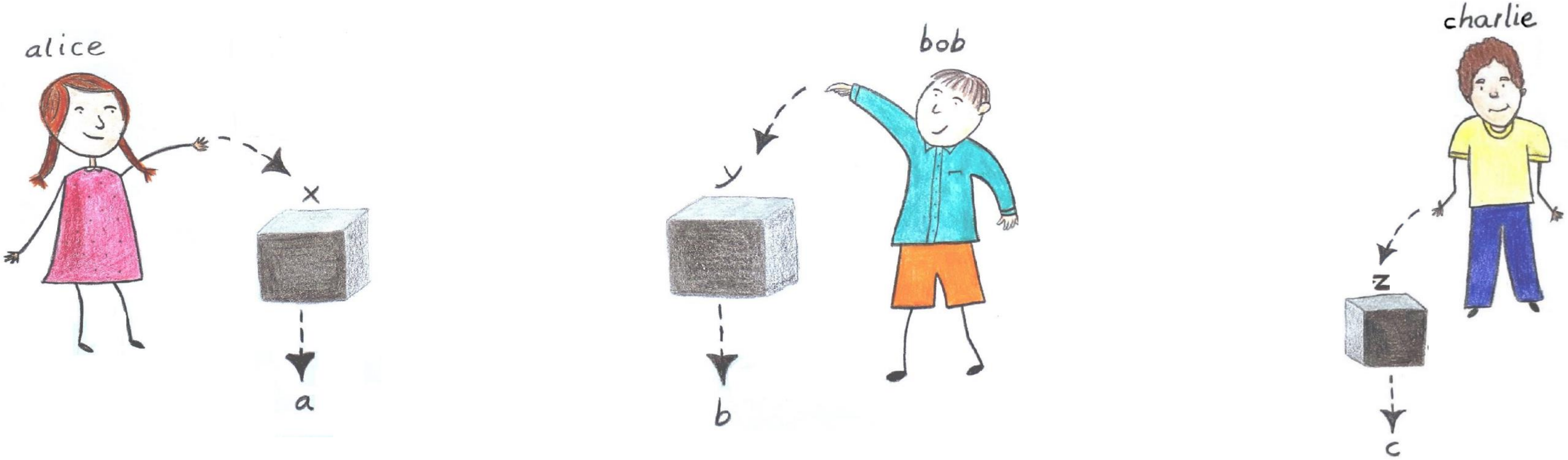
Bell Theorem and its generalizations

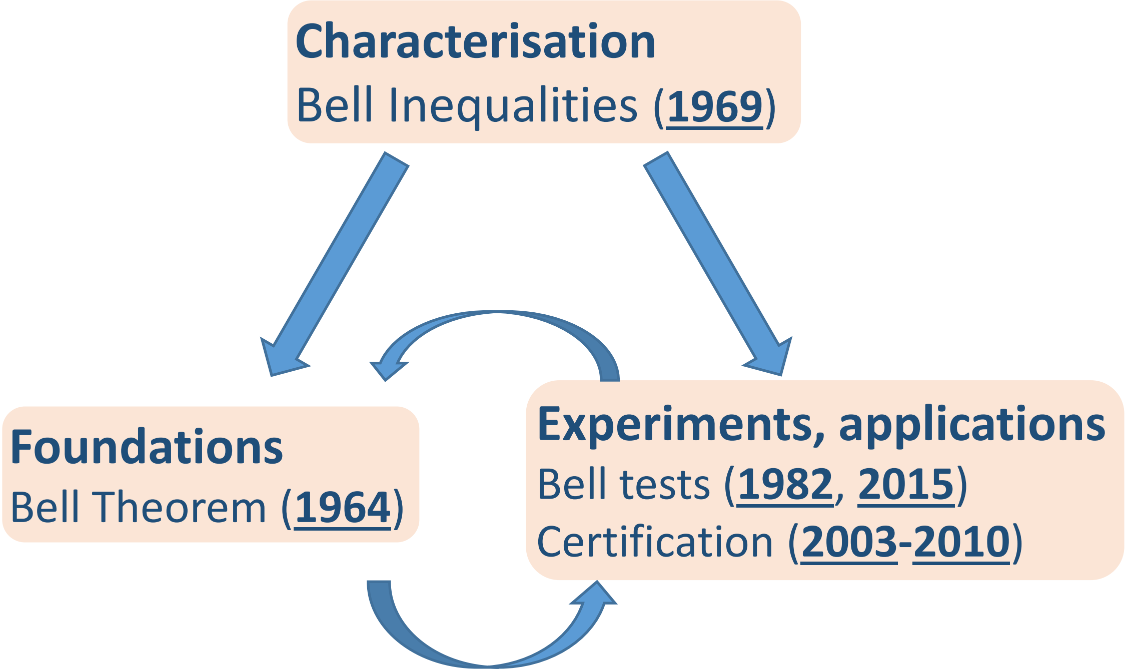


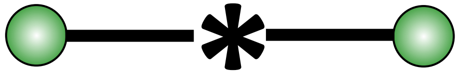
Grace Seminar

Marc-Olivier Renou
Junior Professor Chair INRIA Paris Saclay
Computer Science Laboratory / Center for Theoretical Physics
Ecole Polytechnique

Overview

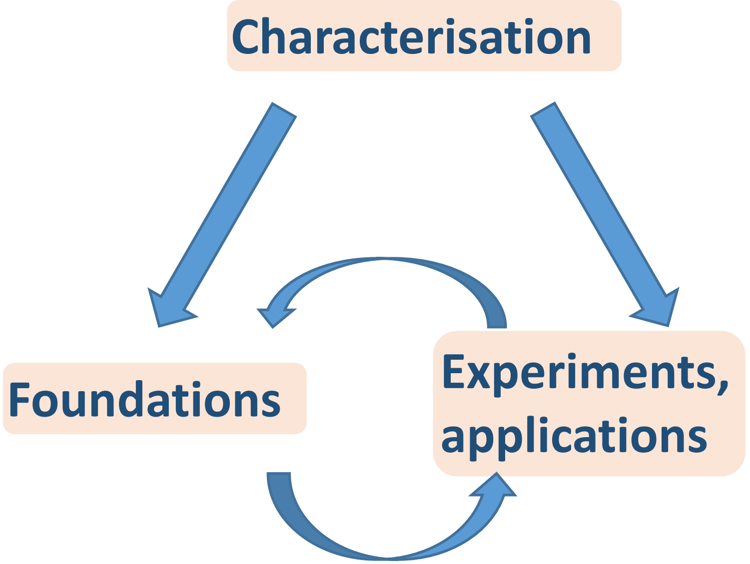
Single state quantum correlations

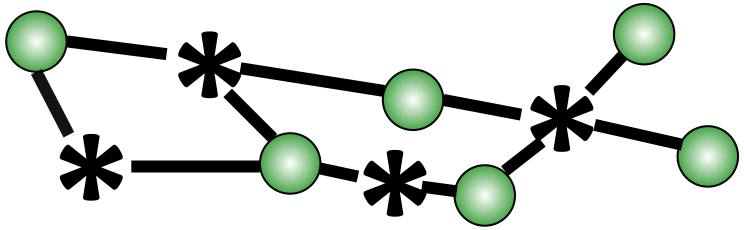




Overview

Causal network quantum correlations





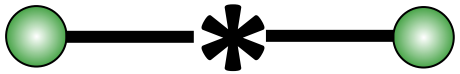
Overview

Single state quantum correlations

Characterisation
Bell Inequalities (1969)

Foundations
Bell Theorem (1964)

Experiments, applications
Bell tests (1982, 2015)
Certification (2003-2010)



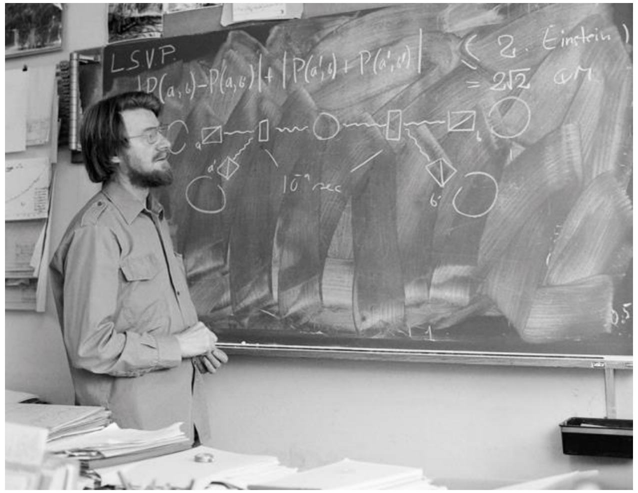
Characterisation

Foundations

Experiments, applications

Bell theorem

the Bell theorem is <u>not</u> about quantum theory



Bell's theorem 1964

Bell theorem:

Quantum theory predictions incompatible with 'a natural notion of locality'

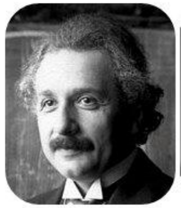
Main ingredient:

'classical physics correlations ≠ quantum correlations

Bell theorem: ‘with the eyes of a detective’

Experimentalist (e.g., Aspect)

Detective (e.g., Einstein)



Bell theorem: 'with the eyes of a detective'

Experimentalist (e.g., Aspect)

- Master Quantum theory

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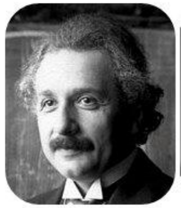

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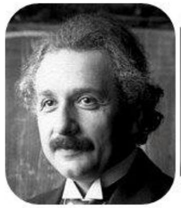

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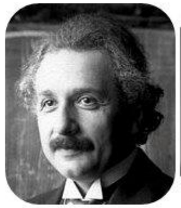

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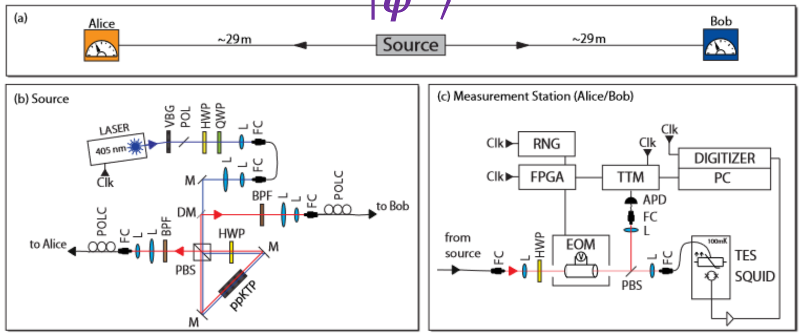
  - Information carriers do not travel faster than light

Bell theorem: ‘with the eyes of a detective’

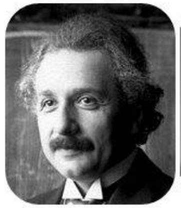
Experimentalist (e.g., Aspect)

- Master Quantum theory
- Construct a **concrete experiement**

$|\psi^+\rangle$



Detective (e.g., Einstein)



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$|\psi^+\rangle = (|0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B)/\sqrt{2}$

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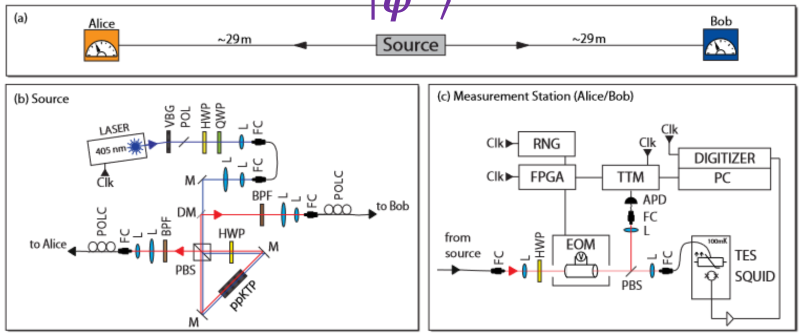

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  - $\boldsymbol{P(a,b|x,y)}$ such that $\mathbf{CHSH} = \mathbf{2\sqrt{2}}$

$\text{i.e.}\, \boldsymbol{p(a \oplus b = x \cdot y) = \cos^2\left(\frac{\pi}{8}\right) \approx 0.85}$

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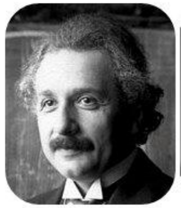

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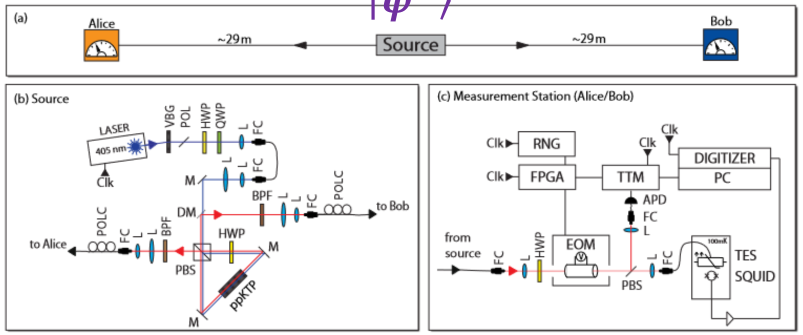

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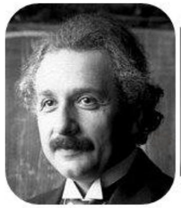

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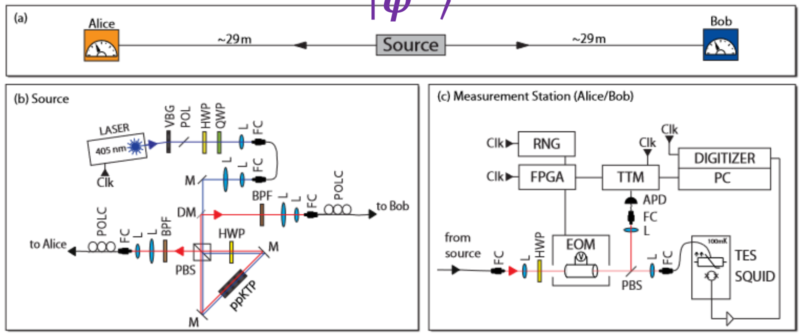

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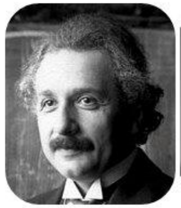

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  - Fails: is restricted to $\mathbf{CHSH} \leq 2$

$\text{i.e.}\; p(a \oplus b = x \cdot y) \leq 0.75$

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- Construct a **concrete experiement**

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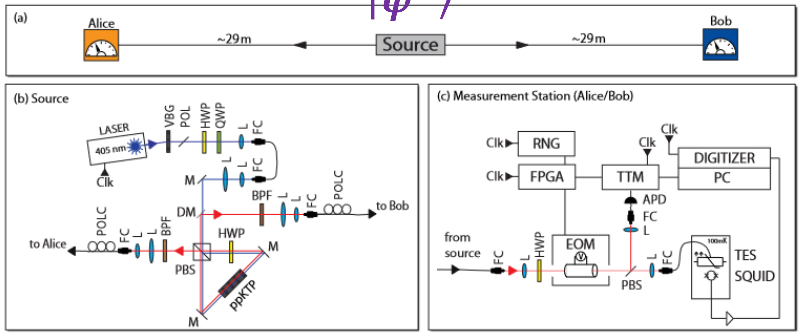

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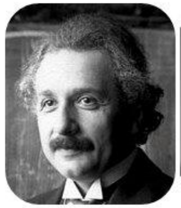

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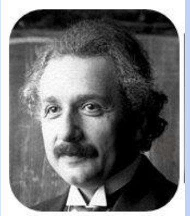
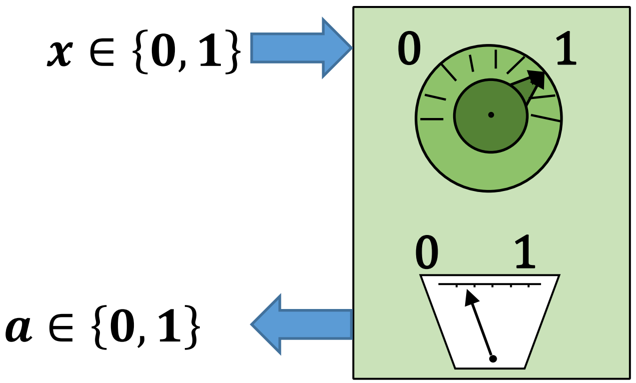
Bell Theorem [1964, 1969]: Proof of the failure of the detective

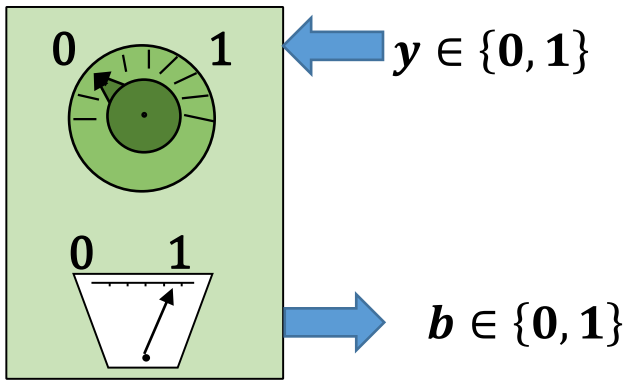


The CHSH experiment

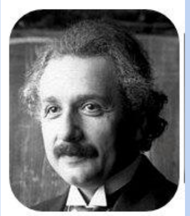
as observed by the detective

Alice, in Bordeaux and Bob, in Saclay





can select a measurement 0 or 1 **at random**
and obtain a result 0 or 1



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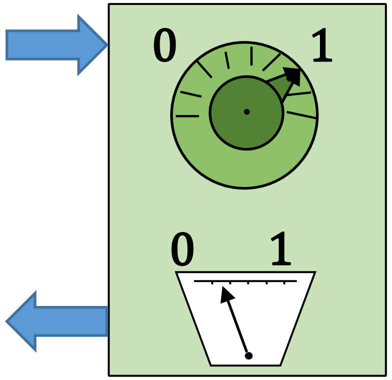
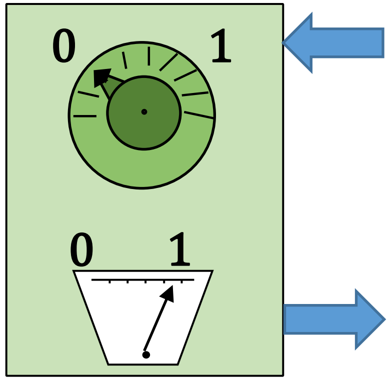
$x \in \{0,1\}$

$a \in \{0,1\}$

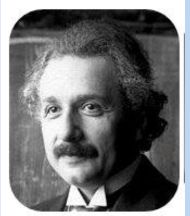


$y \in \{0,1\}$

$b \in \{0,1\}$



They do it many time, to accumulate statistics



CHSH inequality

CHSH game

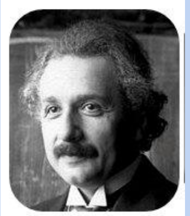
Alice, in Bordeaux

Bob, in Saclay

i	$x^{(i)}$	$a^{(i)}$	$y^{(i)}$	$b^{(i)}$	
1	1	0	0	0	
2	0	1	0	1	
3	0	0	0	0	
4	1	0	1	1	
5	0	1	1	0	
6	1	1	0	1	
7	1	1	1	1	
8	1	0	0	0	

Game

- Many test $N \gg 1$ of the device, in different rounds $i = 1, \dots, N$, with uniformly **random** inputs $x^{(i)}, y^{(i)}$, outputs $a^{(i)}, b^{(i)}$
- Accumulation of statistics



CHSH inequality

CHSH game

i	$x^{(i)}$	$a^{(i)}$	$y^{(i)}$	$b^{(i)}$	$S^{(i)}$
1	1	0	0	0	1
2	0	1	0	1	1
3	0	0	0	0	1
4	1	0	1	1	1
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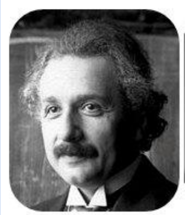

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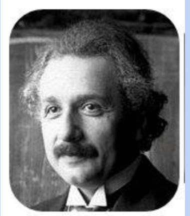

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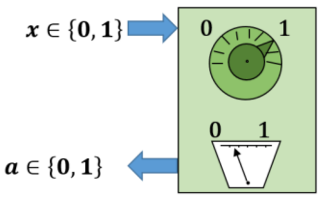
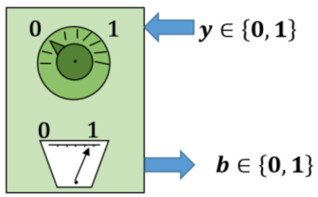


Bob, in Saclay



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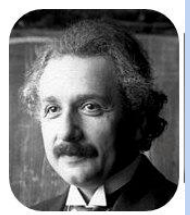
➢ The detective sees

$$p(a \oplus b = x \cdot y) \approx 0.85$$



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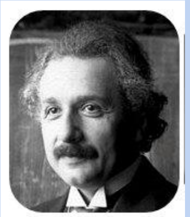
$$\Leftrightarrow \text{CHSH} \equiv \langle A_0 B_0 \rangle + \langle A_0 B_1 \rangle + \langle A_1 B_0 \rangle - \langle A_1 B_1 \rangle = 2\sqrt{2}$$

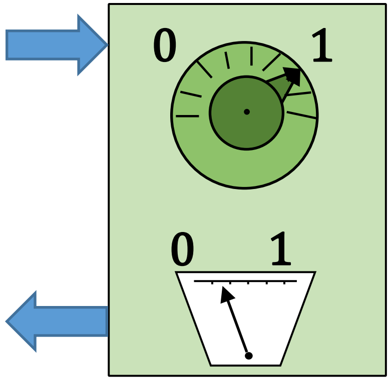


The CHSH experiment

as observed by the detective

Alice, in Bordeaux

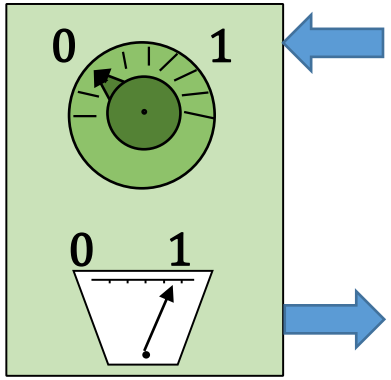
$x \in \{0, 1\}$



$a \in \{0, 1\}$

Bob, in Saclay

$y \in \{0, 1\}$



$b \in \{0, 1\}$

Correlated behavior:

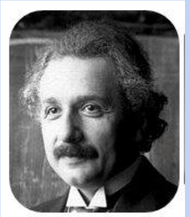
- If $x = y = 1$:

$$p(a = b) < p(a \neq b)$$

- If not:

$$p(a = b) > p(a \neq b)$$

$$p(a \oplus b = x \cdot y) \approx 0.85$$



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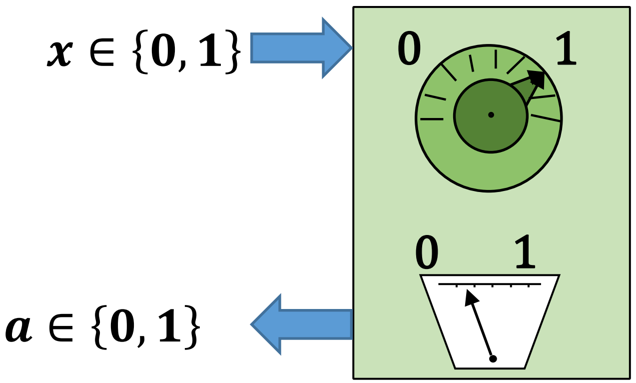

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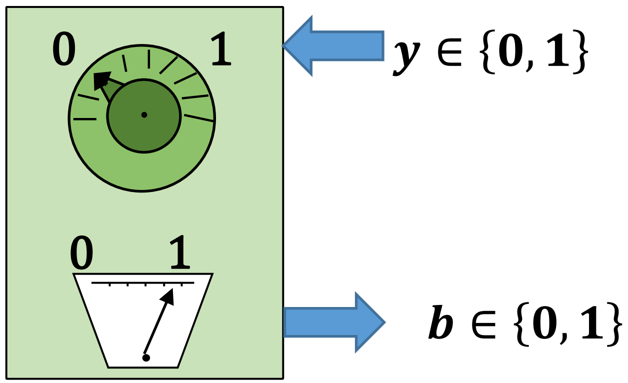

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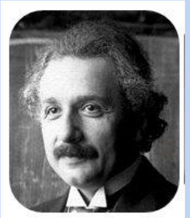
$$p(a = b) < p(a \neq b)$$

- If not:

$$p(a = b) > p(a \neq b)$$

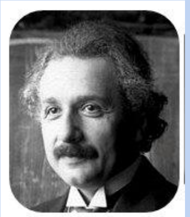
$$p(a \oplus b = x \cdot y) \approx 0.85$$

➢ **Detective's question**: Where does it come from?



