Contexts, Systems and Modalities: a new ontology for quantum mechanics.

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A. Auffeves & P. Grangier, Found. Phys. 46, 121 (2016) http://arxiv.org/abs/1409.2120
A. Auffeves & P. Grangier, Sci. Rep. 7, 43365 (2017) http://arxiv.org/abs/1610.06164
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P. Grangier & A. Auffeves, Phil. Trans. R. Soc. A (2018) http://arxiv.org/abs/1804.04807

Sketch of the talk

1. Einstein, Bohr, Bell, and the experiments

From the EPR-Bohr debate (1935) to loophole-free Bell tests (2015)

2. Can we define a quantum state in physical terms ?

Let us forget about Hilbert space and operators and...

- define a (contextually) objective quantum state then …
- deduce probabilities from quantization.

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3. Contextual objectivity at work :

- Reconsidering entanglement and Bell's hypothesis

  A. Auffèves & P. Grangier, Int. J. Quantum Inf. 14, 1640002 (2016)
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- Reconstructing the quantum formalism

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- Some other issues... and a philosophical outlook

Quantum Physics

* « Quantum Mechanics » elaborated at the end of the 1920's (1925 - 1927 : Schrödinger, Heisenberg, Dirac, Bohr, Born…)

« Greatest intellectual adventure of the 20th century » ?

* **Theory at the basis of our understanding of physical world :** stability and structure of matter, nature of light, interactions between matter and light, superconductivity, superfluidity...

* **Perfectly coherent formalism, huge success, incredible number of applications :** transistor (electronics and computers), laser (telecommunications and internet, medecine, biology…)

* **But... keeps a « mysterious » character :** non-deterministic theory, non-locality (in a subtle way...), no simple correspondance between « quantum objects » and the usual (macroscopic) world.

The Einstein-Bohr debate

* Einstein, Podolski, Rosen (EPR) 1935 : quantum mechanics is incomplete ("hidden information")

* Bohr disagrees, intense debate over many years but not much attention from majority of physicists

- Quantum mechanics accumulates success:
  - Understanding nature: structure and properties of matter, quantum theory of light, interactions between light and matter...
  - New concepts, and revolutionary inventions: transistor, laser…
  - No disagreement on the validity of quantum predictions, only on its interpretation: debate considered as "philosophical".

The situation changed radically with Bell' theorem (1964) and the acknowledgement of its importance (1969-82...) : One can make experimental tests of « local realism »

Physics ABOUT BROWSE PRESS

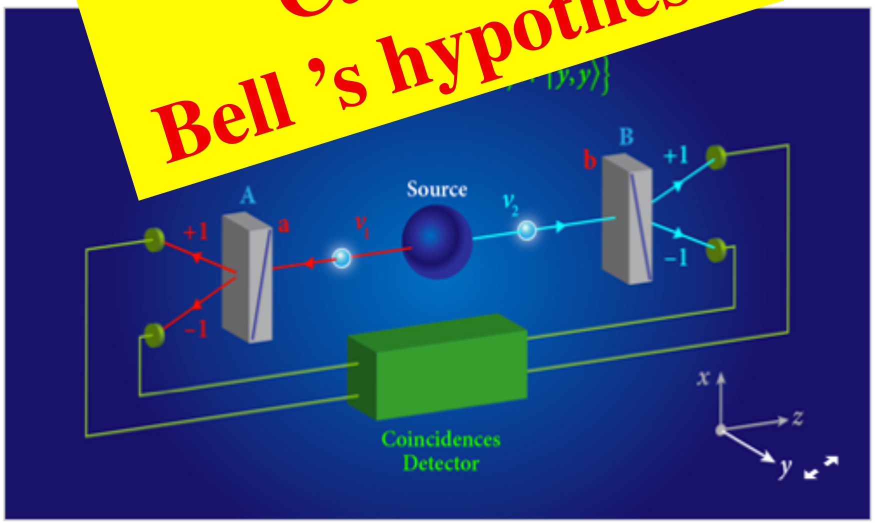
Viewpoint: Closing the Door on Einstein and Bohr's Quantum Debate

Alain Aspect, Laboratoire Charles Fabry, Institut d'Optique Graduate School, ...
Palaiseau, France

December 16, 2015 • *Physics* 8, 123

By closing two loopholes at ... remove the last doubts that we should renoun... ...antum information technologies.

Careful but unavoidable conclusion :
Bell 's hypotheses (local realism) are untenable !



