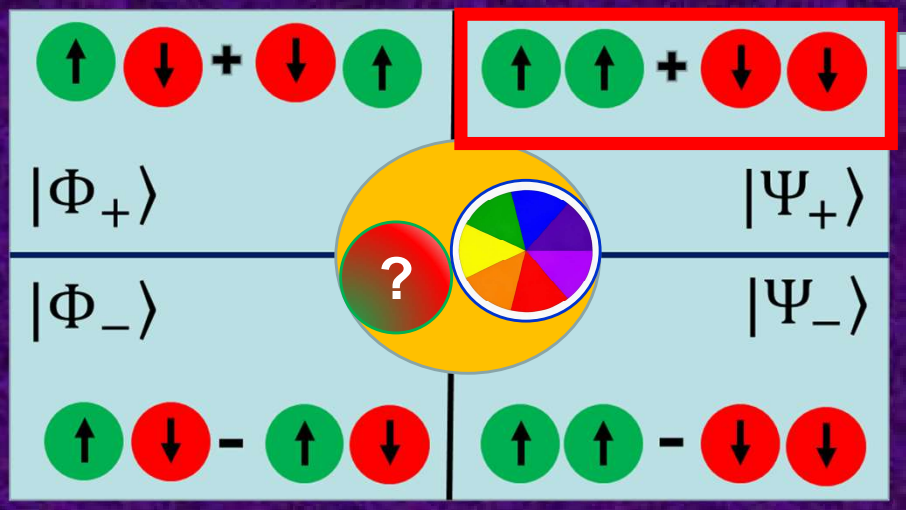
Too dangerous to send a particle directly

Step 1: share entangled pair





Step 2: make Bell measurement



Step 3: prescribe the treatment for the remaining particle to turn in into the original!

Experimental quantum teleportation

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

Institut für Experimentalphysik, Universität Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria

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.