Correlations = Influence or Common Cause

Only two possibilities:



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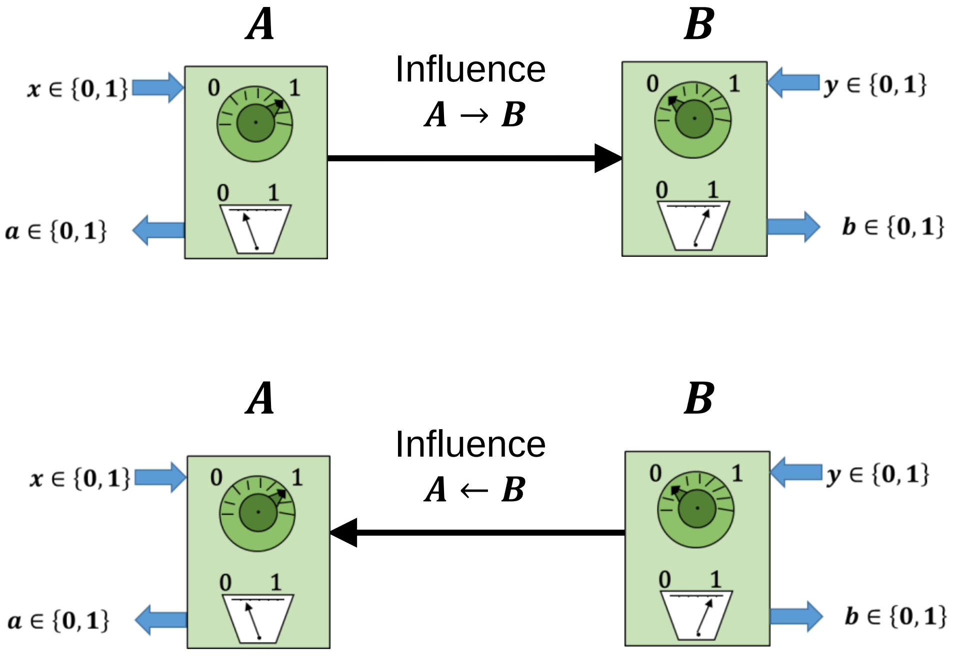

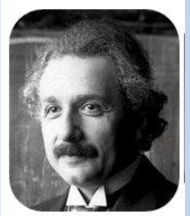

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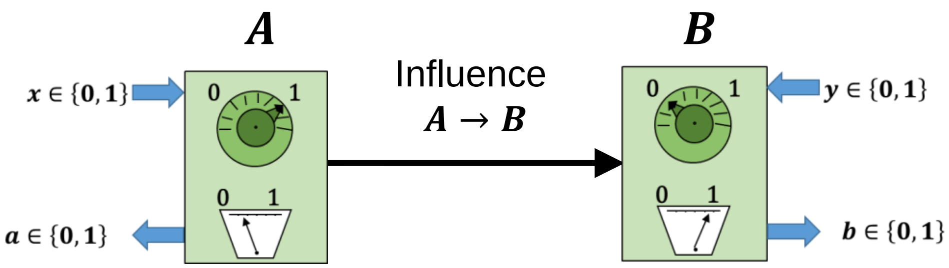
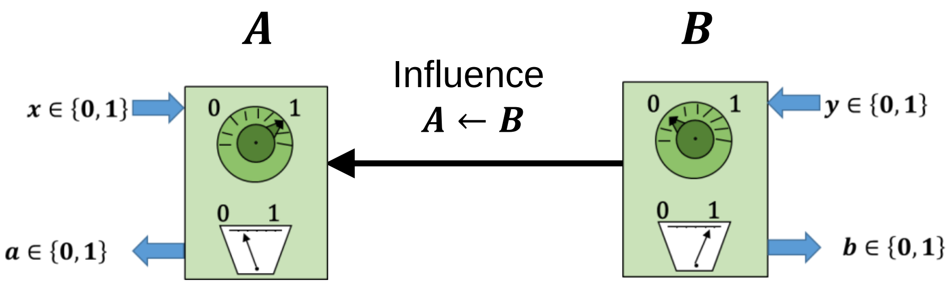
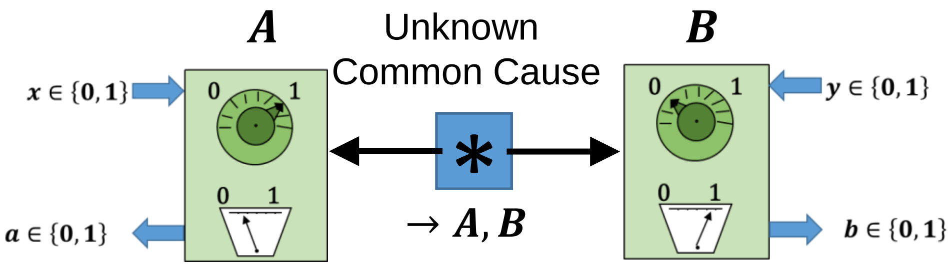
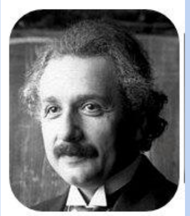




Common cause





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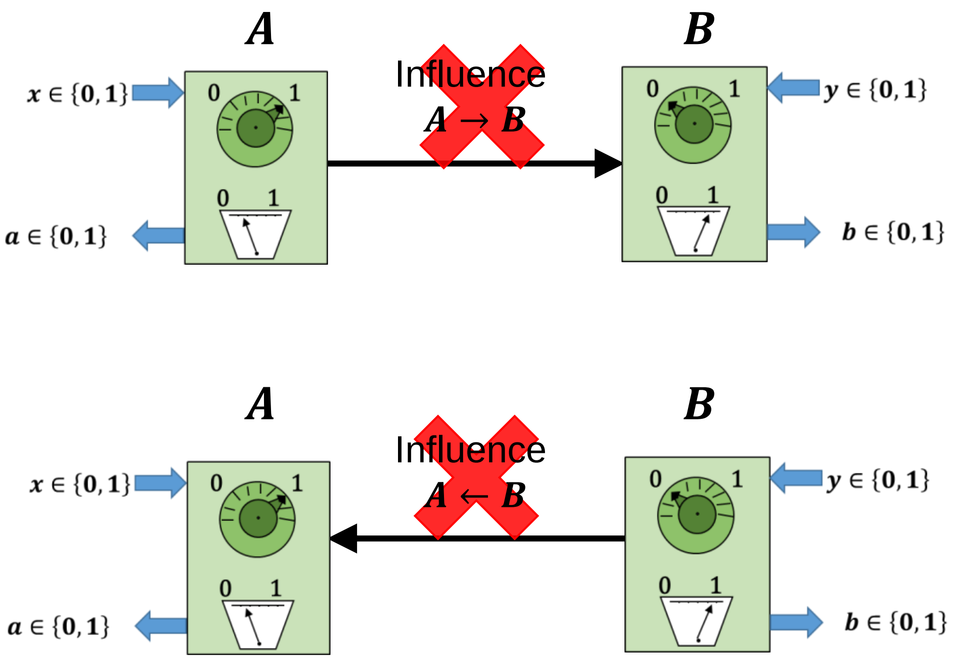

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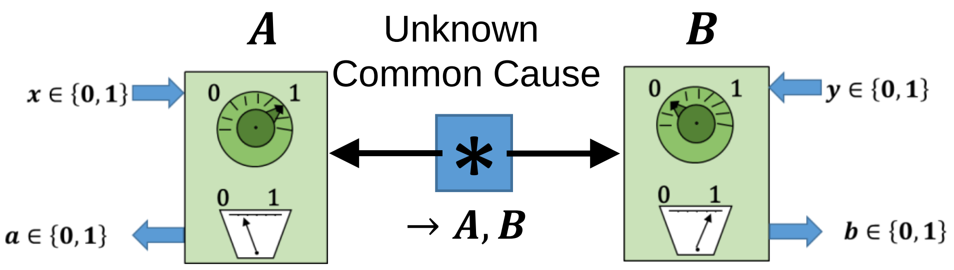
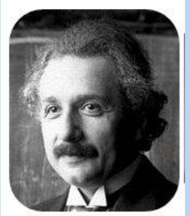


Space-like separation = Distance + Synchronization + no faster than light communications

= **No-Signalling Hypothesis**



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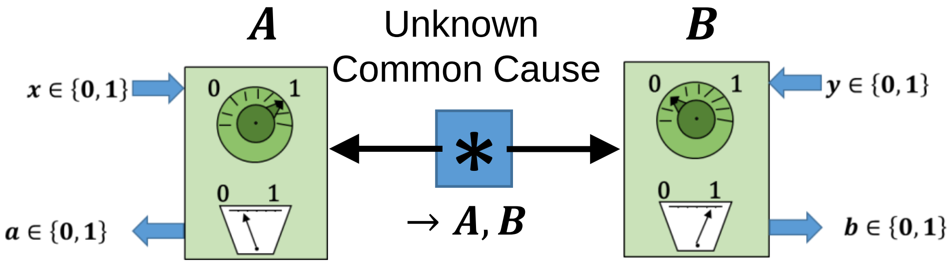

- The experimentalist **agrees** with deduction: for him, it is $|\psi^+\rangle = (|0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B)/\sqrt{2}$

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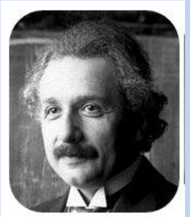

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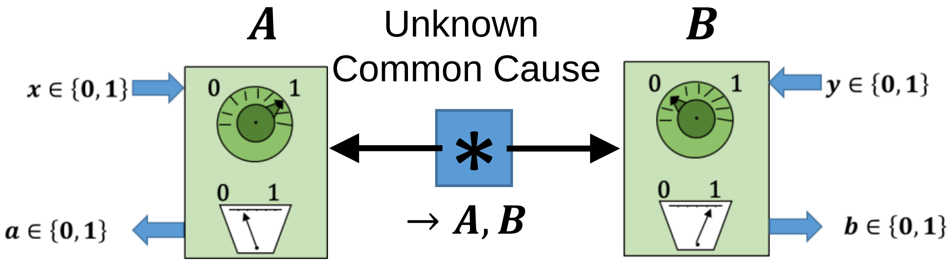
Common cause



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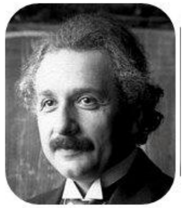
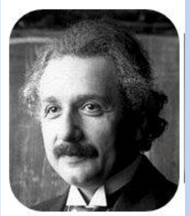
- For the detective, **the detectors might not use the photons.**





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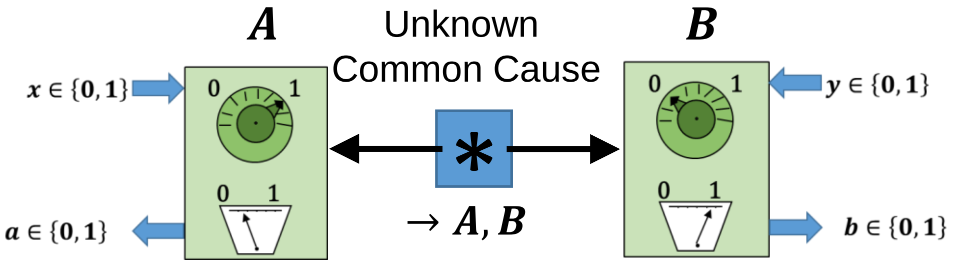

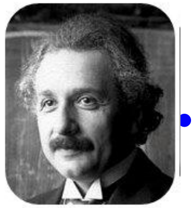

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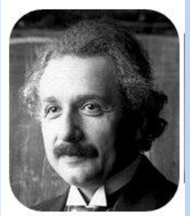
- For the detective, **the detectors might not use the photons.**
- Could be seismic vibrations, cosmic rays, … Whatever it is, this is the « Common Cause ».

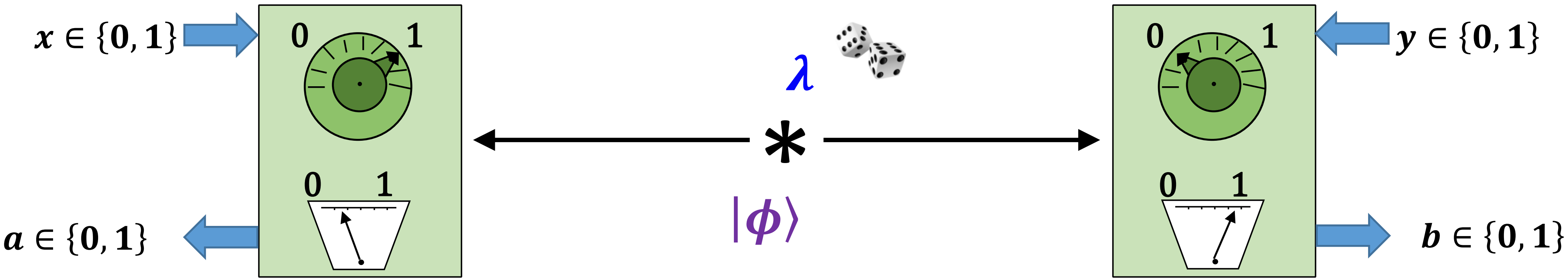


The CHSH experiment

as observed by the detective

Alice, in Bordeaux

Bob, in Saclay



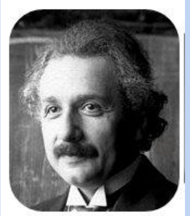
We must have a pre-established source of correlations

Classical source

local source of randomness λ

$\neq$

Quantum source $|\phi\rangle$

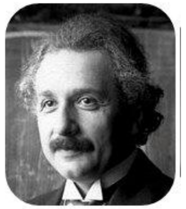


CHSH inequality

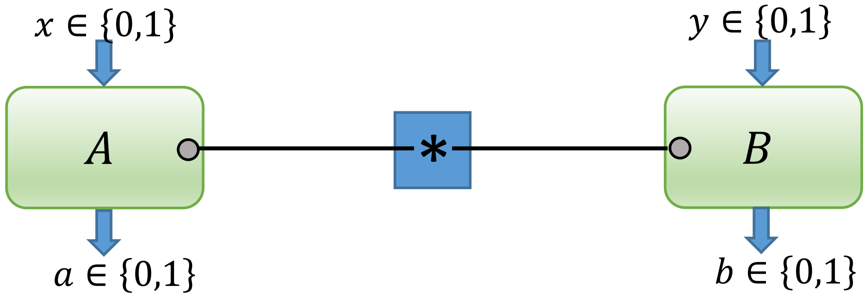
The detective model: LHV model

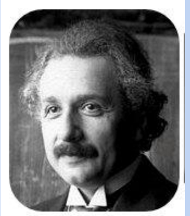
Local Hidden Variable model

= ‘classical physics’ = ‘shared randomness’



Local strategies





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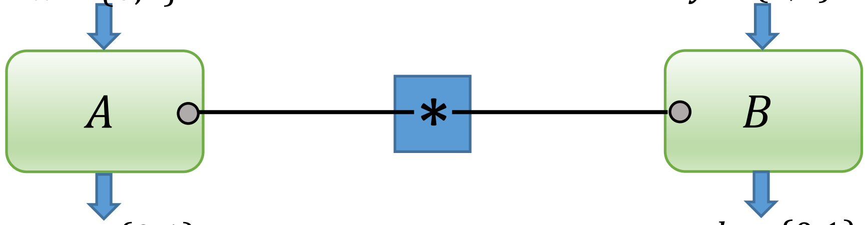

Local Hidden Variable model

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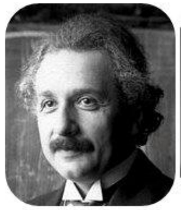
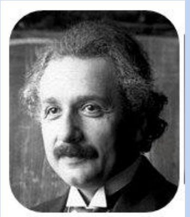


- Two carriers of information **travel contiguously** from source to parties



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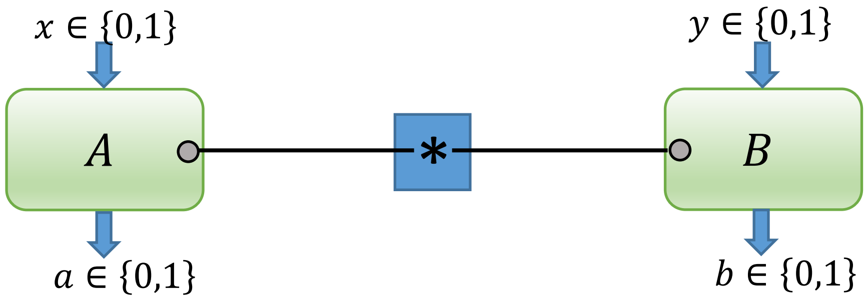

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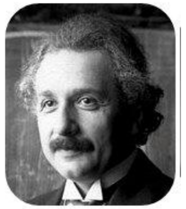

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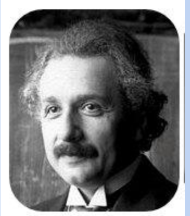

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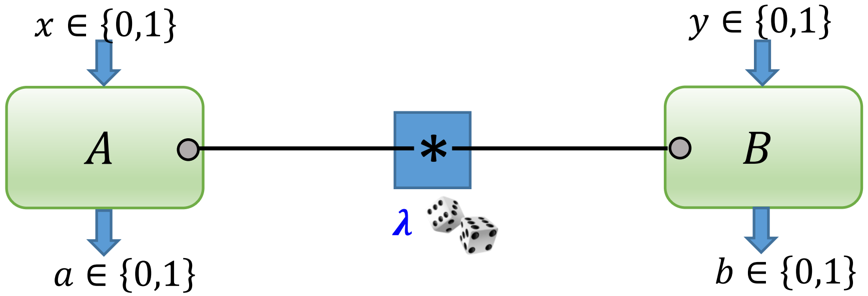

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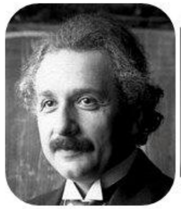

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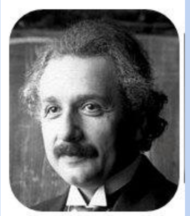
The experimentalist **does not agree** with this second detective deduction

In $|\boldsymbol{\psi}^+\rangle = (|\mathbf{0}\rangle_{\boldsymbol{A}}|\mathbf{1}\rangle_{\boldsymbol{B}} + |\mathbf{1}\rangle_{\boldsymbol{A}}|\mathbf{0}\rangle_{\boldsymbol{B}})/\sqrt{\mathbf{2}}$, even far, the two photons are “one system”



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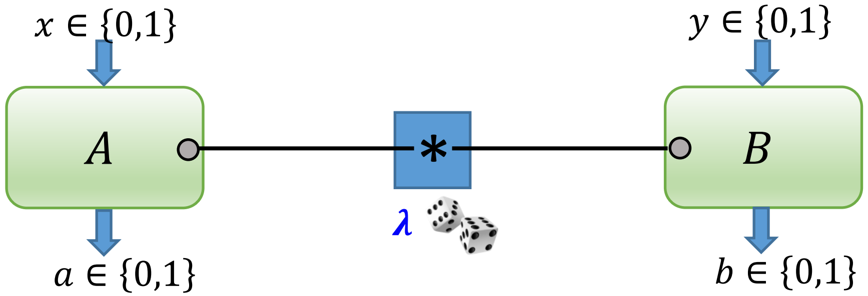

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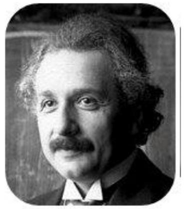

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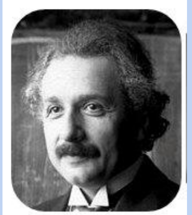