APS/Alan Stonebraker

B. Hensen et al., Nature 526, 682 (2015).
"Loophole-free Bell Inequality Violation Using Electron Spins Separated by 1.3 Kilometres"

M. Giustina et al., Phys. Rev. Lett. 115, 250401 (2015).
"Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons"

L. K. Shalm et al., Phys. Rev. Lett. 115, 250402 (2015).
"Strong Loophole-Free Test of Local Realism"

W. Rosenfeld et al, Phys. Rev. Lett. 119, 010402 (2017).
"Event-ready Bell test using entangled atoms simultaneously closing detection and locality loopholes"

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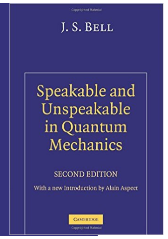
J. S. Bell

Speakable and Unspeakable in Quantum Mechanics



Let us anticipate that quantum mechanics works also for Aspect. How do we stand? I will list four of the attitudes that could be adopted.

(1) ~~The inefficiencies of the counter, and so on, are essential. Quantum mechanics will fail in sufficiently critical experiments.~~

(2) There *are* influences going faster than light, even if we cannot control them for practical telegraphy. Einstein local causality fails, and we must live with this. [must be instaneous: N. Gisin et al, Nat. Phys. 8, 868 (2012)]

(3) The quantities *a* and *b* are not independently variable as we supposed. (...). Then Einstein local causality can survive. But apparently separate parts of the world become deeply entangled, and our apparent free will is entangled with them.

(4) The whole analysis can be ignored. The lesson of quantum mechanics is not to look behind the predictions of the formalism. As for the correlations, well, that's quantum mechanics.

"Can Quantum-Mechanical Description of Physical Reality be Considered Complete?"

A. Einstein, B. Podolsky and N. Rosen, Phys. Rev. 47, 777 (1935) :

« One would **not** arrive at our conclusion by insisting that **if the quantities P and Q (in the second system) cannot be both simultaneously predicted, then they are not simultaneously real.** This would make the reality of P and Q depend upon the process of measurement carried out on the first system, **which does not disturb the second system in any way**. **No reasonable definition of reality could be expected to permit this.** »

N. Bohr, Phys. Rev. 48, 696 (1935) :

« EPR's criterion of physical reality contains an ambiguity in the meaning of "**without in any way disturbing a system**". Of course there is no mechanical disturbance of the system under investigation, but there is an influence on **the very conditions which define the possible types of predictions regarding the future behavior of the system**. These conditions constitute an **inherent element of the description of any phenomenon to which the term "physical reality" can be properly attached.** »

What are these « very conditions » required by Bohr to speak about the physical reality of quantum phenomena ?

Philosophical standpoint

Many physicists (including me) will support **Physical Realism**, understood as :
The purpose of physics is to study entities of the natural world, existing independently from any particular observer's perception, and obeying universal and intelligible rules.

Many physicists (inc. me) look at **certain and reproducible events as real,** so we like :
If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.

but Bell tests show that this view does not work as such... **so don't forget Bohr** :
The very conditions which define the possible types of predictions regarding the future behavior of the system constitute an inherent element of the description of any phenomenon to which the term "physical reality" can be properly attached.

Could all these statements be made compatible together ?
We will propose an answer later, but remember:

Sir Arthur Conan Doyle (1920's) : Once you eliminate the impossible, whatever remains, no matter how improbable, must be the truth.

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Classical Physics :
Systems and Properties

Classical physics :

* A **« System »** is an entity of the natural world that can be isolated well enough to carry physical properties with definite values, such as mass, charge, position...

* Such properties are measured by using devices external to the system, and attributed to the system itself: **a particle « has » a mass, a position, a velocity...**

* Strictly speaking one should say: ..**when it is measured by this given apparatus.** The complete specification of this apparatus will be called a **« Context »** , but it can be forgotten in classical physics, only the results of the measurement matter.

* Once measured, the properties are « known », they can be measured repeatedly, and the results can be predicted with certainty, taking into account the dynamical evolution of the system : **the properties « belong » to the system (ID card).**

Quantum Physics :
Systems, Contexts, and Modalities

Quantum physics :

* A « **System** » is an entity of the natural world that can be isolated well enough to carry properties with definite values, such as mass, charge, position...