CHSH inequality

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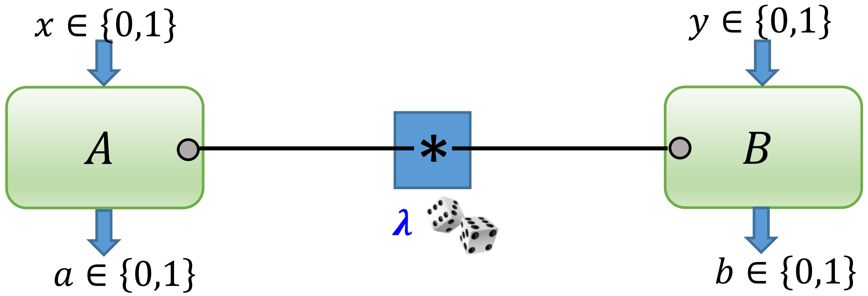

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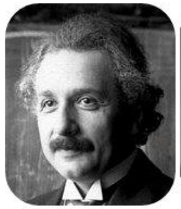

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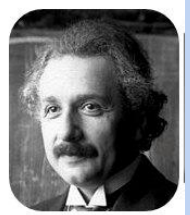
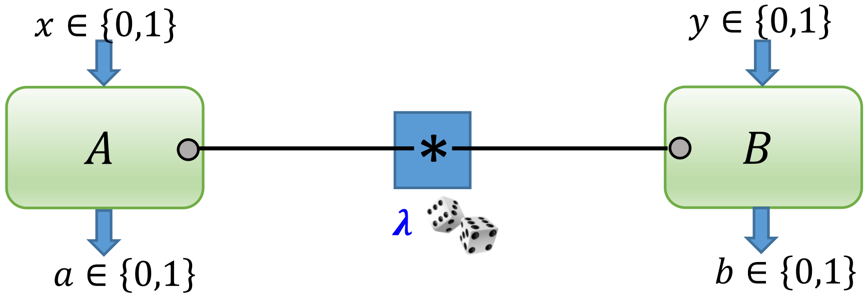


CHSH inequality

The detective model: LHV model

Local strategies



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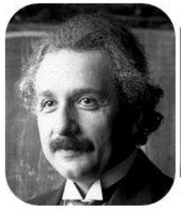

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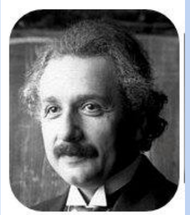
Bell Theorem [CHSH]:

1. For any LHV model $\boldsymbol{\lambda}$:

$$\boldsymbol{S = p(a \oplus b = x \cdot y) \leq \frac{3}{4} = 0.75}$$



CHSH inequality

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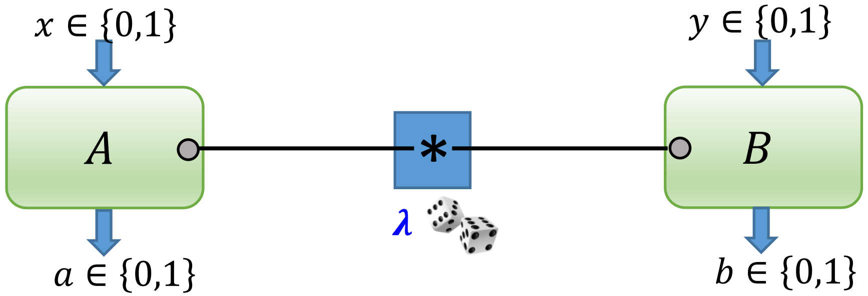

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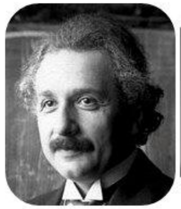

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Bell Theorem [CHSH]:

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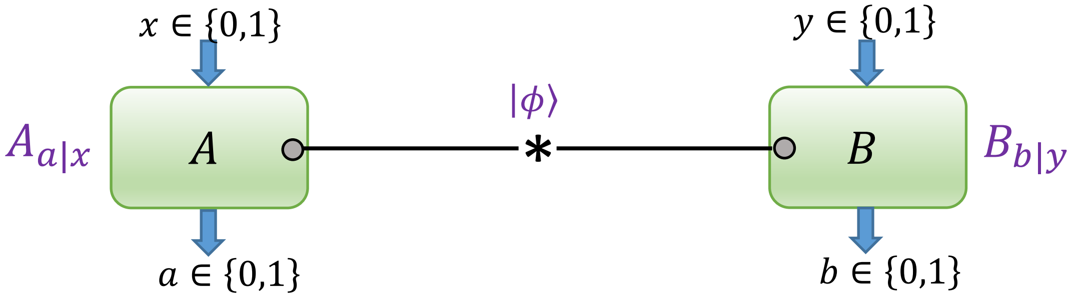
PROOF (1.):

- $p(ab|xy)$ is a linear superposition of deterministic strategies
- Deterministic strategies have $S \leq \frac{3}{4}$
- $S = p(a \oplus b = x \cdot y)$ is a linear score

CHSH inequality
Quantum model

Quantum strategy



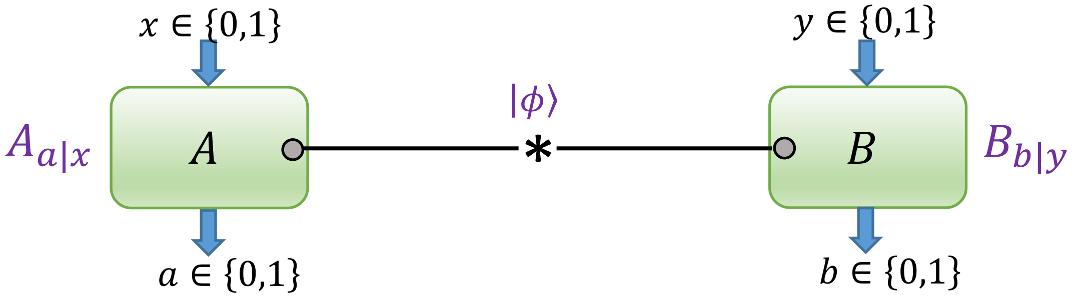
Quantum strategy

- The parties share a quantum state $|\boldsymbol{\phi}\rangle$
- They have measurement operators $\boldsymbol{A_{a|x}}, \boldsymbol{B_{b|y}}$
- The observation probabilities are:
  $\boldsymbol{p(ab|xy)} = \langle\boldsymbol{\phi}|\boldsymbol{A_{a|x}} \otimes \boldsymbol{B_{b|y}}|\boldsymbol{\phi}\rangle$

CHSH inequality

Quantum model

Quantum strategy



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Bell Theorem [CHSH, 1964, 1969]:

1. For any LHV model λ:

$$S = p(a \oplus b = x \cdot y) \leq \frac{3}{4} = 0.75$$

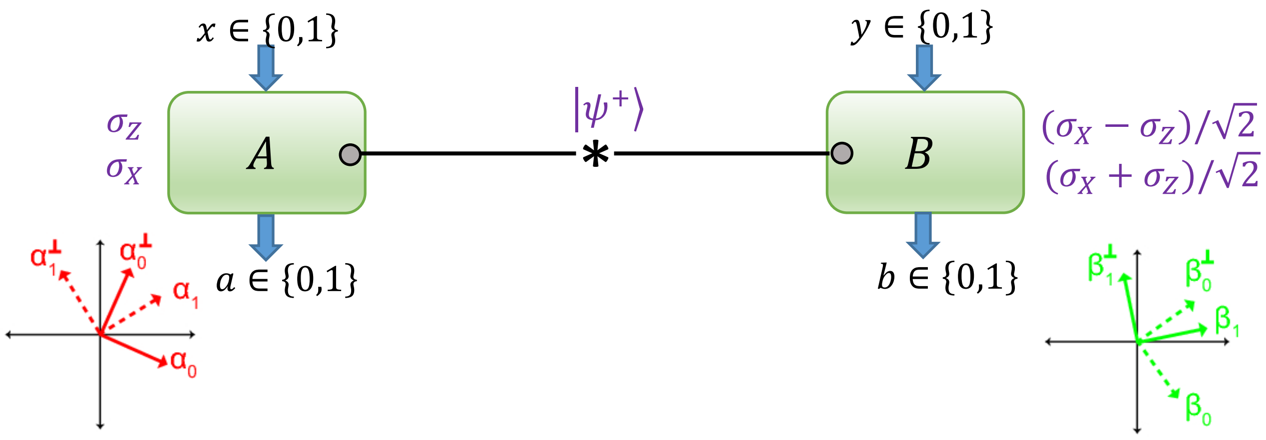
2. **For some quantum strategy:**

$$S = p(a \oplus b = x \cdot y) = \cos^2\left(\frac{\pi}{8}\right) \approx 0.85$$

CHSH inequality

Quantum model

Quantum strategy



PROOF (2.):

- $|\boldsymbol{\phi}\rangle = |\boldsymbol{\psi}^+\rangle = \frac{1}{\sqrt{2}}(|\mathbf{01}\rangle + |\mathbf{10}\rangle)$
- Alice measures $\boldsymbol{\sigma_Z}, \boldsymbol{\sigma_X}$
- Bob measures $\frac{\boldsymbol{\sigma_X} \pm \boldsymbol{\sigma_Z}}{\sqrt{2}}$

Quantum strategy

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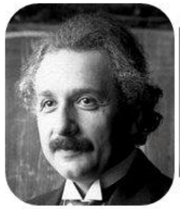

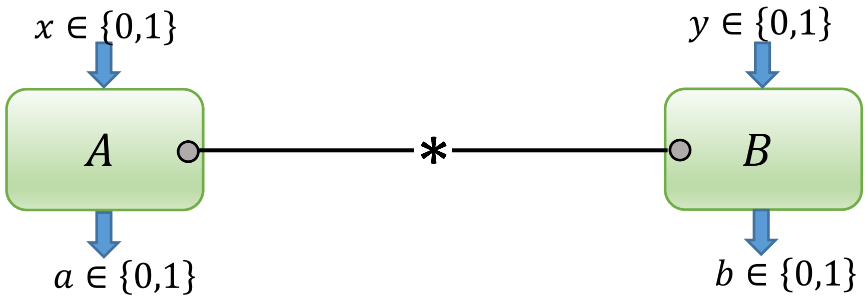

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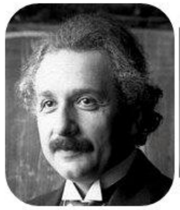
PROOF (2.) [for the detective] :

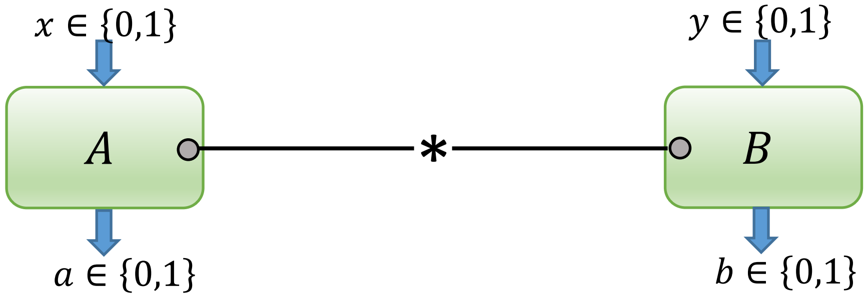
Look at the experiment, **no need to understand quantum theory!**

➢ Bell theorem **is 'not about'** quantum theory

CHSH inequality

Quantum model





Quantum strategy

- The parties share a quantum state $|\phi\rangle$
- They have measurement operators $A_{a|x}, B_{b|y}$
- The observation probabilities are:

$$p(ab|xy) = \langle\phi|A_{a|x} \otimes B_{b|y}|\phi\rangle$$

Bell Theorem [CHSH, 1964, 1969]:

1. For any LHV model λ:

$$S = p(a \oplus b = x \cdot y) \leq \frac{3}{4} = 0.75$$

2. **For some quantum strategy:**

$$S = p(a \oplus b = x \cdot y) = \cos^2\left(\frac{\pi}{8}\right) \approx 0.85$$

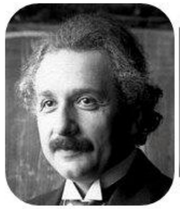
PROOF (2.) [for the detective] :

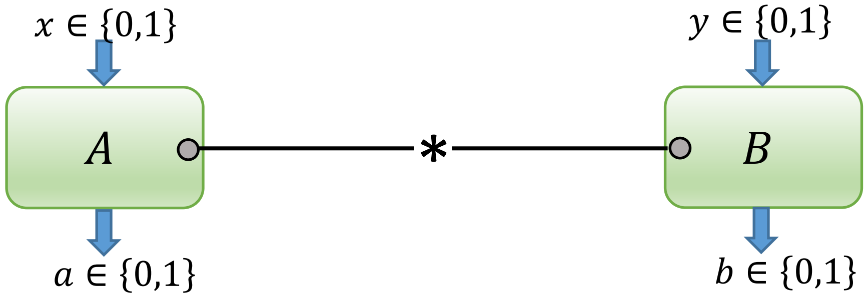
Look at the experiment, **no need to understand quantum theory!**

- Bell theorem **is 'not about'** quantum theory
- Bell theorem **is about** any theory of physics explaining **operational observations**

CHSH inequality

Quantum model





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- Bell theorem **is 'not about'** quantum theory
- Bell theorem **is about** any theory of physics explaining **operational observations**
- Such theory must be ***more crazy*** *than any crazy explanation compatible with the classical principles*

Overview

Single state quantum correlations

Characterisation
Bell Inequalities (1969)

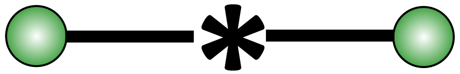
Foundations
Bell Theorem (1964)

Experiments, applications
Bell tests (1982, 2015)
Certification (2003-2010)

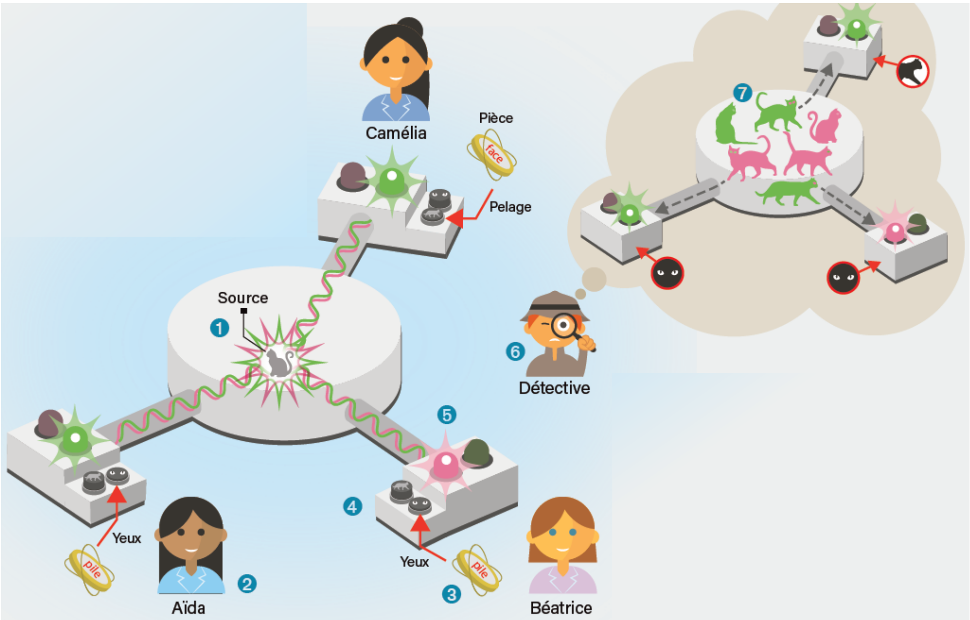
Characterisation

Foundations

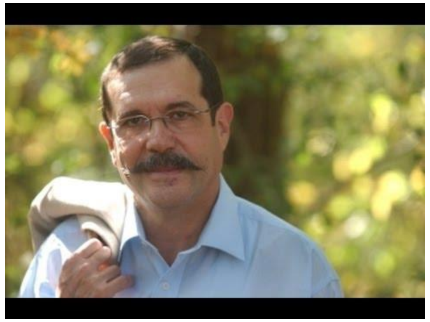
Experiments, applications



Consequences for Physics foundations, applications



M-O. Renou, N. Brunner, N. Gisin, La non-localité quantique à l'ère des réseaux
Pour la Science Octobre 2021



Aspect experiment 1981

Any theory of physics explaining operational observations:

- Is Nonlocal
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- Does not allow cloning of information
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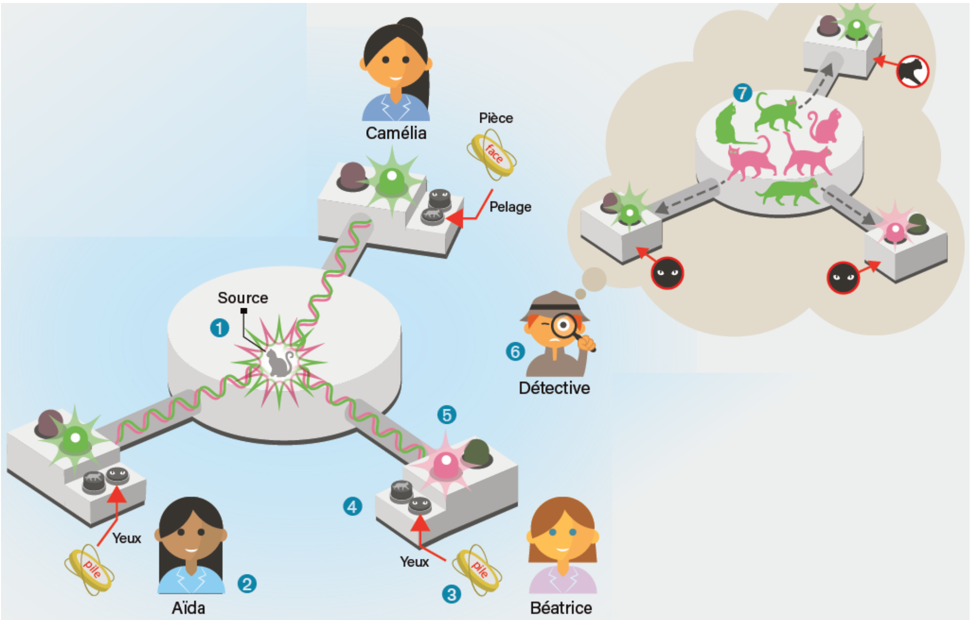

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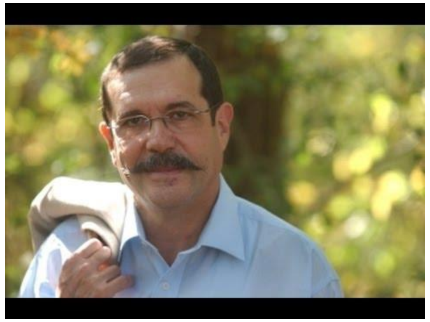

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Commercial Quantum Random Number Generator

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Applications :

Can be certified *Device Independently*, from the observed correlations only, **<u>even if an adversary controls the devices</u>**

- Nonlocality
  - ➢ DI certification of quantum devices (2003)
- No cloning
  - ➢ DI quantum key distribution (2007)
- Non determinist
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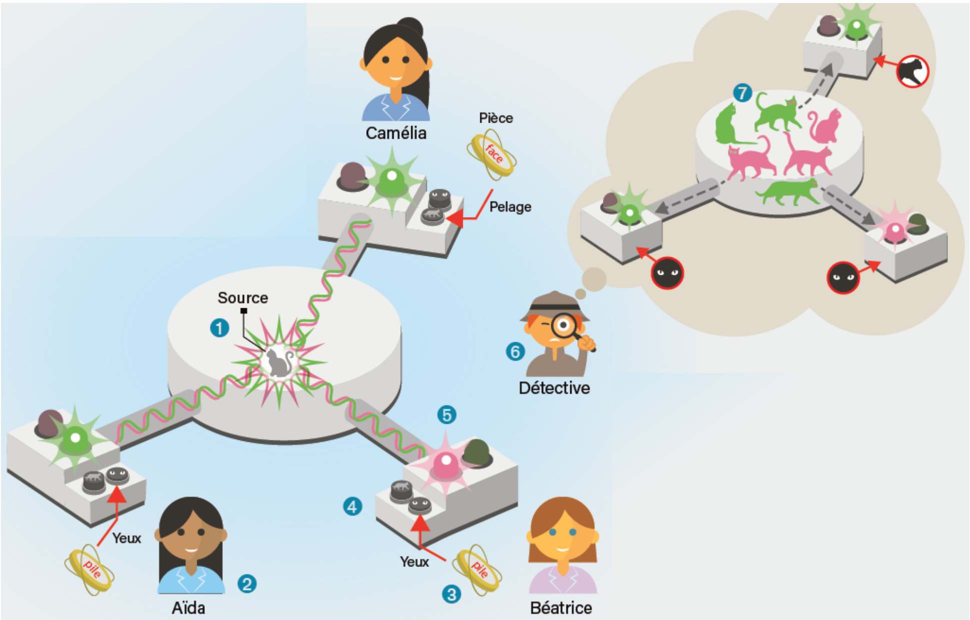
Consequences for Physics foundations, applications



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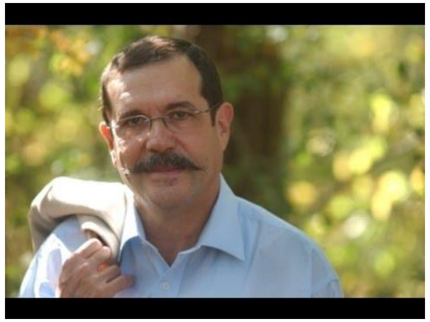

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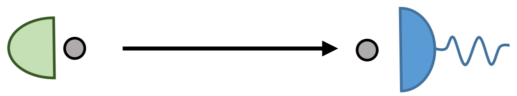
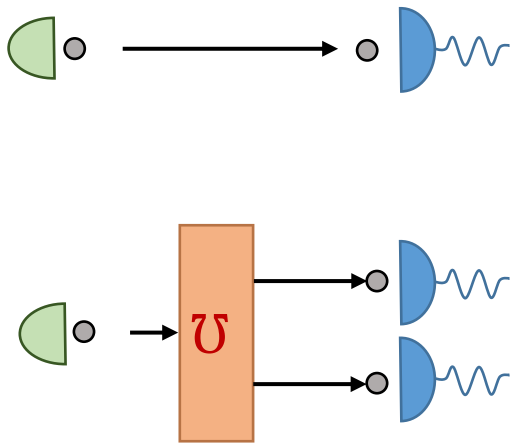
No-cloning from Bell theorem



What is a cloner?

- Causal process with an information carrier traveling

No-cloning from Bell theorem



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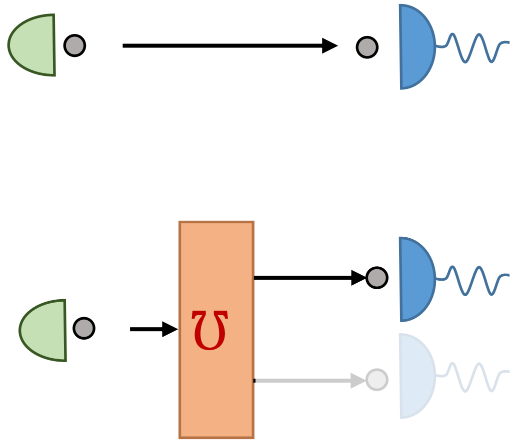

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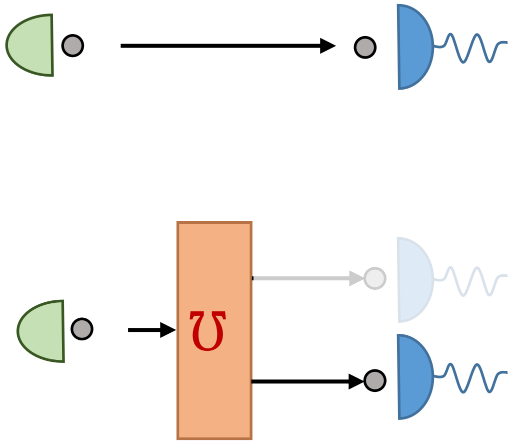

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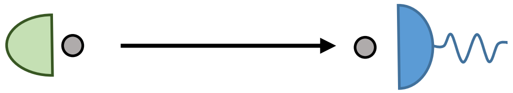

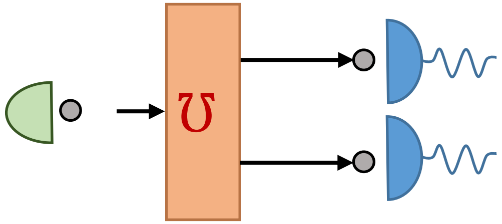

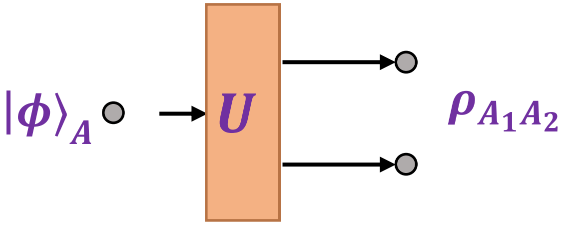

s.t. $\rho_{A_1} \coloneqq \mathrm{Tr}_{A_2}\left(\rho_{A_1A_2}\right) = |\phi\rangle_{A_1}$

$\rho_{A_2} \coloneqq \mathrm{Tr}_{A_1}\left(\rho_{A_1A_2}\right) = |\phi\rangle_{A_2}$

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According to Quantum Theory

➢ Does not exist

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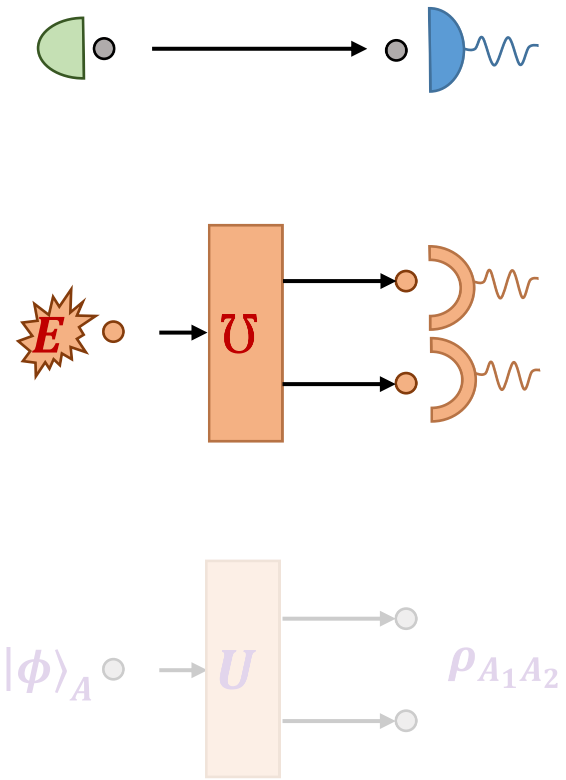

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According to Quantum Theory

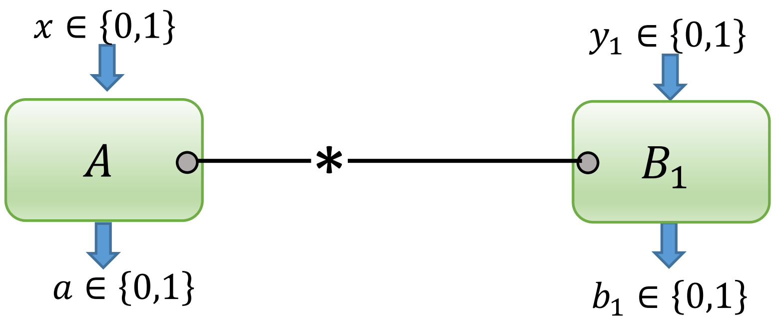
- ➢ Does not exist

According to an other 'reasonable theory'

- ➢ Cannot exist!
- ➢ Consequence of Bell theorem

No-cloning from Bell theorem

$P(a \oplus b = x \cdot y) \approx \mathbf{0.85}$



Proof by contradiction

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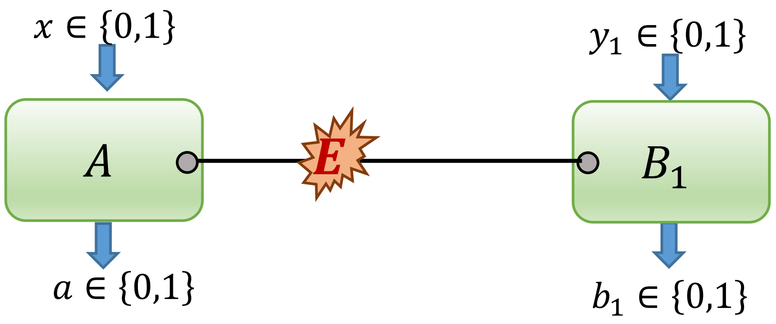

Proof by contradiction

- Start from the CHSH game
- Assume **some 'reasonable' theory of physics** explains it and **allows for cloning**

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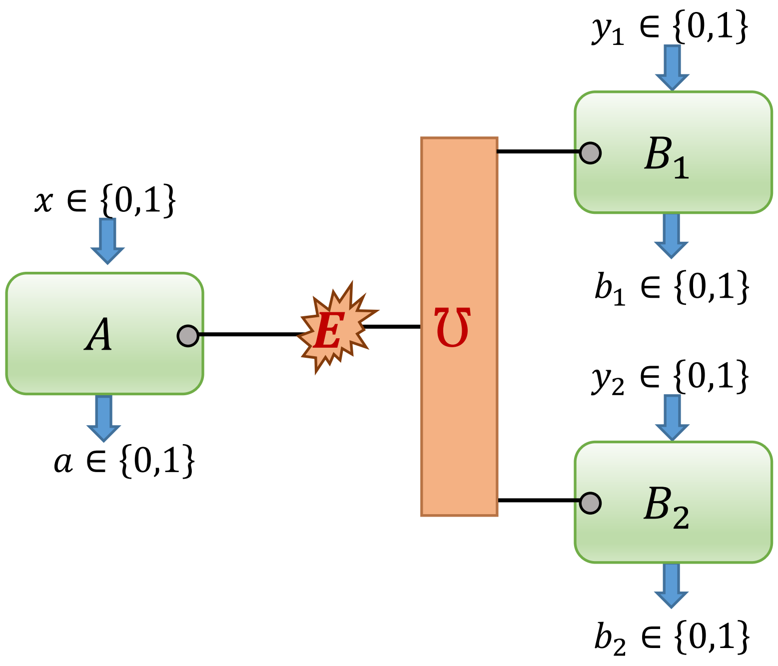

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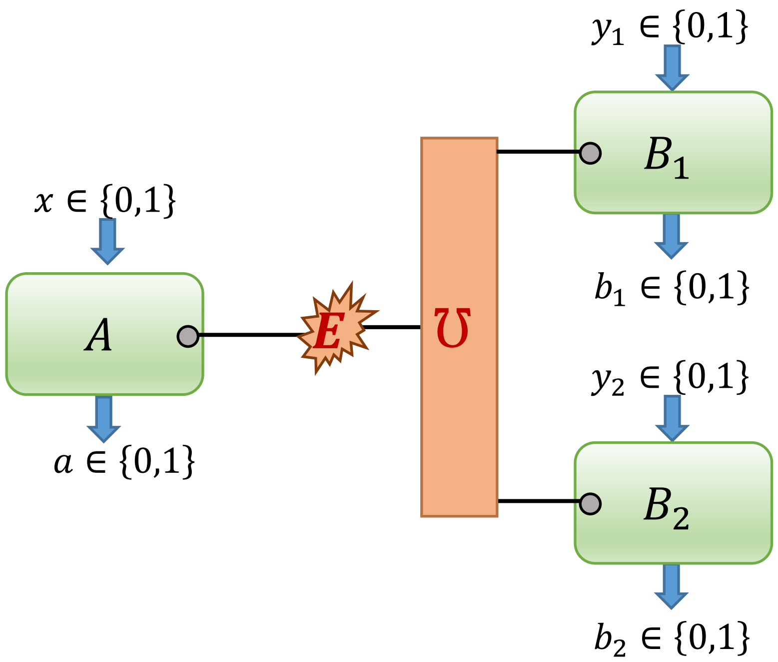
No-cloning from Bell theorem

$P(a \oplus b = x \cdot y) = \mathbf{1}$



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Simplification of the proof $\mathbf{0.85 \to 1}$

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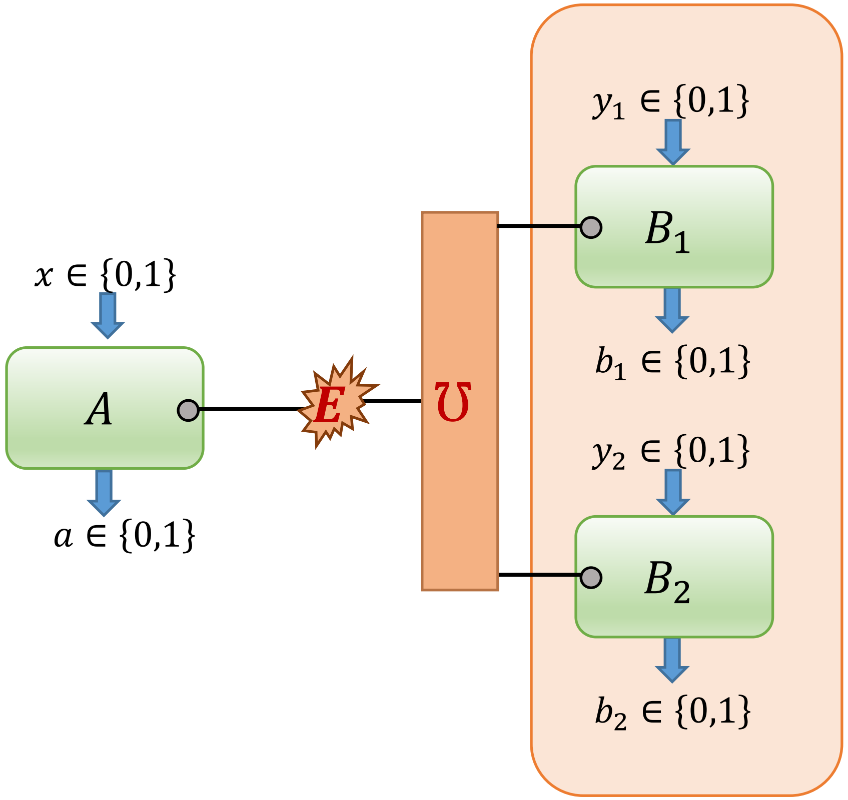

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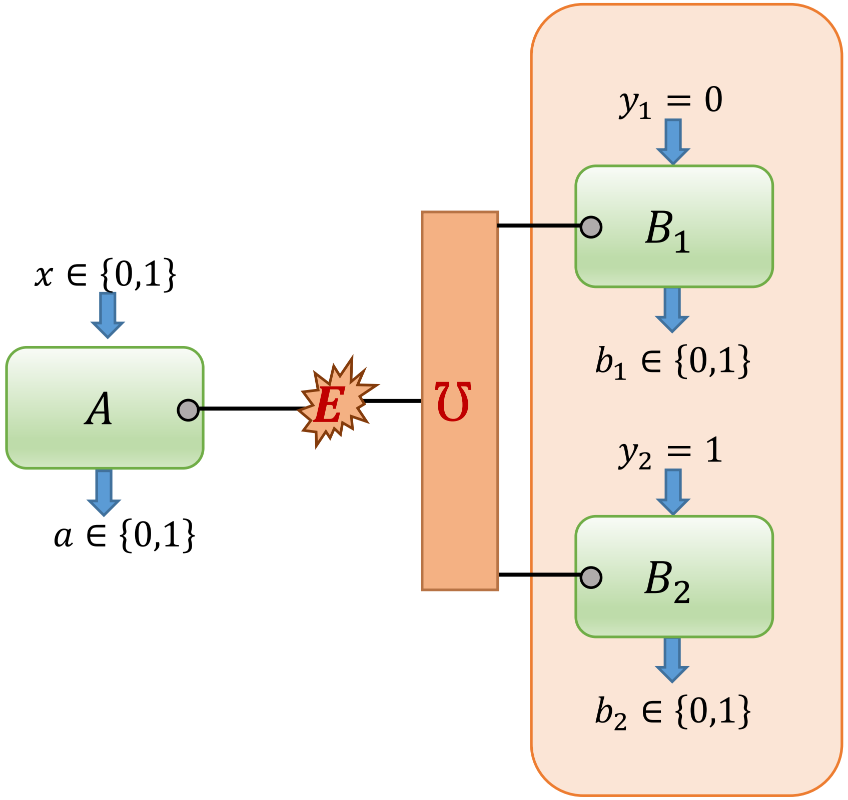

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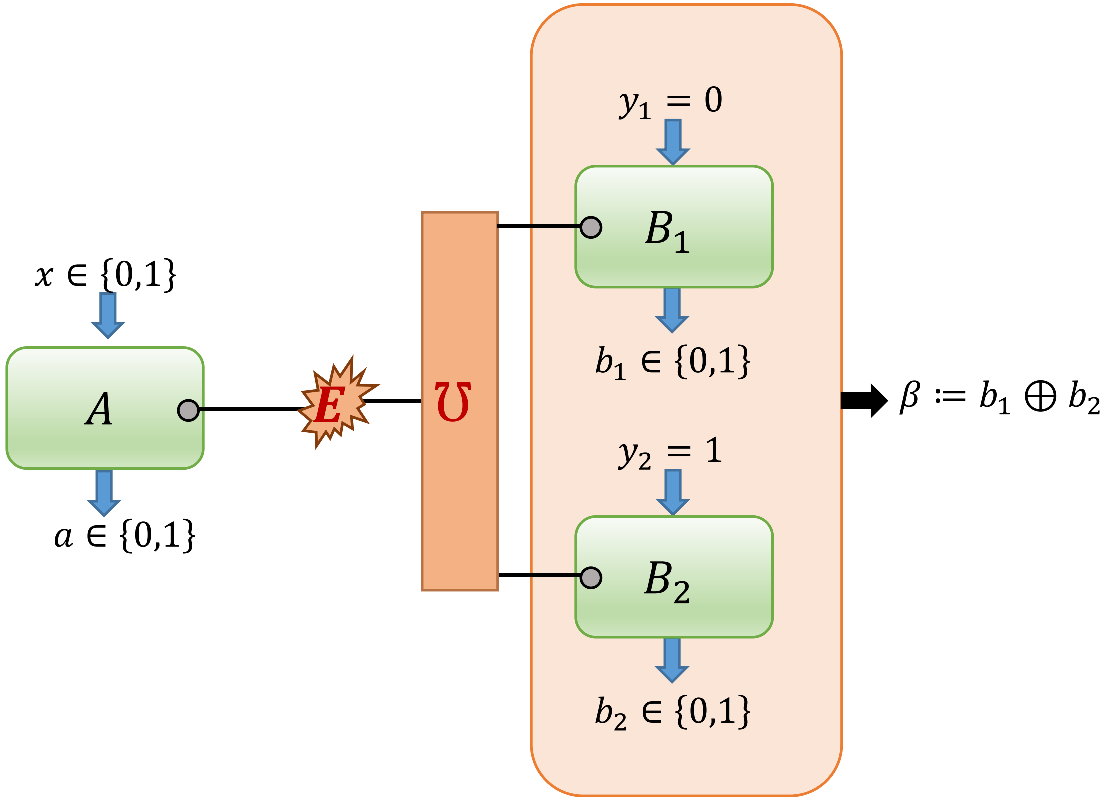

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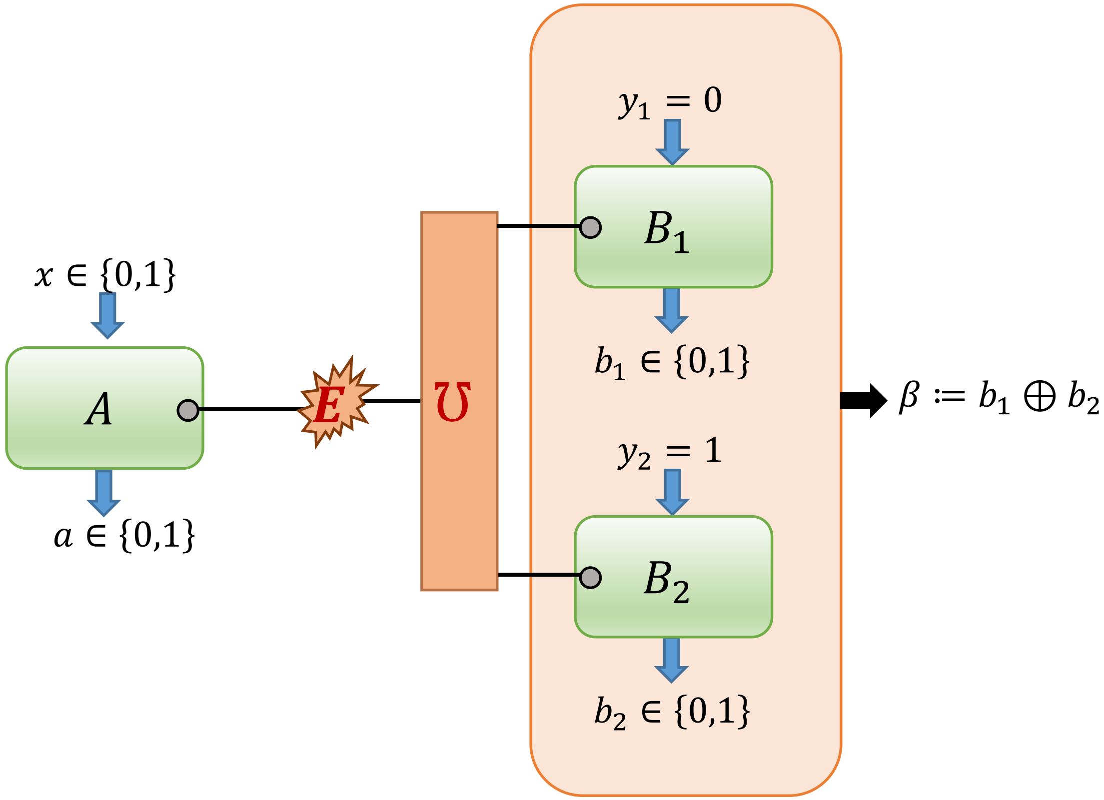

We have:

$a \oplus b_1 = x \cdot y_1 = x \cdot 0 = 0$

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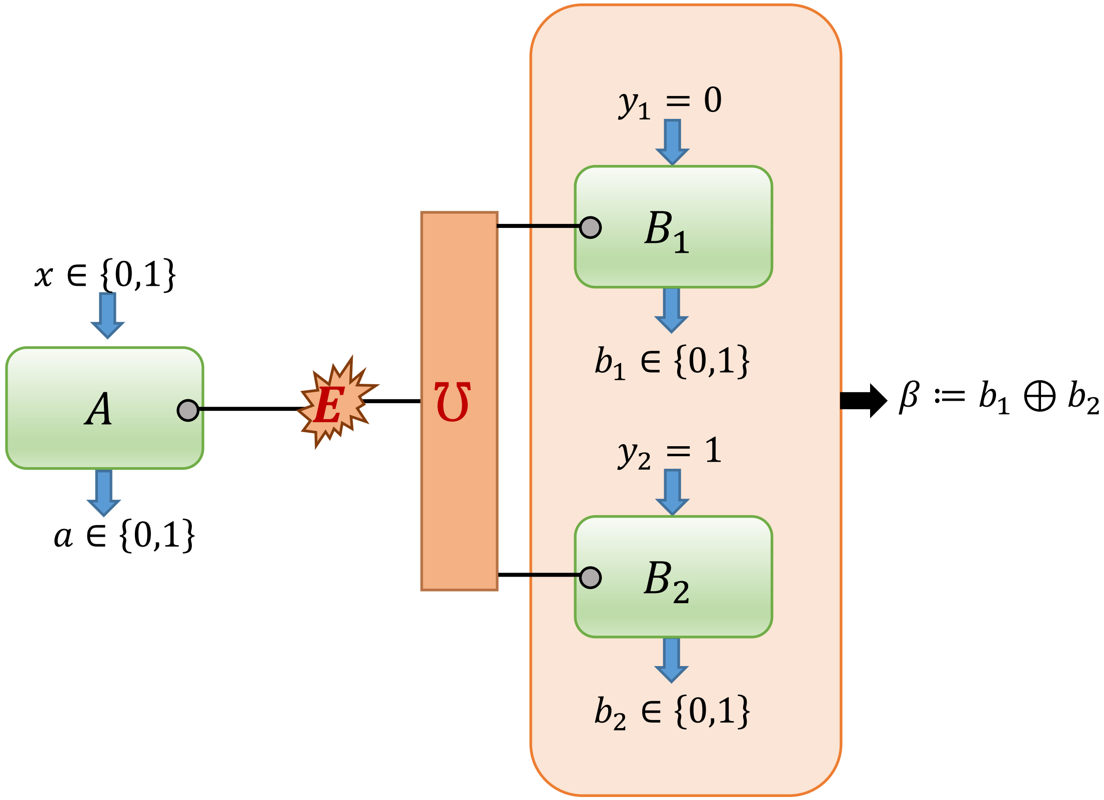