* Such properties are measured by using devices external to the system, and the complete specification of the measurement apparatus will be called a « **Context** »

*** Once measured, the values of the properties can be measured repeatedly, and the results can be predicted with certainty, in a given context.**

*** The set of definite (fully predictable) values of the physical properties belongs jointly to the system and the context, and it will be called a modality.**

***What is « real » is the combination of Context, System and Modality (CSM)**

Usual langage (classical...) : a photon « has » a polarization oriented at 45°
CSM : the photon (system) is transmitted with certainty (modality) through a polarizer oriented at 45° (context)

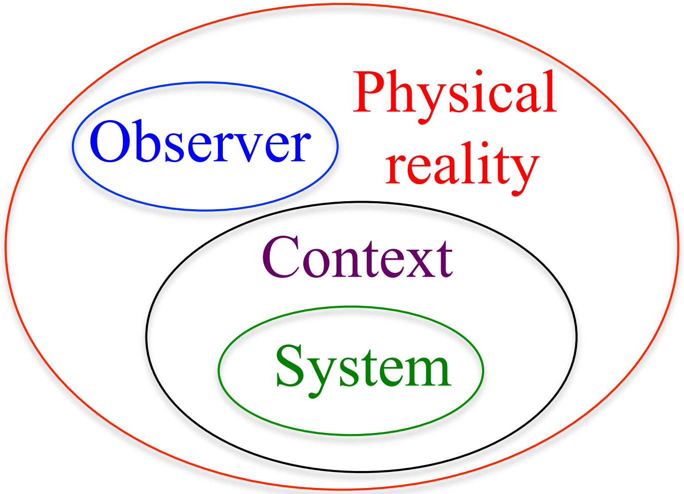
Element of physical reality vs modality

If, without in any way disturbing a system **neither changing the context,** we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element physical reality corresponding to this physical quantity. **It is called a modality.**

* This statement agrees with both the **« certainty » required by Einstein and the « very conditions » required by Bohr** to make and to check definite and reproducible predictions (i.e. with objectivity, taken as contextual).

* Therefore **the « object »** carrying the element of physical reality **is a system within a context.**

* The « split » between system and context is not a problem for CSM, because a modality is defined in terms of both the system and the context, and the system **cannot include the context.**



« Quantum mechanics can explain anything, but not everything »

A. Peres and W. H. Zurek, Am. J. Phys. 50, 807 (1982)

The Quantization Principle

What prevents to have a unique context where all modalities would be defined ? (this would be back to classical physics)

1. Within a given context, the modalities are mutually exclusive, i.e. if one of them is realized (or true), the other ones are not realized (or wrong). In a different context, there will be a different set of mutually exclusive modalities.

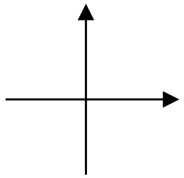
2. Modalities taken from two different contexts are generally « non mutually exclusive », or « incompatible », i.e. if one one of them is realized, one cannot tell whether the other ones are realized or not. Incompatible modalities are « non-classical » : classically, it should be possible to distinguish them by making more measurements, i.e. by extending the context.

3. Quantization principle : the number N of mutually exclusive modalities is a property of the quantum system, and it is independant of the context.

Example of polarized photons

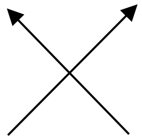
2 exclusive modalities

context
« + »



woman
man

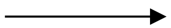
context
« x »



smoking
non smoking

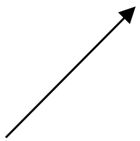
4 classical cases :
smoking man
smoking woman
non smoking man
non smoking woman

1. context
« + »



Select woman

2. context
« x »



Select smoking woman

3. context
« + »

Select man ? yes !

Classical conclusion:
Half of smoking women are actually men !

Why nonsense ?
Because « smoking » and « woman » are **non-exclusive modalities** (cannot be combined)

Usual langage (classical...) : the photon « has » a polarization oriented at 45°
CSM : the photon (system) is transmitted with certainty (modality) through a polarizer oriented at 45° (context)

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Why probabilities ?

The quantization principle implies that one must use probabilities !

Given one system and two contexts C and C', each with N modalities, **combining the incompatible modalities** b_n from C and b_m' from C' in a single context with more than N modalities **is forbidden by the quantization principle.**

Ex. for N=2	Vertical polarizer Tv or Rv	Diagonal polarizer Td or Rd	Combined results TvTd, TvRd, RvTd, RvRd
	Two mutually exclusive modalities, ok	Two mutually exclusive modalities, ok	Four modalities, not a context if N = 2.

Therefore the only relevant question that can be answered by the theory is:
if the initial modality is b_n in context C, what is the probability for obtaining modality b_m' from a quantum measurement in context C' ?