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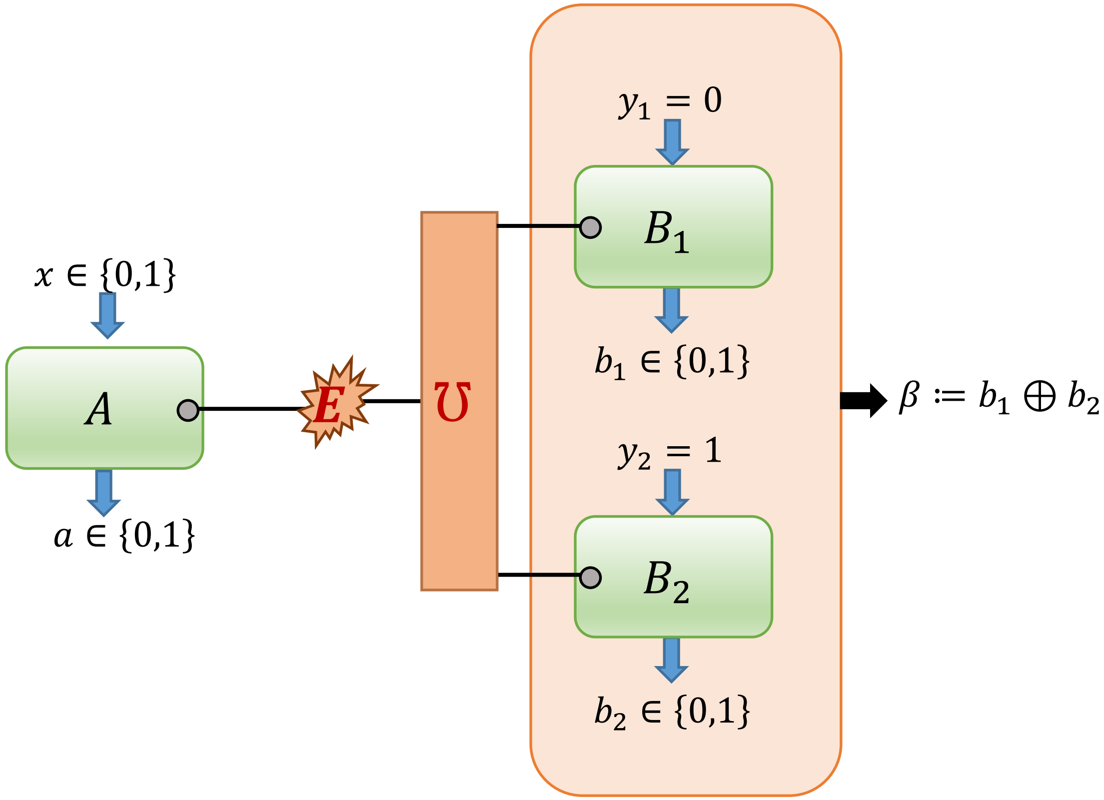

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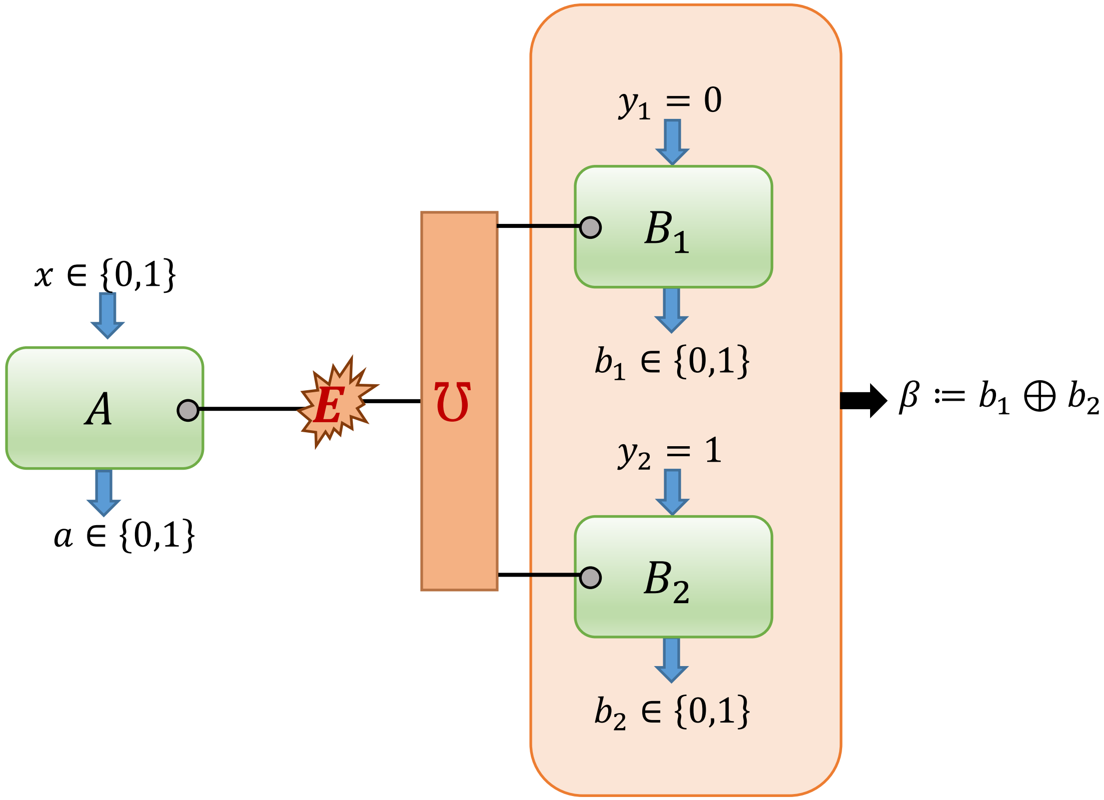

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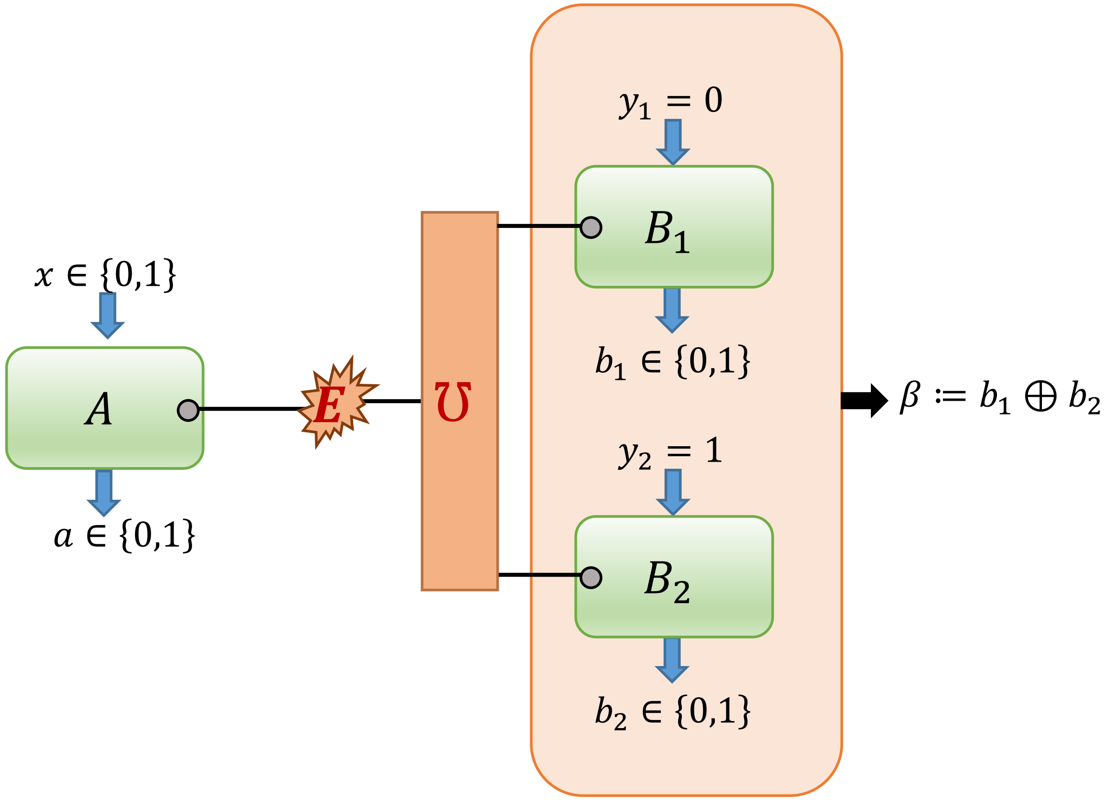

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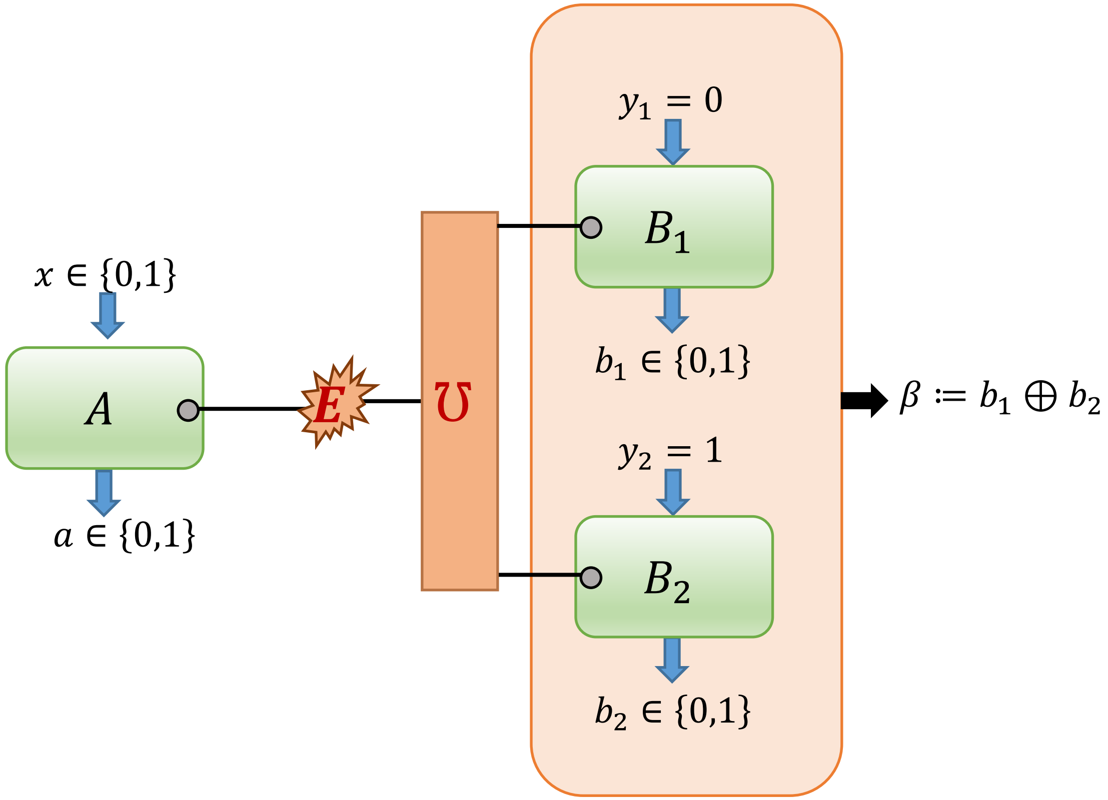

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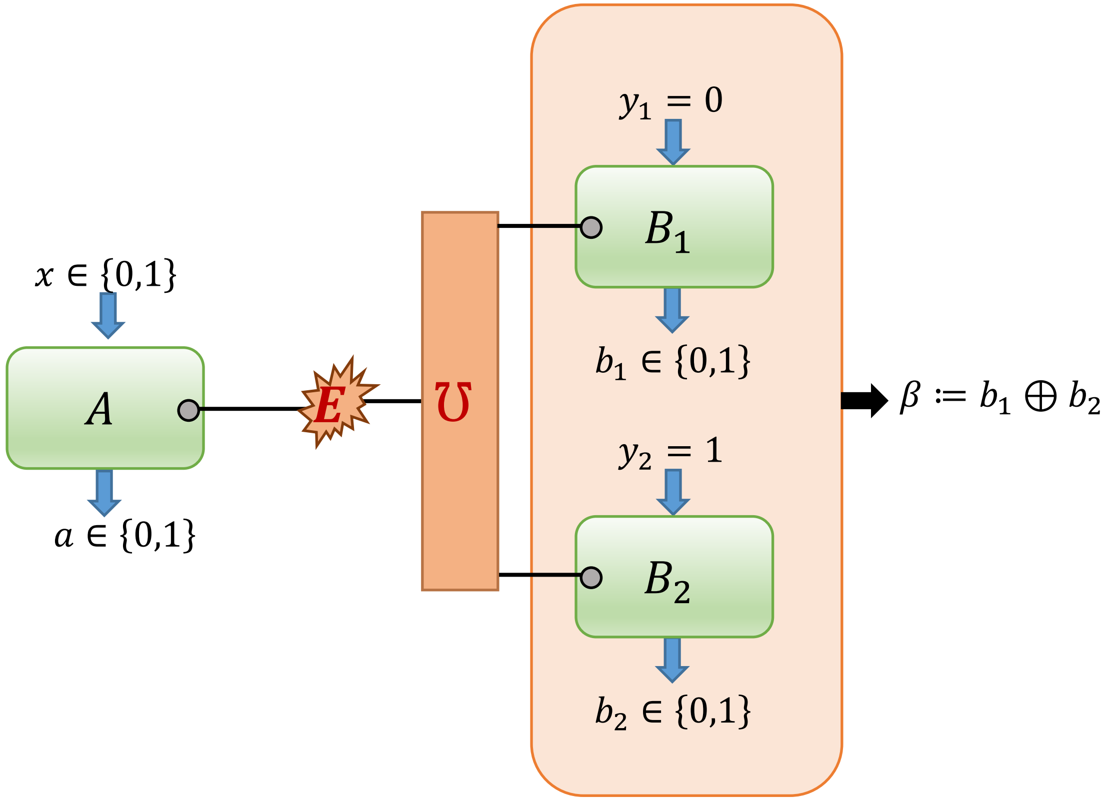
  - ➢ Then $\beta = x$!
- ➢ "Signalling"! ☠ ☠ ☠ Not **'reasonable'** !

No-cloning from Bell theorem

$P(a \oplus b = x \cdot y) = \mathbf{1}$



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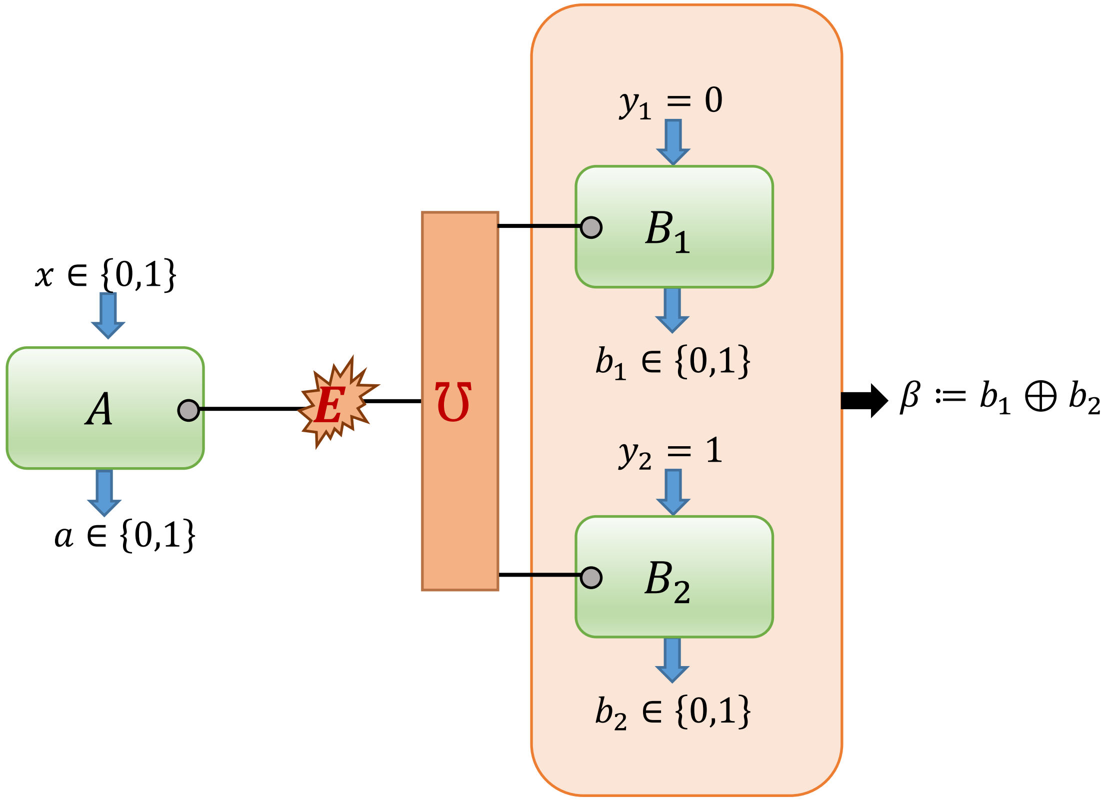
  - ➢ Then $\beta = x$!
- ➢ "Signalling"!  Not **'reasonable'** !

Without simplification? $\mathbf{0.85}$

- ➢ With $\mathbf{1}$: 'maximally signalling'

No-cloning from Bell theorem

$P(a \oplus b = x \cdot y) = \mathbf{1}$



We have:

$a \oplus b_1 = x \cdot y_1 = x \cdot 0 = 0$: $b_1 = a$

$a \oplus b_2 = x \cdot y_2 = x \cdot 1 = x$: $b_1 = a \oplus x$

Hence $\beta = b_1 \oplus b_2 = a \oplus a \oplus x = x$

Proof by contradiction

- Start from the CHSH game
- Assume **some 'reasonable' theory of physics** explains it and **allows for cloning**
- Insert the cloner:
  - obtain $P(a, b_1, b_2 | x, y_1, y_2)$
  - such that $P(a \oplus b_1 = x \cdot y_1) = \mathbf{1}$, $P(a \oplus b_2 = x \cdot y_2) = \mathbf{1}$

Simplification of the proof $\mathbf{0.85} \rightarrow \mathbf{1}$

- Place B_1, B_2 in a same location:
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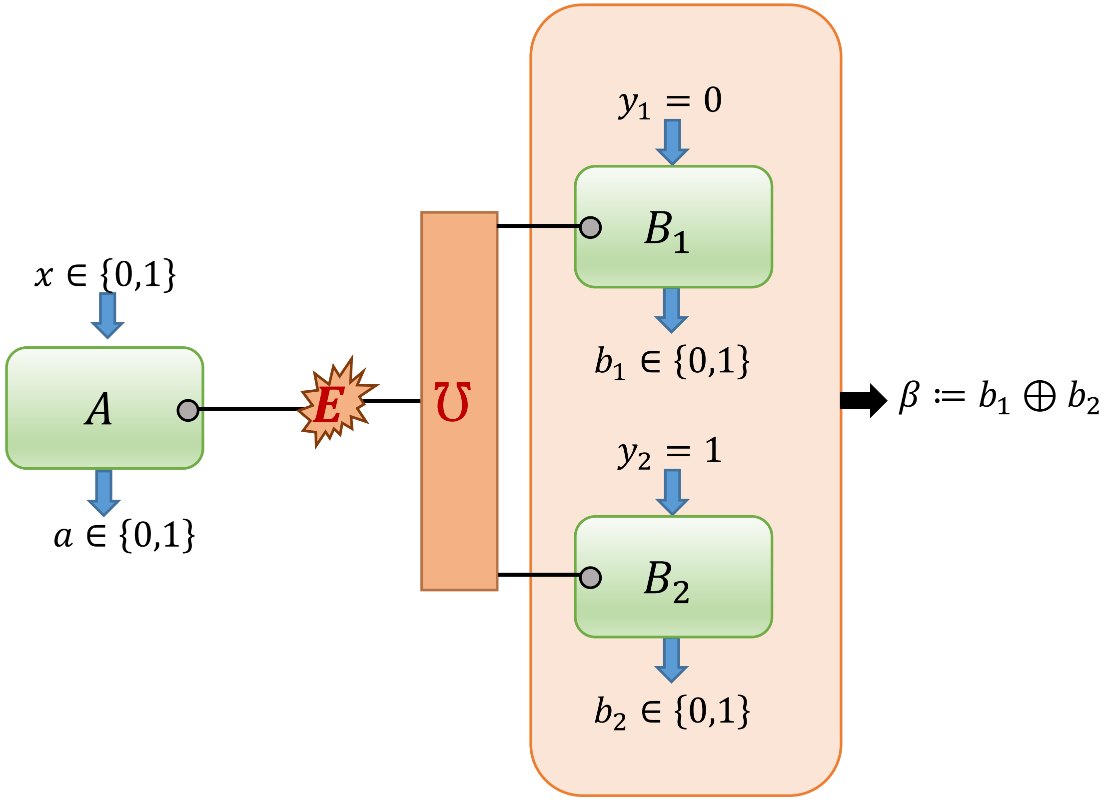

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- ➢ With $\mathbf{1}$: 'maximally signalling'
- ➢ 'ϵ signalling' is already not **reasonable as can be amplified**
- ➢ As soon as $\mathbf{CHSH > 2}$, the proof holds: **no 'reasonable' theory of physics with cloning can explain any CHSH violation**

Device independence

General idea

Proofs that “*any reasonable future theory of physics*” satisfies:

Non locality / Randomness / No cloning / …

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X Trusted sources / measurements