Probabilities are not related to any ignorance, but to the ontology of the theory : there is no "global context" where all modalities can be made mutually exclusive.

A. A. & P. G. , Found. Phys. 46, 121 (2016) http://arxiv.org/abs/1409.2120

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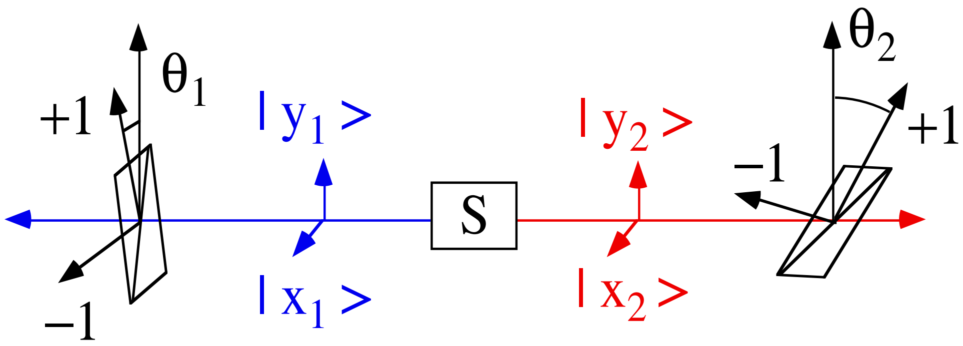
From Einstein, Podolsky and Rosen to Bell's inequalities



Source S emitting pairs of photons "1" and "2" in the quantum state :
$(| x_1\, x_2 > + | y_1\, y_2 >)/\sqrt{2}$
Entangled state !

« Hidden variables » or « supplementary parameters » denoted λ,

with a normalized statistical distribution $\rho(\lambda)$: $\int d\lambda\ \rho(\lambda) = 1$

$\varepsilon_1 = \pm 1$, $\varepsilon_2 = \pm 1$, $E(\theta_1, \theta_2) = \sum_{\varepsilon_1 \varepsilon_2} \int d\lambda\ \rho(\lambda)\ \varepsilon_1 \varepsilon_2\ p(\varepsilon_1 | \lambda, \theta_1)\ p(\varepsilon_2 | \lambda, \theta_2)$

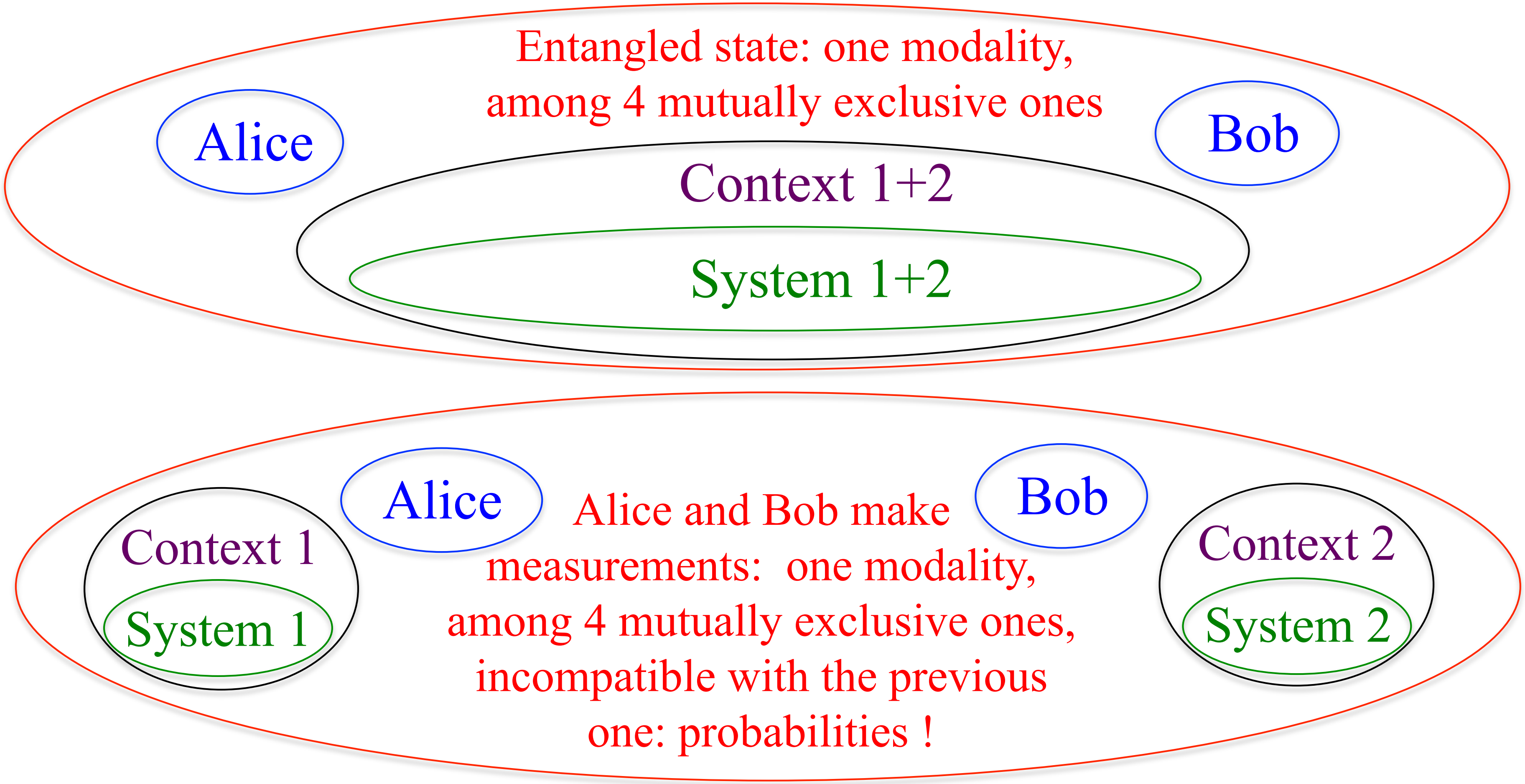
locality / freedom of choice

then : $-2 \leq S \leq 2$ with :

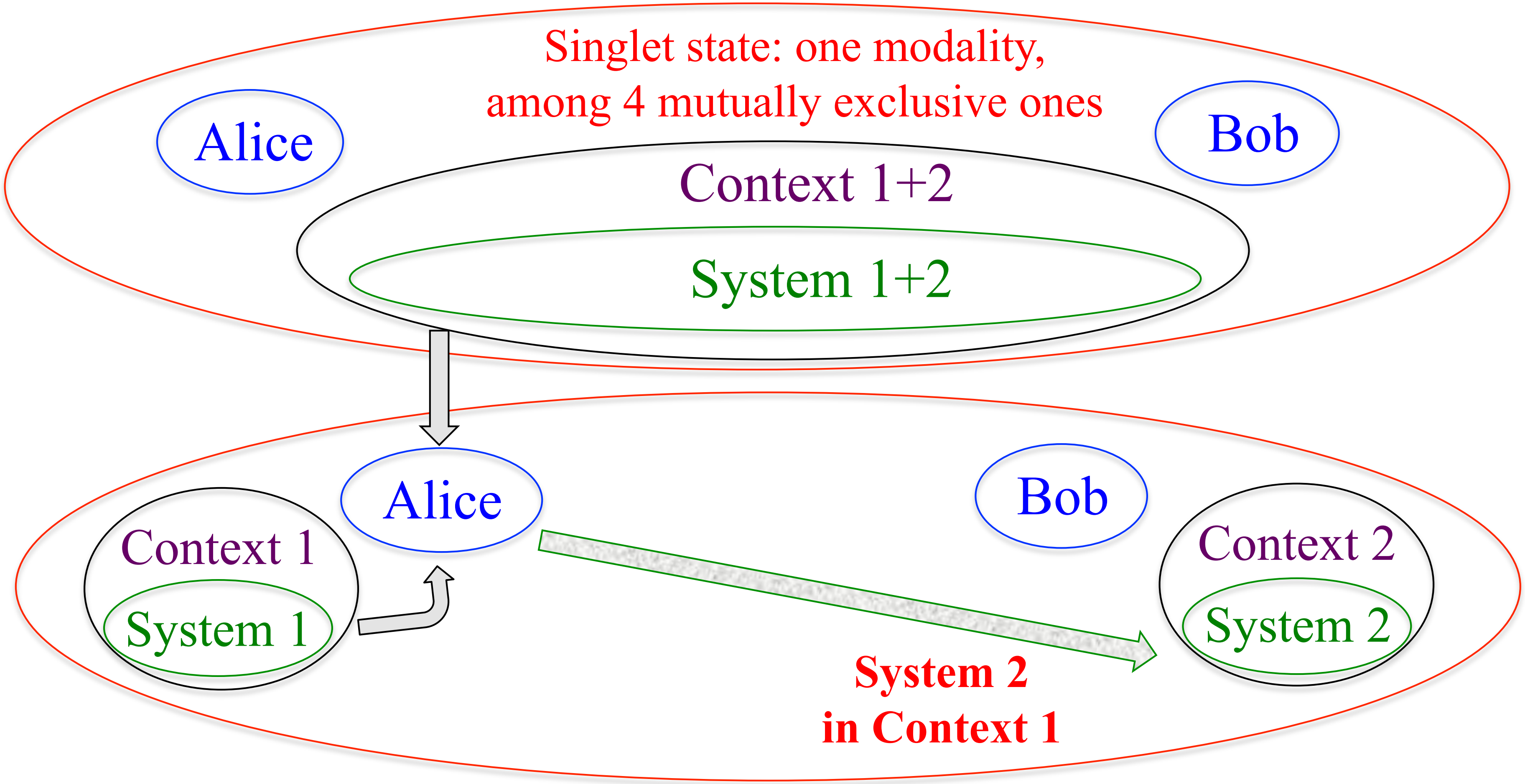
$S = E(\theta_1, \theta_2) + E(\theta'_1, \theta_2) + E(\theta'_1, \theta'_2) - E(\theta_1, \theta'_2)$