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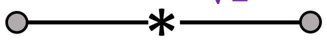
✓ **No Signalling**

✓ **No super-determinism**

Device independence

Foundational physics

$$|\psi^+\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$



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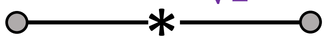

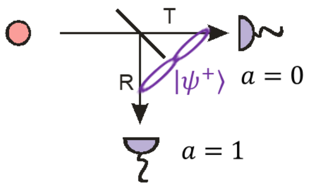

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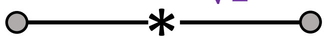

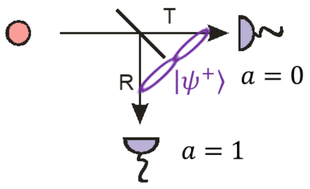

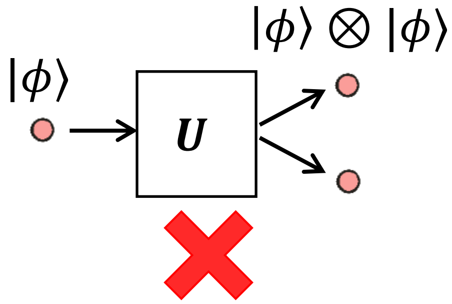

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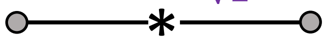

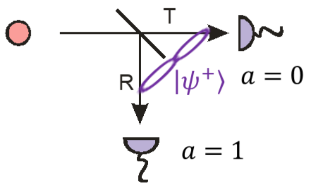

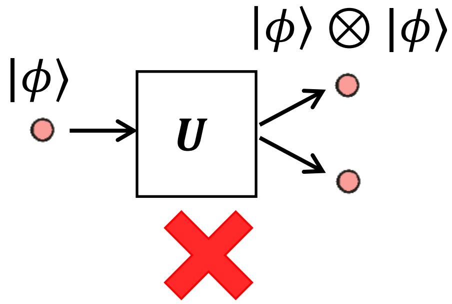

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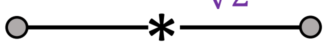

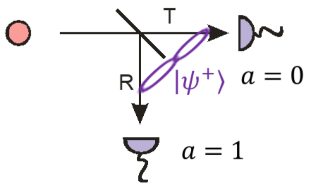

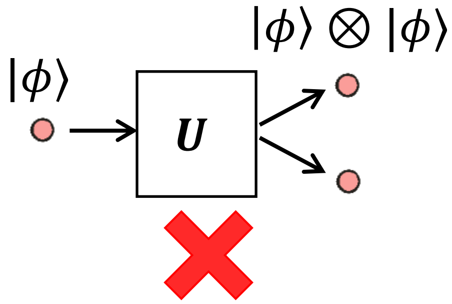

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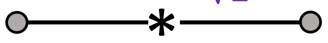

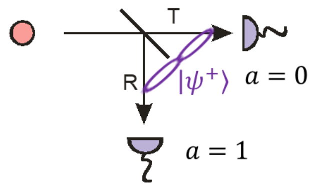

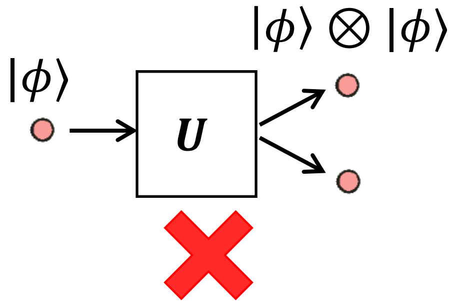

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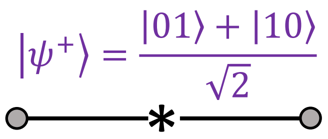

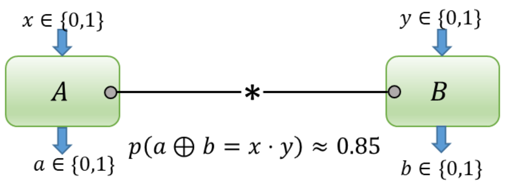

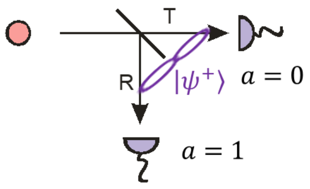

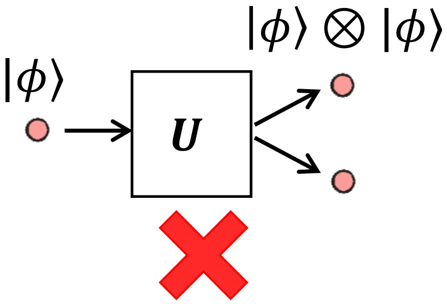

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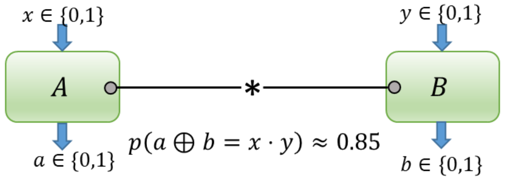

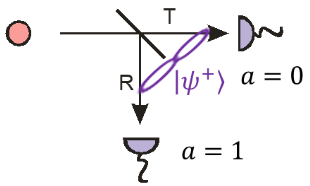

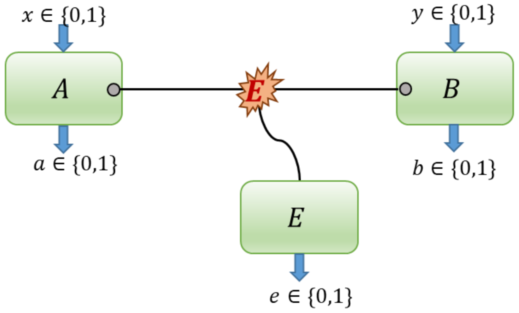

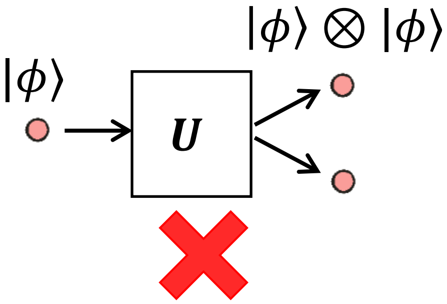

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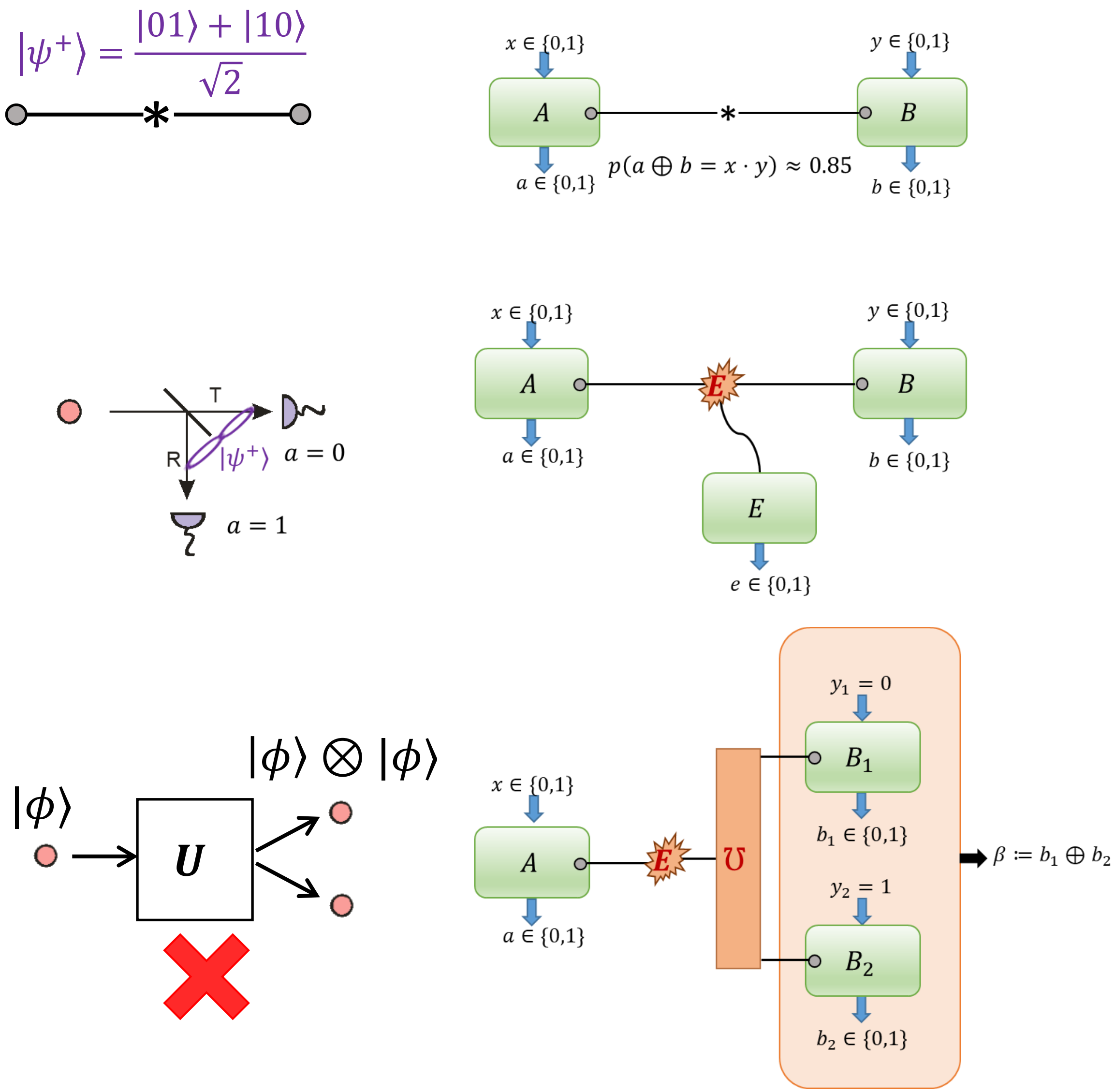

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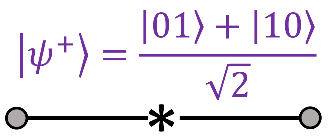

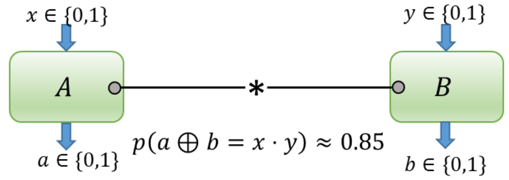

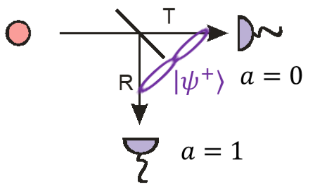

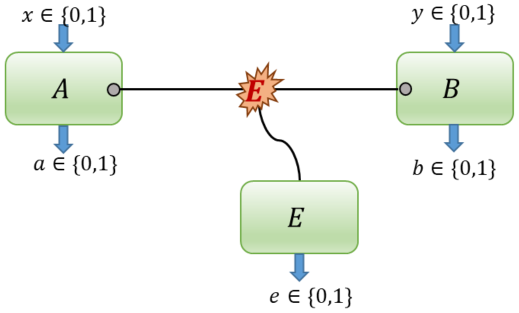

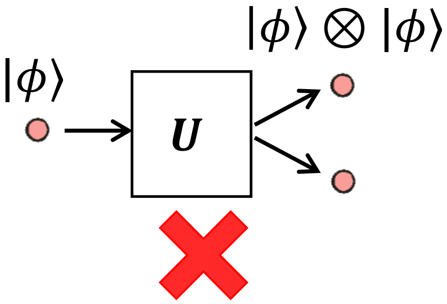

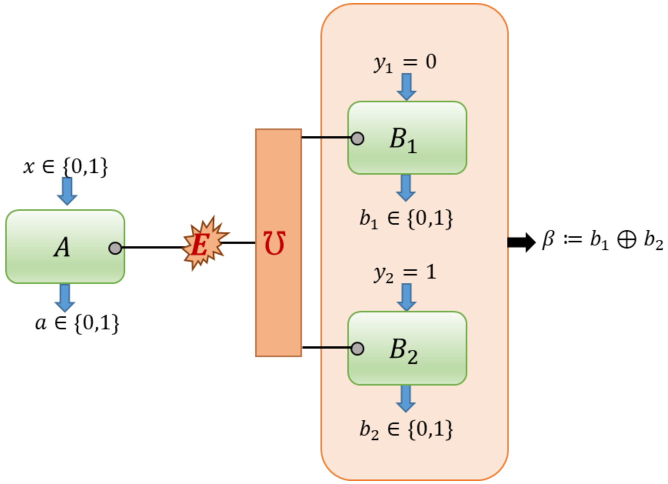

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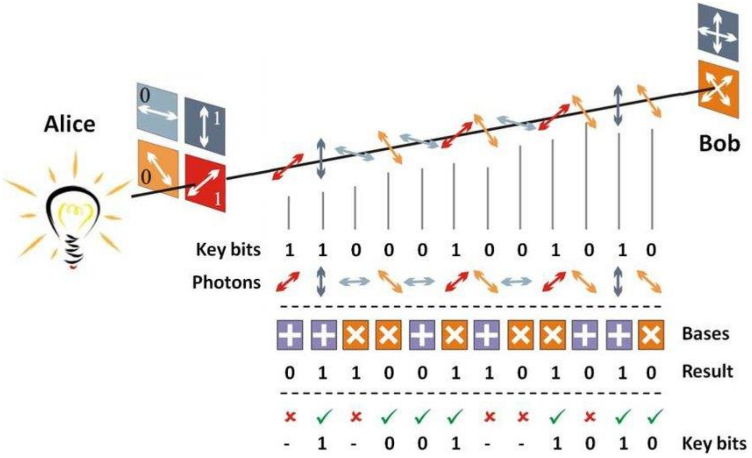
➢ **‘Device/theory Independent’ certification of these properties**

Device independence

Applications of quantum physics: QKD



BB84 protocol

- Quantum Key Distribution (QKD)
  - BB84 protocol

Device independence

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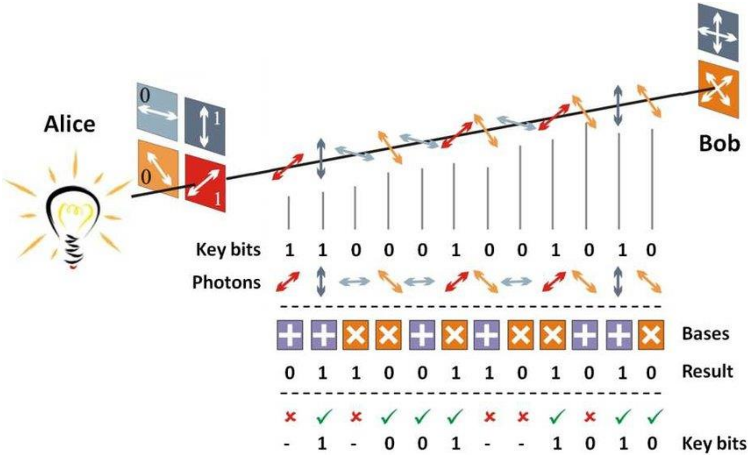

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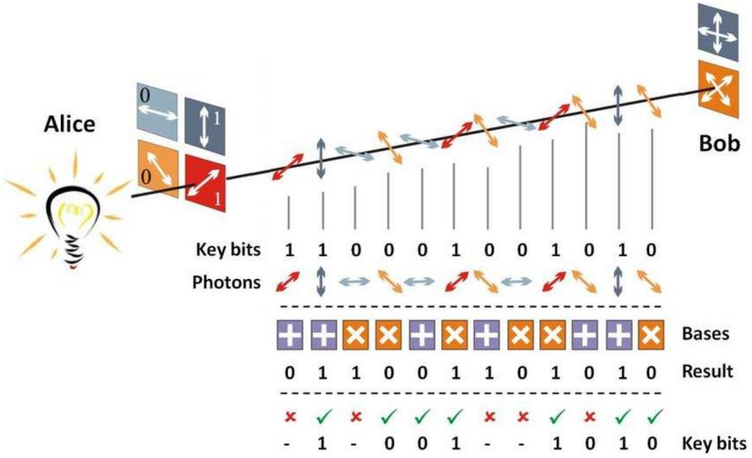

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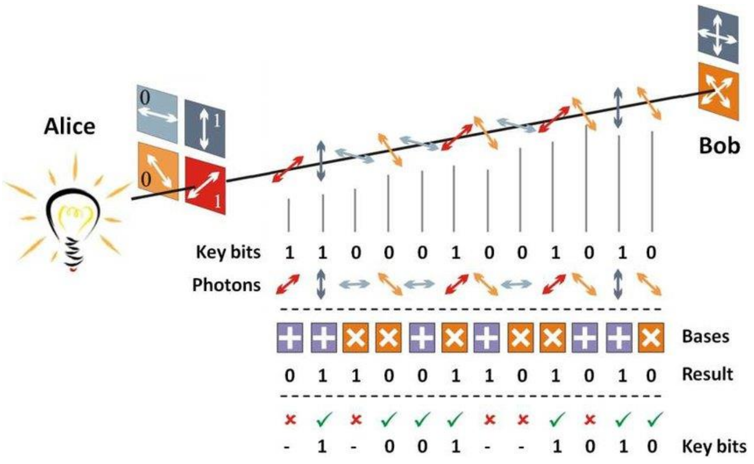

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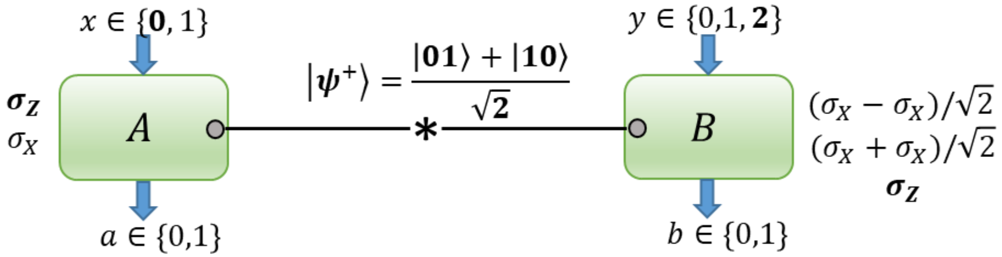

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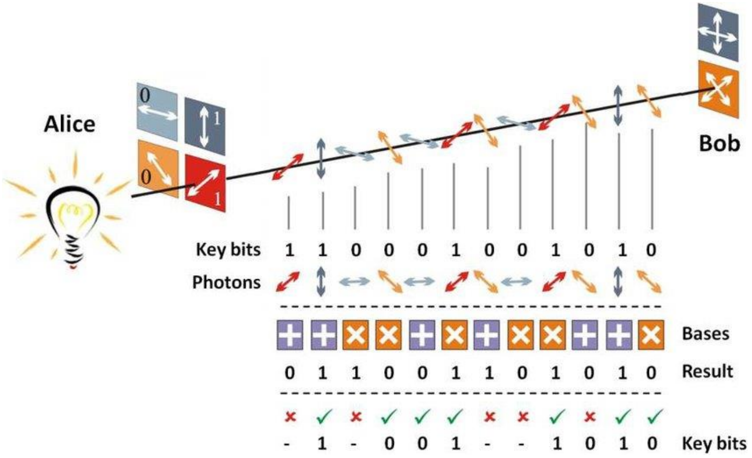

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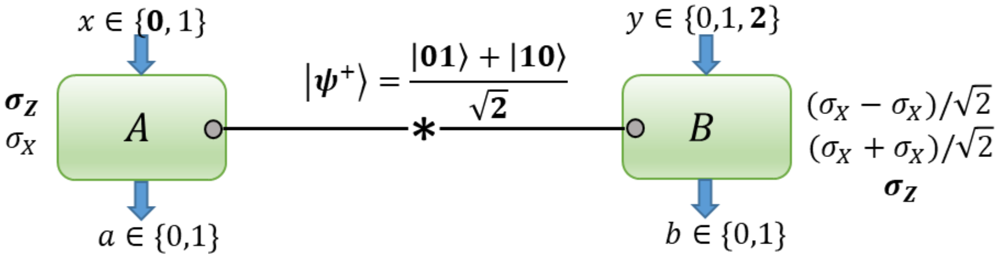

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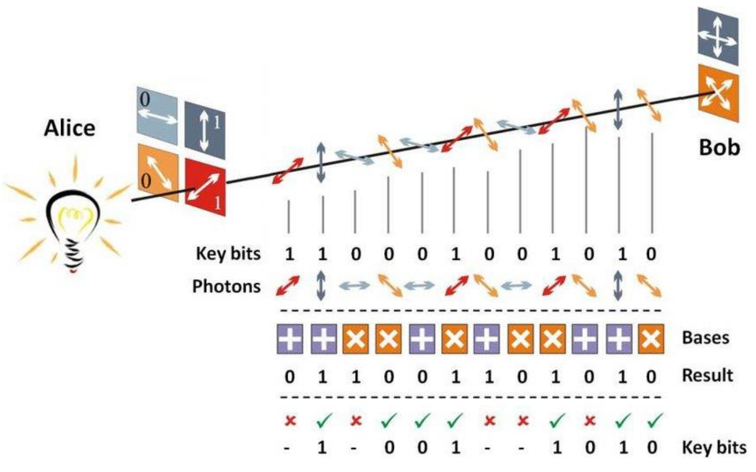

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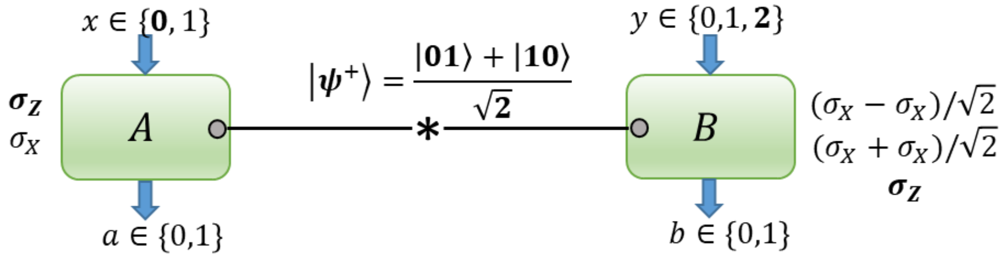