One can get $S_{QM} = 2\sqrt{2}$ => Conflict => Experiments => QM wins !

Why quantum non-locality ?



Why quantum non-locality ?



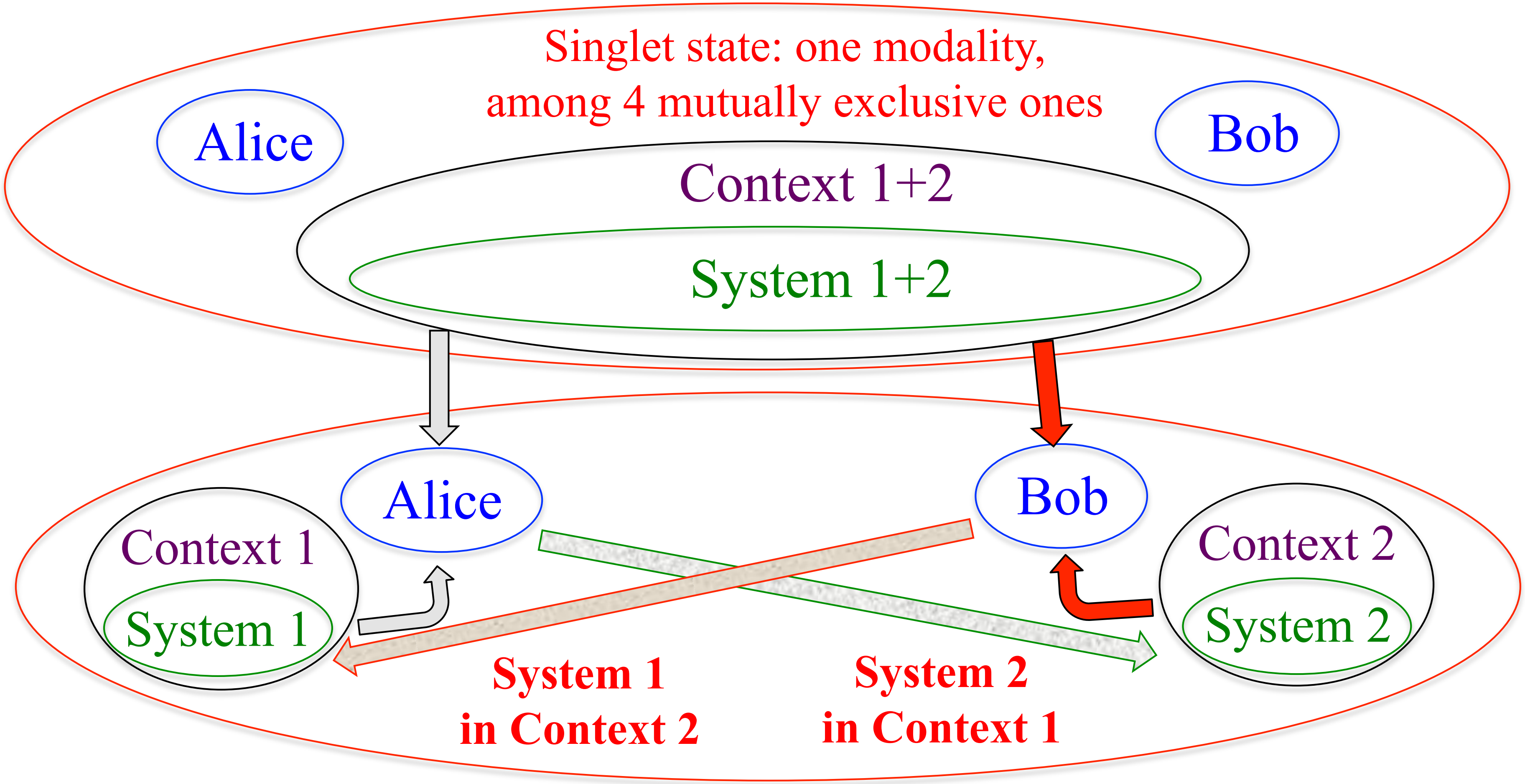
After measuring on one side (by Alice), what happens on Bob's side ?

Just nothing ! But Alice can predict Bob's state with certainty, in **her** context

Alice has the context, and Bob has the system, and both are needed !

They can be combined as a modality only in their common future.

Why quantum non-locality ?



Quantum non-locality results from the composite nature (system + context) of the quantum « object ».

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Reconstructing the formalism of QM

Using probabilities is needed due to non-exclusive modalities !

Fundamental question : if we know that the system is in a modality b_n in the context C, what is the probability to find it in a modality b_m' in the context C' ?

Useful mathematical object : (N x N) probability matrix Π, giving the probability $p(b_m' | b_n)$ to find the system in a modality b_m' in the context C', knowing that it is in a modality b_n in the context C.

Context C'

$$\text{Context C} \quad \begin{matrix} & b_1' & b_2' & b_3' & b_4' & \ldots \\ b_1 \\ b_2 \\ b_3 \\ b_4 \\ \ldots \end{matrix} \begin{pmatrix} p_{11} & p_{12} & p_{13} & \ldots \\ p_{21} & p_{22} & p_{23} & \ldots \\ p_{31} & p_{32} & p_{33} & \ldots \\ \ldots & \ldots & \ldots & \\ \end{pmatrix} = \Pi$$

All lines sum to 1 : this is a stochastic matrix

The axioms

Sci. Rep. 7, 43365 (2017) [arxiv/1610.06164]

Axiom 1 (modalities) : A modality is defined by the fully predictable and reproducible values of a complete set of of physical properties. The modality is attributed jointly to a system and a context, which constitute the « quantum object ».

Axiom 2 (quantization) : For a given context, there are N mutually exclusive modalities. The value of N, called the dimension, is a characteristic property of a given quantum system, and is the same in all relevant contexts.

Axiom 3 (contexts) : Given axioms 1 and 2, the different relevant contexts relative to a quantum system are related between themselves by continuous transformations which are associative, have a neutral element (no change), and an inverse.

Crucial remark : By definition modalities cannot show up independently of a context, but the same physical properties may have the same values in different contexts, with the same conditions of repeatability and certainty.

* In classical physics this is always the case (non-contextuality or uni-contextuality)
* It might also be never the case (each context owns its properties: full contextuality)
* **In quantum physics this is partly the case : extra-contextuality.**

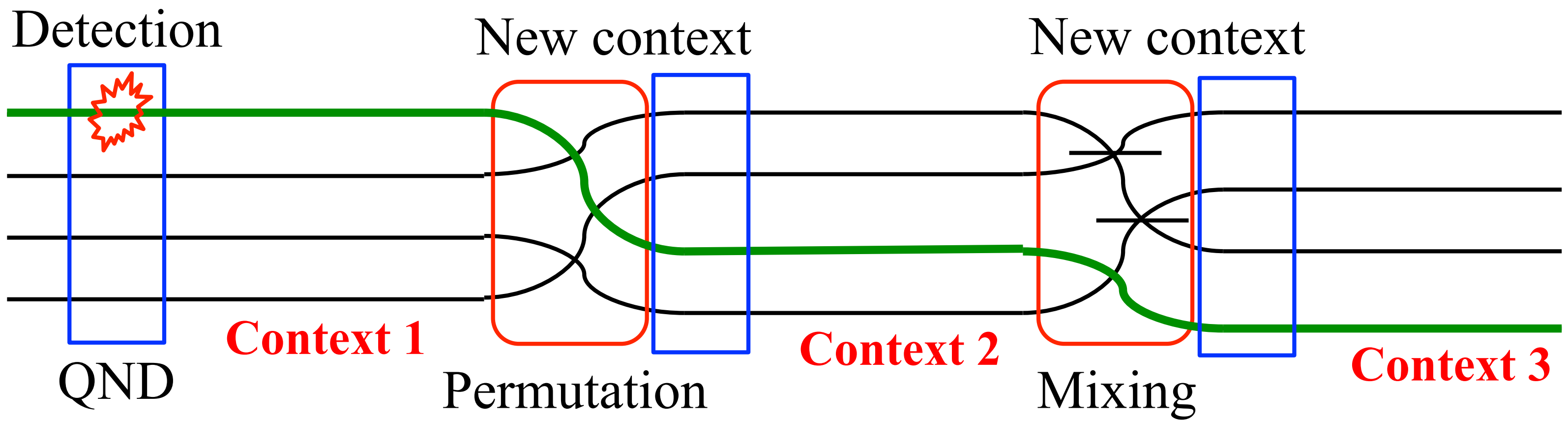
Extra-contextuality (1)