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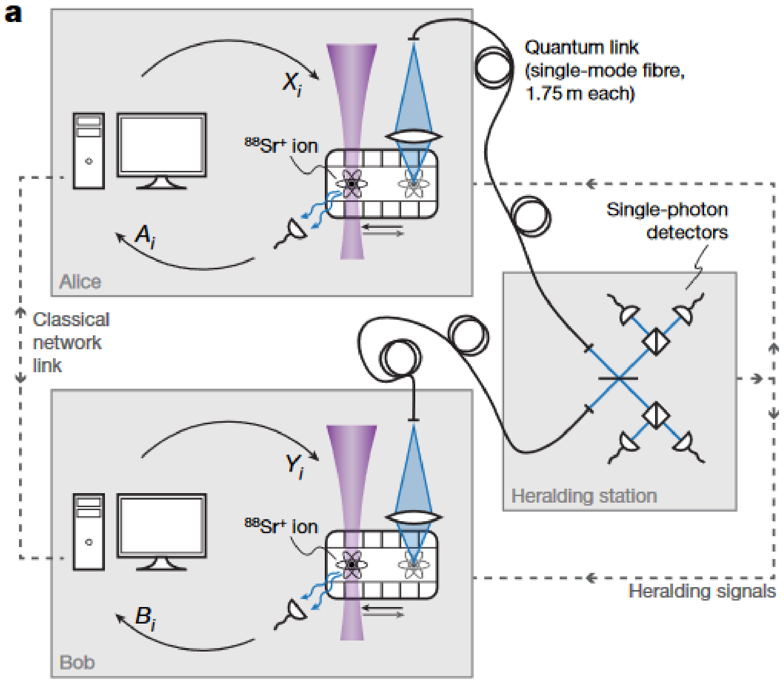
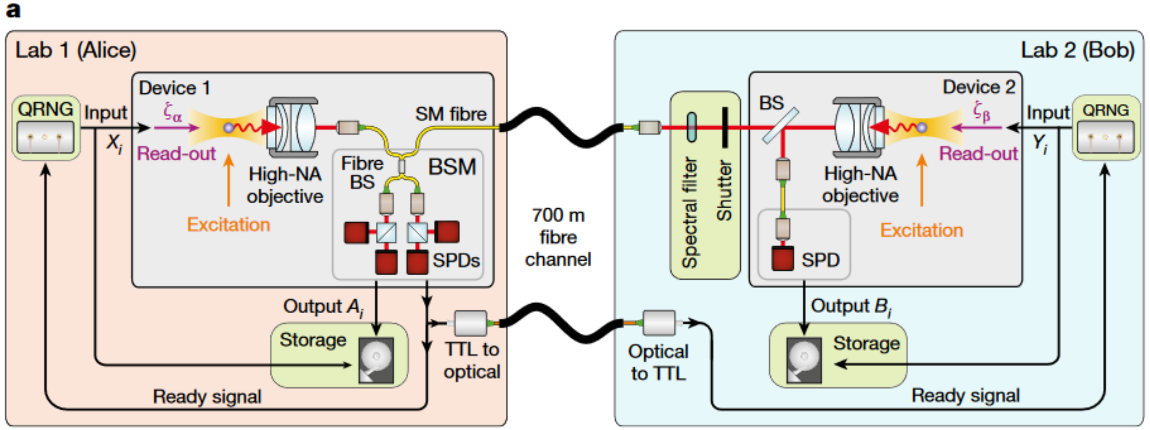
➢ **‘Device Independent’ certification of quantum key distribution**

Device independence

Applications of quantum physics: QKD





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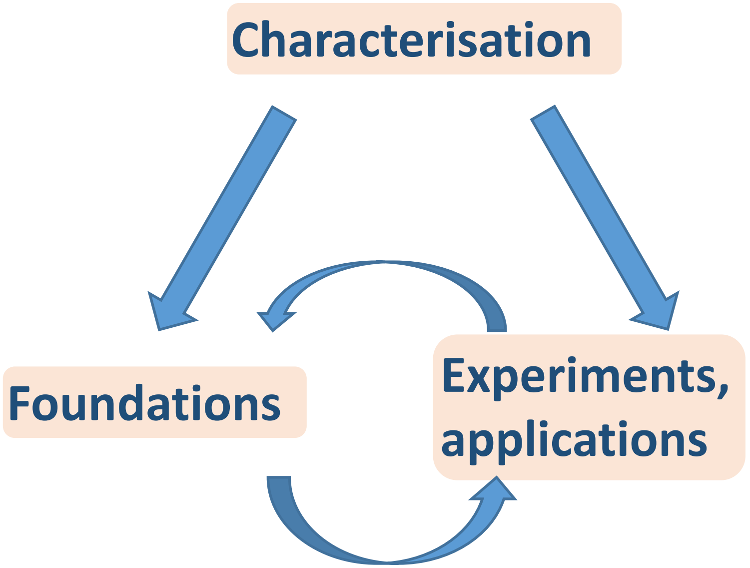
- 2022: First two experimental realisation

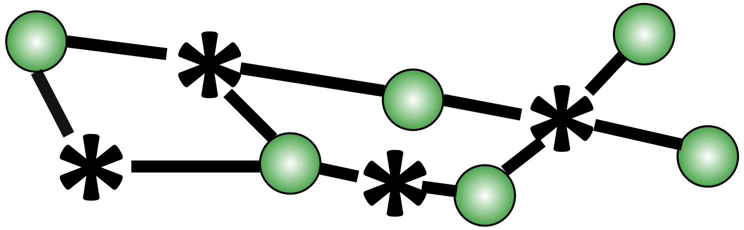
  1st expt: 95628 key bits in 8 hours, 2m distance

  2nd expt: Only valid in ‘infinit running time’, 700m

Overview

Causal network quantum correlations





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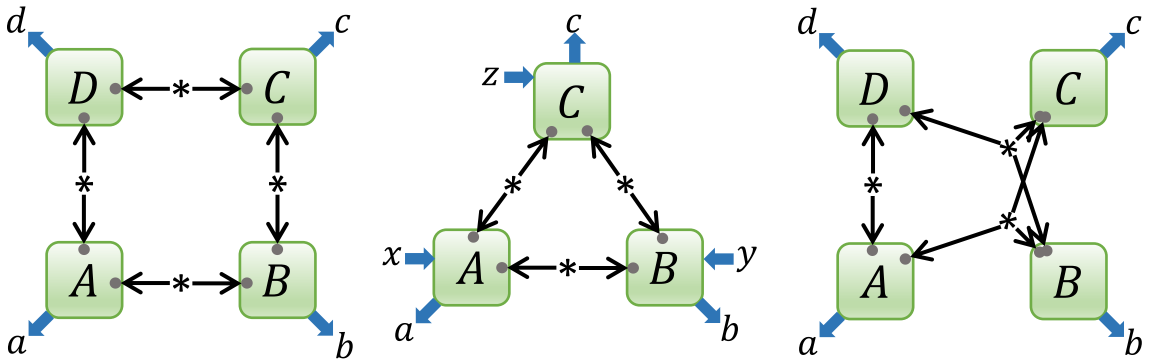
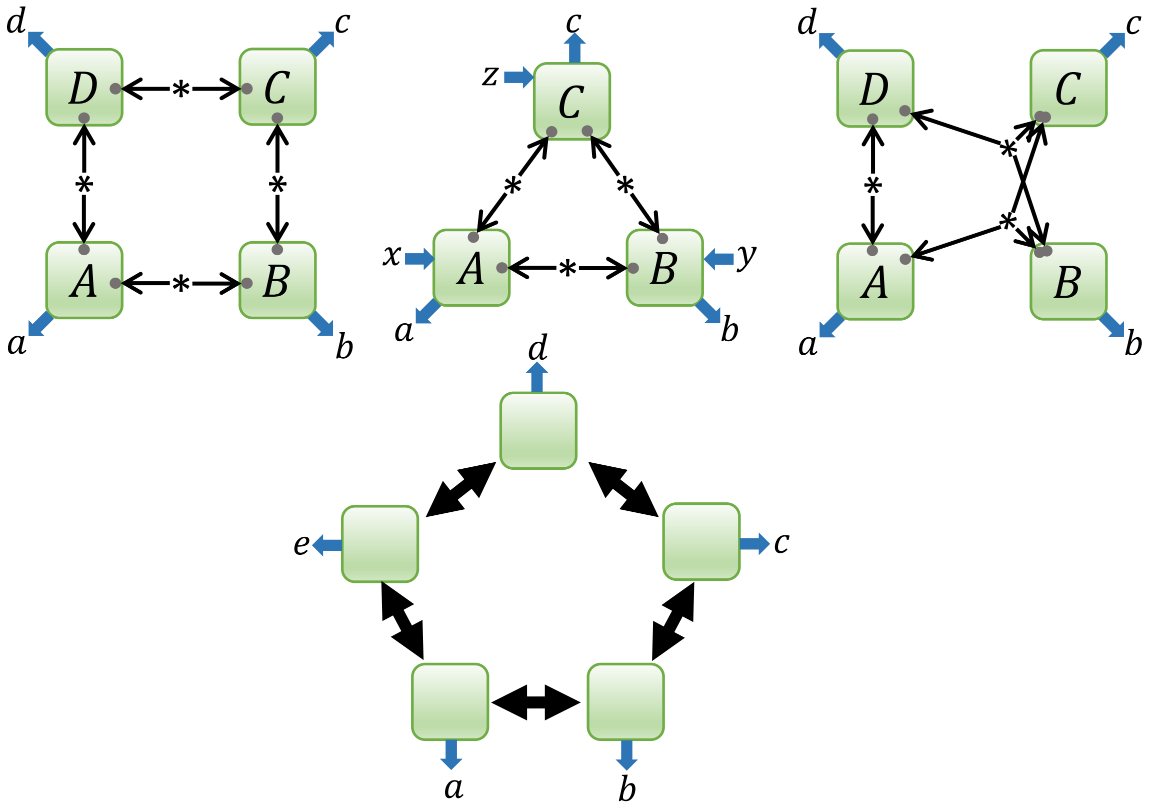


(Quantum) causal network:

Several hidden sources distributed and measured in a quantum network

Can they win a concrete game, e.g.
$\boldsymbol{p}(\boldsymbol{a} \oplus \boldsymbol{b} \oplus \boldsymbol{c} = \boldsymbol{x} \cdot \boldsymbol{y} \cdot \boldsymbol{z}) > \mathbf{0.7}$*, with classical/quantum theory?*

Causal network quantum correlations



(Quantum) causal network:

Several hidden sources distributed and measured in a quantum network

Can they win a concrete game, e.g.
$\boldsymbol{p(a \oplus b \oplus c = x \cdot y \cdot z) > 0.7}$*, with classical/quantum theory?*

(Quantum) distributed computing structure:

Several processors exchange information (e.g., synchronisation, limited number of communications steps).

Can they find a proper coloring, that is $a \neq b, \dots, e \neq a$*, with 1 synchronised communication step and classical/quantum theory?*

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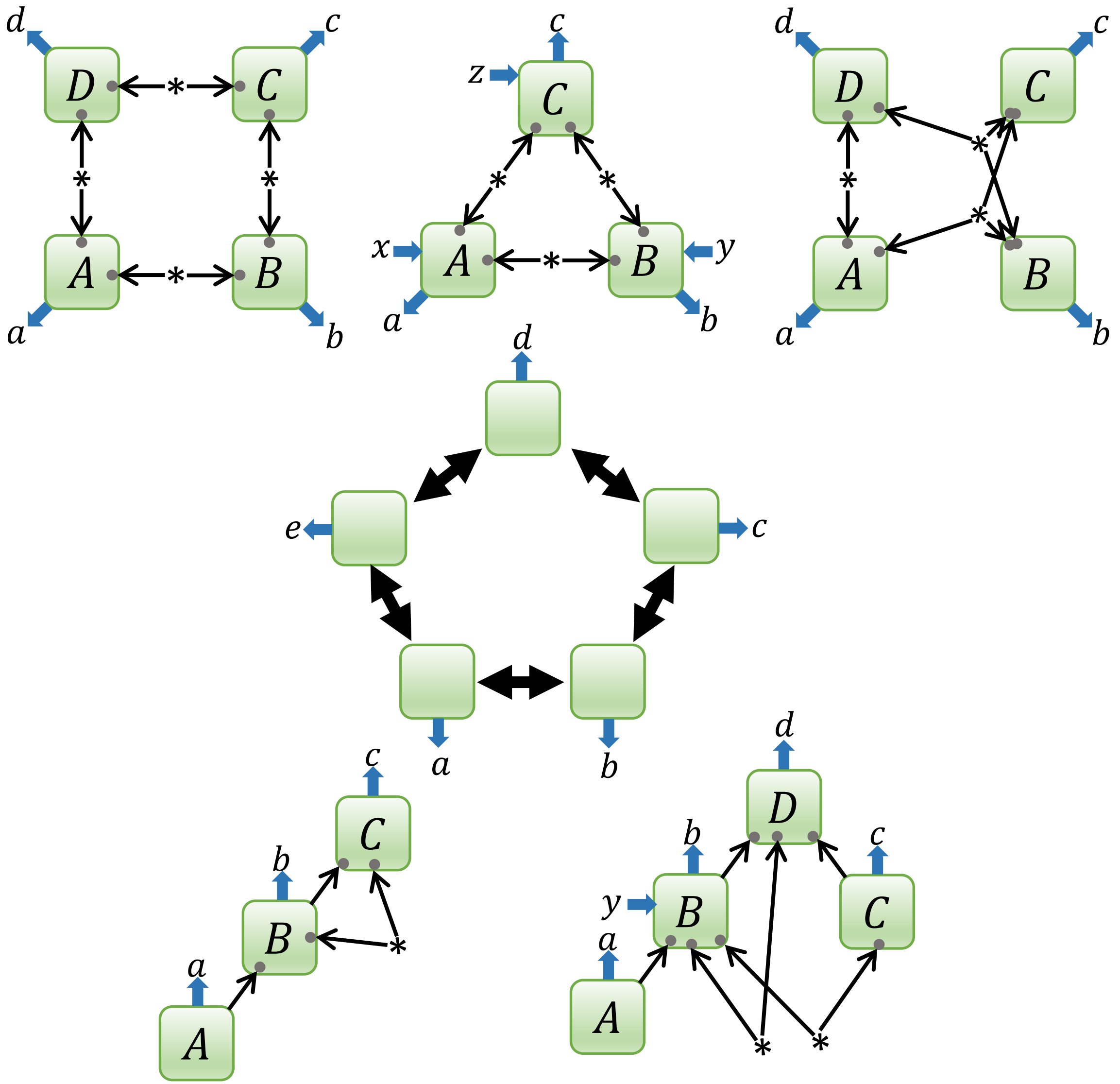

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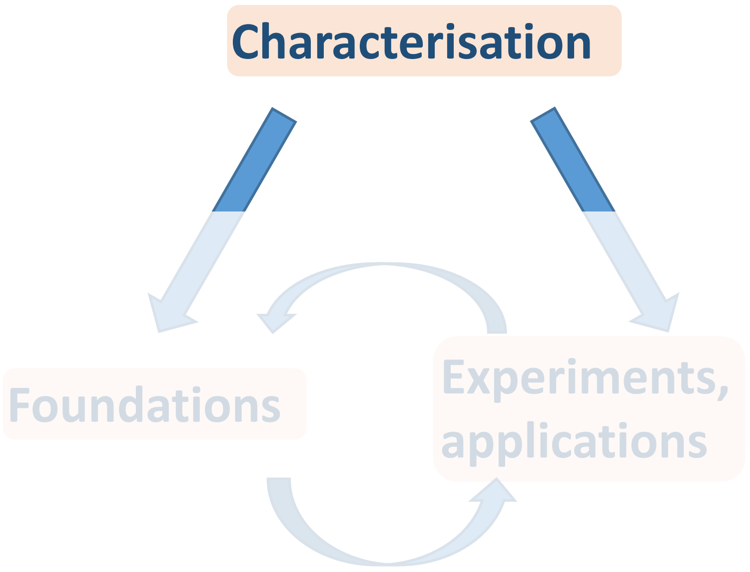
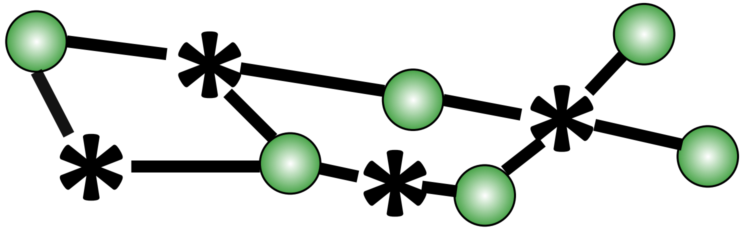
(Quantum) causal structure:

Causal structure involving hidden sources and non-hidden causes

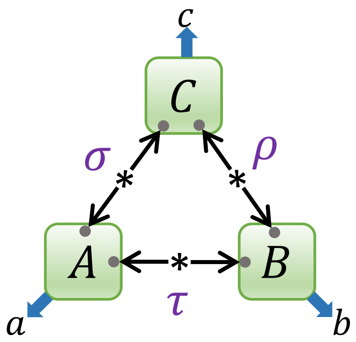
Characterisation





Characterisation

Genuine triangle nonlocality



Concrete ρ, σ, τ and measurements

➢ Give $\boldsymbol{P}$

Genuine nonlocality in the triangle network (2019)

M-O. Renou, E. Bäumer, S. Boreiri, N. Brunner, N. Gisin, S. Beigi, Phys. Rev. Lett. 123, 140401 (2019)
M-O. Renou, S. Beigi, Phys. Rev. Lett. 128, 060401 (2022)
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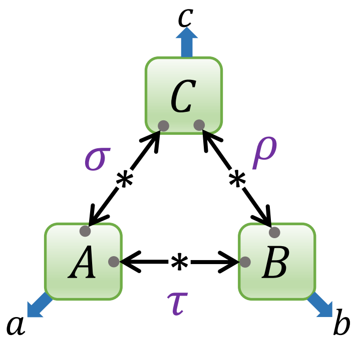

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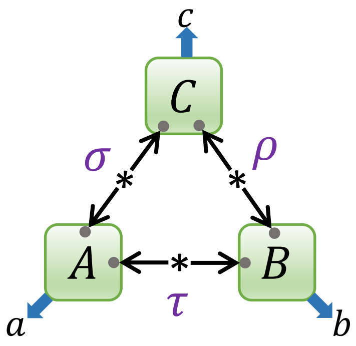

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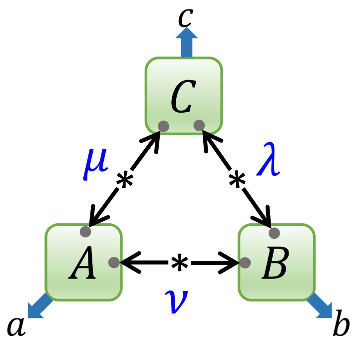

$\forall \lambda, \mu, \nu$ and processing

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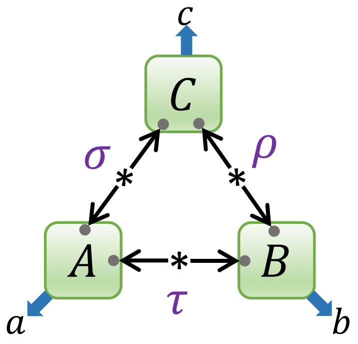

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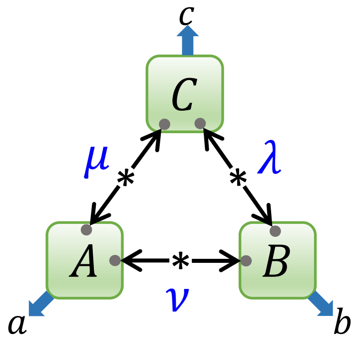

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Genuine nonlocality in the triangle network (2019)

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- Generalisation to other networks
  - ➢ Method fundamentally different from standard Bell arguments

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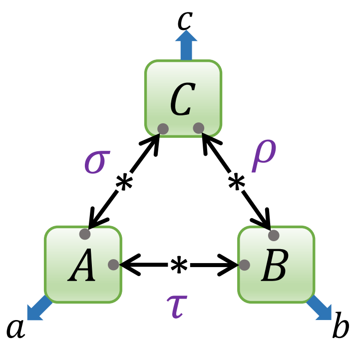

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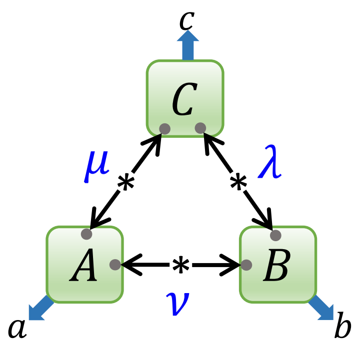

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➢ Cannot give $\boldsymbol{P}$

Genuine nonlocality in the triangle network (2019)

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  - ➢ This allows new applications: « certify randomness without inputs »

M-O. Renou, E. Bäumer, S. Boreiri, N. Brunner, N. Gisin, S. Beigi, Phys. Rev. Lett. 123, 140401 (2019)
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A. Pozas-Kerstjens, N. Gisin, **M-O. Renou**, Phys. Rev. Lett. 130, 090201 (2023)
P. Sekatski, S. Boreiri, N. Brunner, arXiv:2209.09921 (2022)

Foundations

Characterisation
Bell Inequalities (1969)

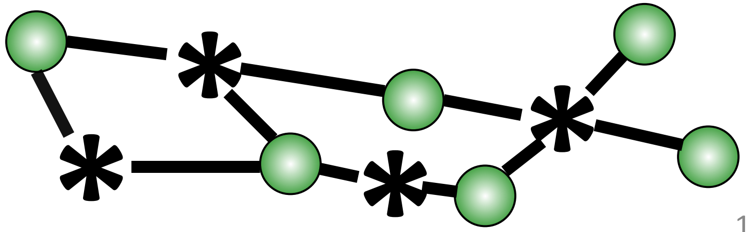
Foundations
Nonlocality (1964)

Experiments, applications
Bell tests (1982, 2015)
Certification (2003-2010)

Characterisation

Foundations

Experiments, applications



Foundations

$\mathbb{R}$-QT can be experimentally ruled out

Experimentalist

- Master standard Quantum Theory

Detective

- Believes in $\mathbb{R}$-QT

M-O. Renou, D. Trillo, M. Weilenmann, T. Le Phuc, A. Tavakoli, N. Gisin, A. Acin, M. Navascues, Nature 600, 625–629 (2021)

Foundations

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1 Particle S

$(i)_{\mathbb{C}}$ State: operator $\rho_S \succcurlyeq 0$ of $\mathbb{C}$-Hilbert Space $\mathcal{H}_S$ with $\mathrm{Tr}(\rho_S) = 1$

(ii) Measurement: operators $M = \{M_r\} \in \mathcal{H}_S$, $M_r \succcurlyeq 0$, $M_r^2 = M_r$, $\sum_r M_r = \mathrm{Id}$

(iii) Born rule: result r has probability $P(r) = \mathrm{Tr}(\rho_S \cdot M_r)$

2 Particles $\{S, T\}$

(iv) Hilbert space: $\mathcal{H}_{ST} = \mathcal{H}_S \otimes \mathcal{H}_T$.