Experimental evidence (expressed in Axiom 1):

the certainty of a modality can be transferred from one context to another.

Simple example with one photon in N transmission lines (qudit, d = N):

One detection only, can be non-destructive (QND measurement)



Can be turned into a rule: the certainty of a modality can be transferred between different contexts, corresponding to the same (or to directly related) physical quantities measured by different ways.

This transfer of certainty is an equivalence relation (symmetric reflexive transitive) **between modalities in different contexts, call it extravalence.**

Extra-contextuality (1)

Experimental evidence (expressed in Axiom 1) :

the certainty of a modality can be transferred from one context to another.

Simple example with two spins ½, dimension N = 2x2 = 4

Measurement of the angular momenta $\mathbf{S_1}$, $\mathbf{S_2}$, $\mathbf{S = S_1 + S_2}$

Three contexts:	**Four modalities:**	
S_{z1}, S_{z2}	m_1 and $m_2 = \pm 1/2$:	$\|+,+\rangle$, $\|+,-\rangle$, $\|-,+\rangle$, $\|-,-\rangle$
Total spin $\mathbf{S^2}$, S_z	S = 0,1 m = -1,0,1 :	$\|1,1\rangle$, $\|1,0\rangle$, $\|0,0\rangle$, $\|1,-1\rangle$
Bell states meas.	4 entangled states : $\|\Phi^{\pm}\rangle = (\|+,+\rangle \pm \|-,-\rangle)/\sqrt{2}$; $\|\Psi^{\pm}\rangle = (\|+,-\rangle \pm \|-,+\rangle)/\sqrt{2}$	$\|\Phi^{+}\rangle$, $\|\Psi^{+}\rangle$, $\|\Psi^{-}\rangle$, $\|\Phi^{-}\rangle$

Can be turned into a rule: the certainty of a modality can be transferred between different contexts, corresponding to the same (or to directly related) physical quantities measured by different ways.

This transfer of certainty is an equivalence relation (symmetric reflexive transitive) **between modalities in different contexts, call it extravalence.**

Extra-contextuality (2)

More general rule (extra-contextuality) : given a modality, the probability to get any other possible modality depends only on the extravalence class of these 2 modalities, and not on their embedding contexts.

As a consequence, this probability will only depend on the two mathematical objects associated with the two extravalence class.

Extra-contextuality + continuity of the contexts change imply the quantum formalism. This can be shown by introducting a general parametrization of stochastic matrices, and imposing extra-contextuality.

A. Auffèves & P. Grangier, Sci. Rep. 7, 43365 (2017)

This conclusion can also be obtained from Gleason's theorem, by explicitly associating projectors to extravalence classes (all other hypotheses are already there)

Take-home message

* In the CSM view of QM, **the physical objects involve jointly a (quantum) system and a (classical) context.** These objects can be given objective (certain, reproducible) properties called **modalities** (elements of physical reality).

* This is related to Bohr's view, but also major differences : **for CSM the « explanation » of quantum behaviour is quantization** (Rovelli, Zeilinger...)

* Contextual quantization implies that **modalities are related probabilistically between different contexts** (probabilities are the only way to manage quantization)

* Modalities are neither fully contextual nor non-contextual, they are **extra-contextual** (i.e. the certainty of modalities can be transferred between contexts).

* Given that, the QM formalism is a **mathematical way to calculate these probabilities**, consistently with the CSM axioms.

Modality		**State vector or projector**
Real physical phenomenon, involving a system and a context.	$\neq$	**Mathematical object, associated to a class of extravalent modalities.**

Thank you for your attention !

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Thank you to Franck Laloë, Anthony Leverrier, Adàn Cabello....