Independent preparations of ρ_S, σ_T: State $\rho_{ST} = \rho_S \otimes \sigma_T$

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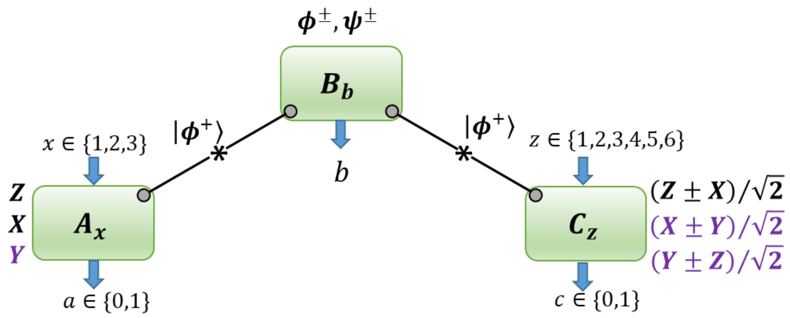
Foundations

$\mathbb{R}$-QT can be experimentally ruled out

Experimentalist

- Master standard Quantum Theory
- Construct a **concrete experiment**



- Obtains **experimental results** (statistics)

$$P(abc|xz): \begin{cases} \text{CHSH}^b(1,2;1,2) = 2\sqrt{2} \\ \text{CHSH}^b(2,3;3,4) = 2\sqrt{2} \\ \text{CHSH}^b(3,1;5,6) = 2\sqrt{2} \end{cases}$$

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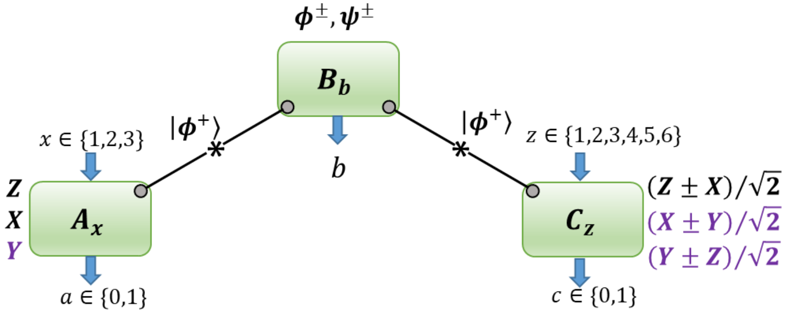

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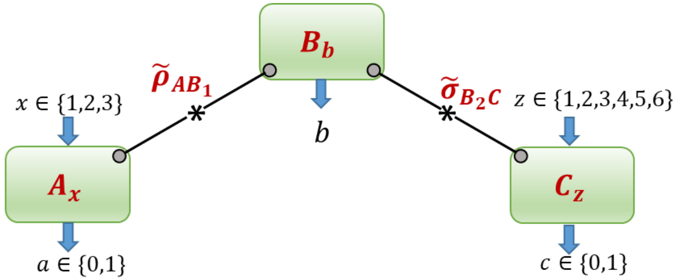
Detective

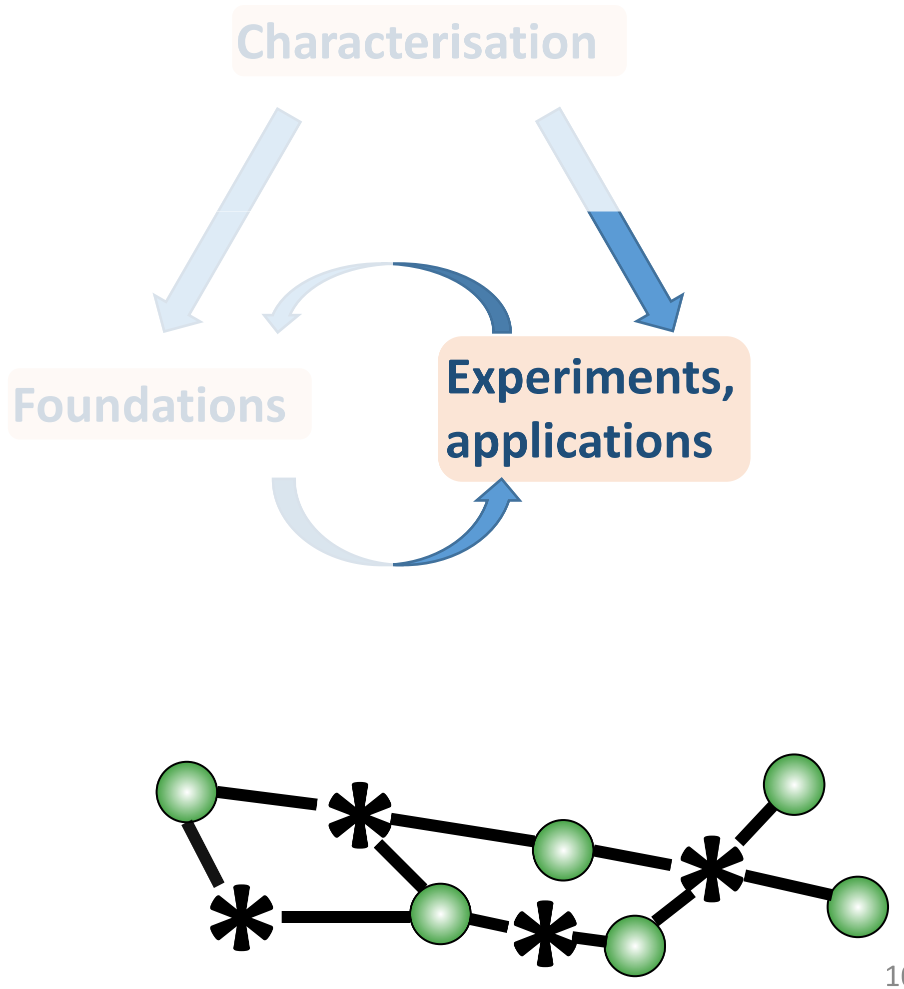
- Believes in $\mathbb{R}$-QT
- Tries to explain these **experimental results** results. **Any 'crazy' explanation** compatible with $\mathbb{R}$-QT is possible.



➢ **Fails**

M-O. Renou, D. Trillo, M. Weilenmann, T. Le Phuc, A. Tavakoli, N. Gisin, A. Acin, M. Navascues, Nature 600, 625–629 (2021)

Applications



Foundations

Bipartite exotic sources are not enough

Experimentalist

- Master standard Quantum Theory
  - Involves bipartite entangled sources

$$|\phi\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

Detective

Foundations

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- Accept**ed** that only "**more crazy theory** than any crazy explanation compatible with classical physics"

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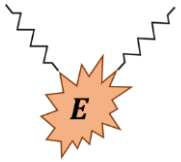

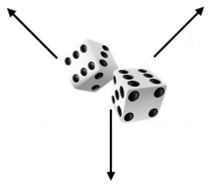

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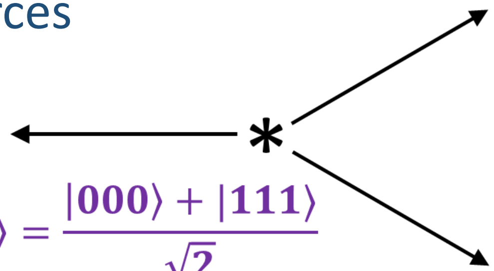
  - ➢ Involves tripartite (and n-partite) entangled sources



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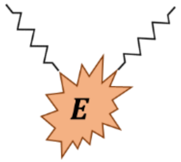

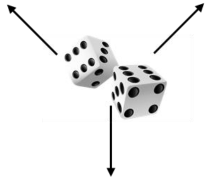

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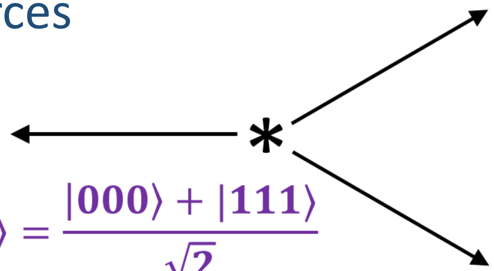

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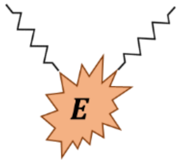
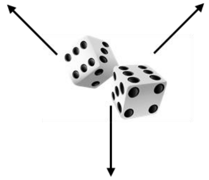
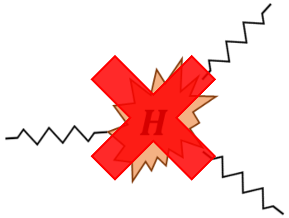




- However, would like to keep this craziness of low degree:
  - Rejects tripartite (or more) « crazy » sources



Foundations

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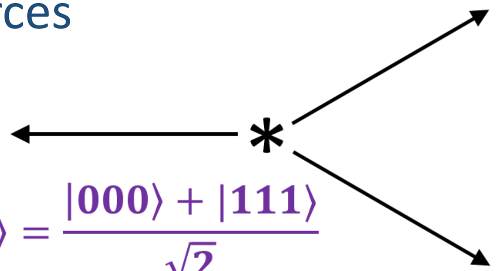

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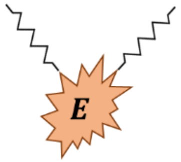

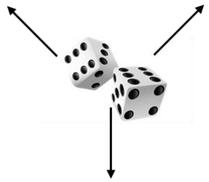

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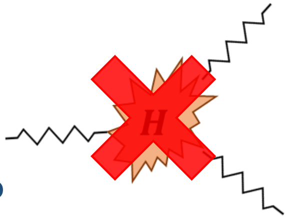

Important question for:

➢**The foundations of QT**: is tripartite entanglement really needed?

Foundations

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  - ➢ Involves bipartite entangled sources

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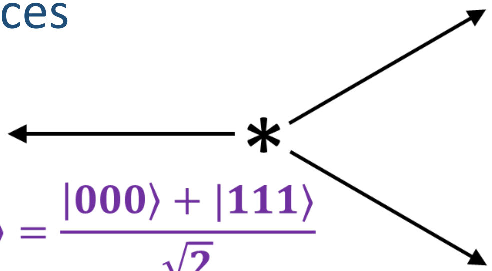

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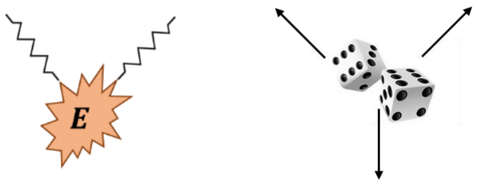

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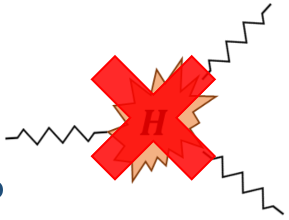

Important question for:

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Foundations

Bipartite exotic sources are not enough

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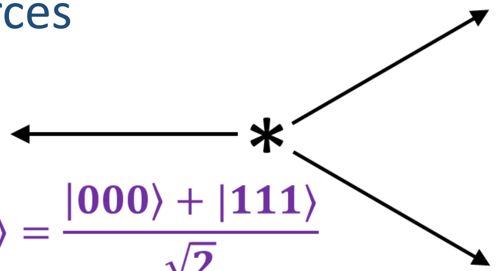

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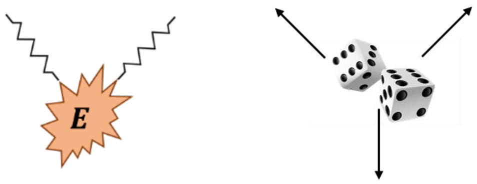

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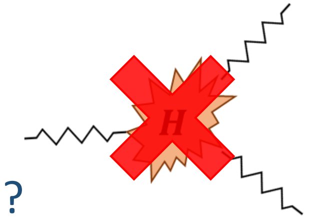

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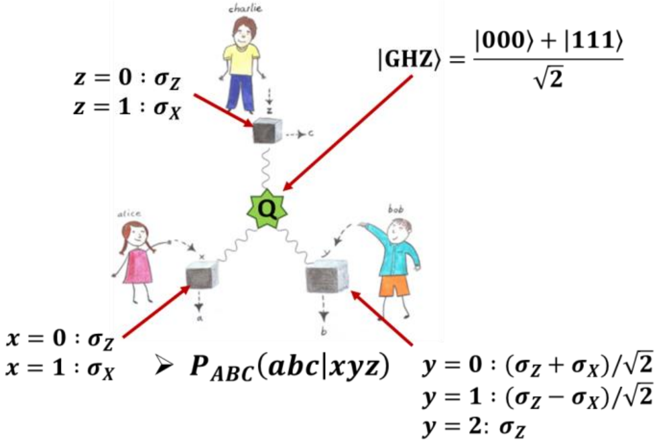
- ➢ **Applications of QT**: Can I do **more** with tripartite entanglement, what?
- ➢ **Benchmark Q systems**: How to prove « I can produce tripartite entanglement »?

Foundations

Bipartite exotic sources are not enough

Experimentalist

- Master standard Quantum Theory
- Construct a **concrete experiement**



- Obtains **experimental results** (statistics)

$$\langle A_0 B_2\rangle + \langle B_2 C_0\rangle = 2,$$

$$\langle A_0 B_0\rangle^{|C_1=1} + \langle A_0 B_1\rangle^{|C_1=1} + \langle A_1 B_0\rangle^{|C_1=1} - \langle A_1 B_1\rangle^{|C_1=1} = 2\sqrt{2}$$

Detective

Foundations

Bipartite exotic sources are not enough

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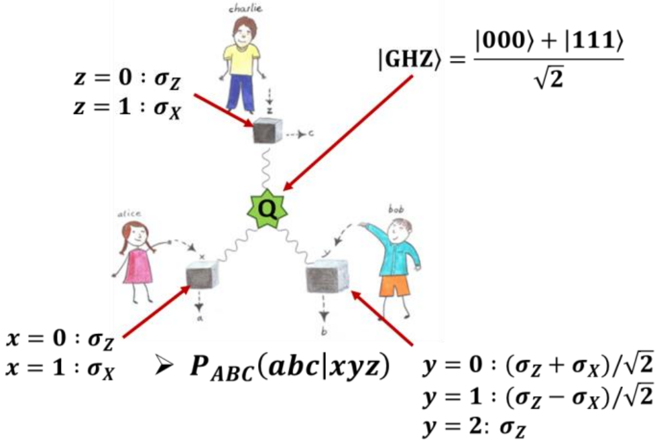

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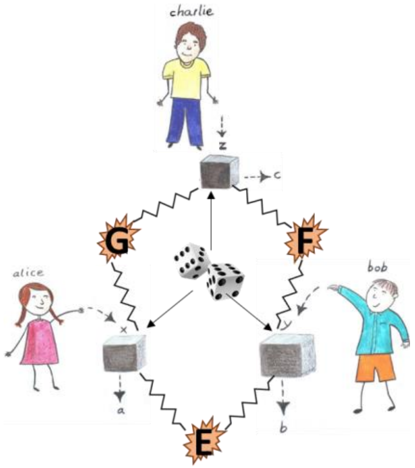

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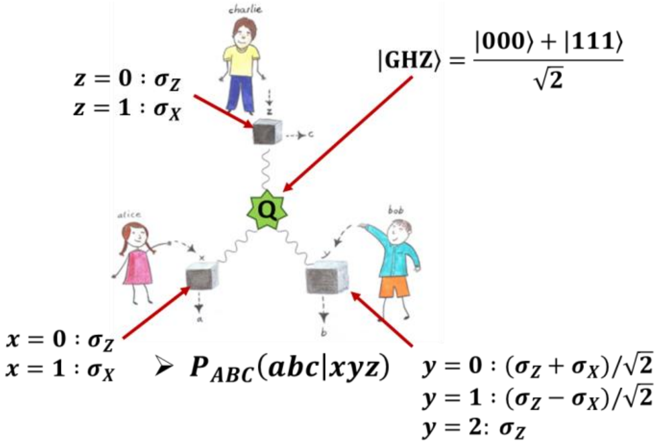

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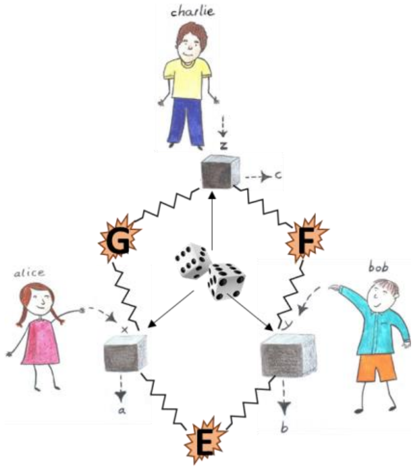

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Applications

Certification of all pure states

$\mathbf{CHSH} = 2\sqrt{2}$

State certification: “self-testing”

- **Observation:** $\mathbf{CHSH} = 2\sqrt{2}$

I. Šupić, J. Bowles, **M-O. Renou**, A. Acín, M. J. Hoban, Nature Physics, 1745-2481 (2023)

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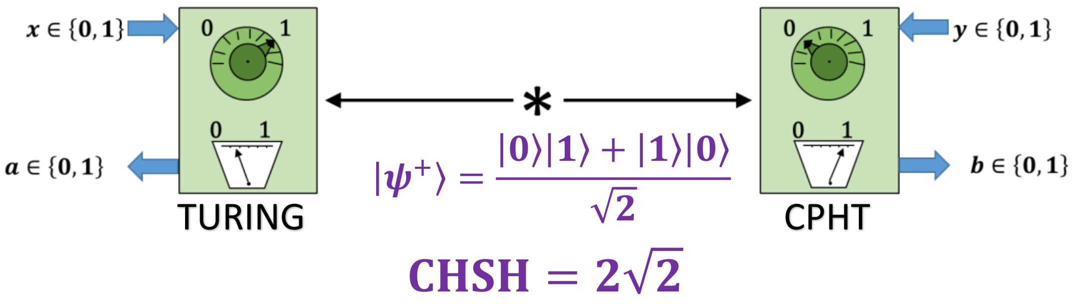

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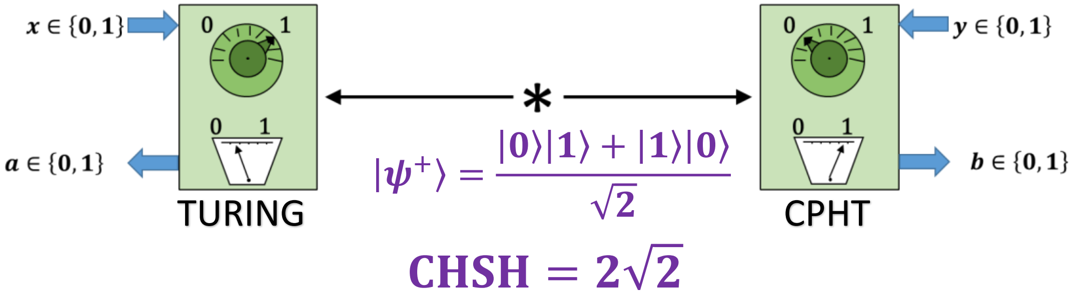

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Open question: is there an operational way to test all pure states?

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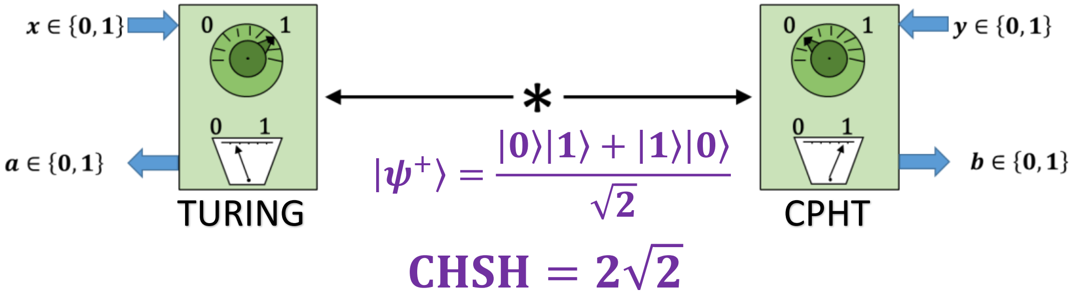

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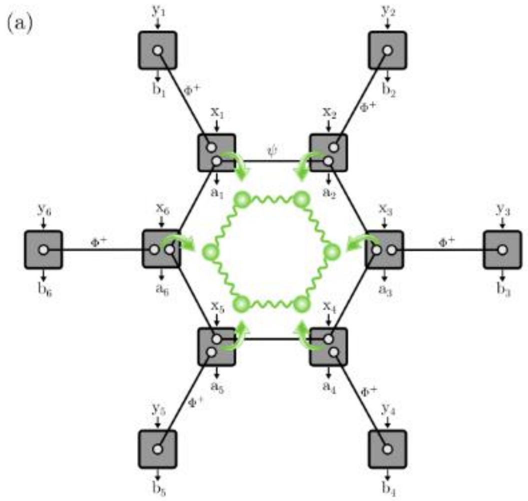
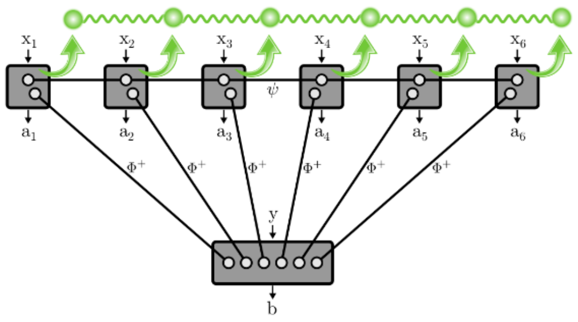
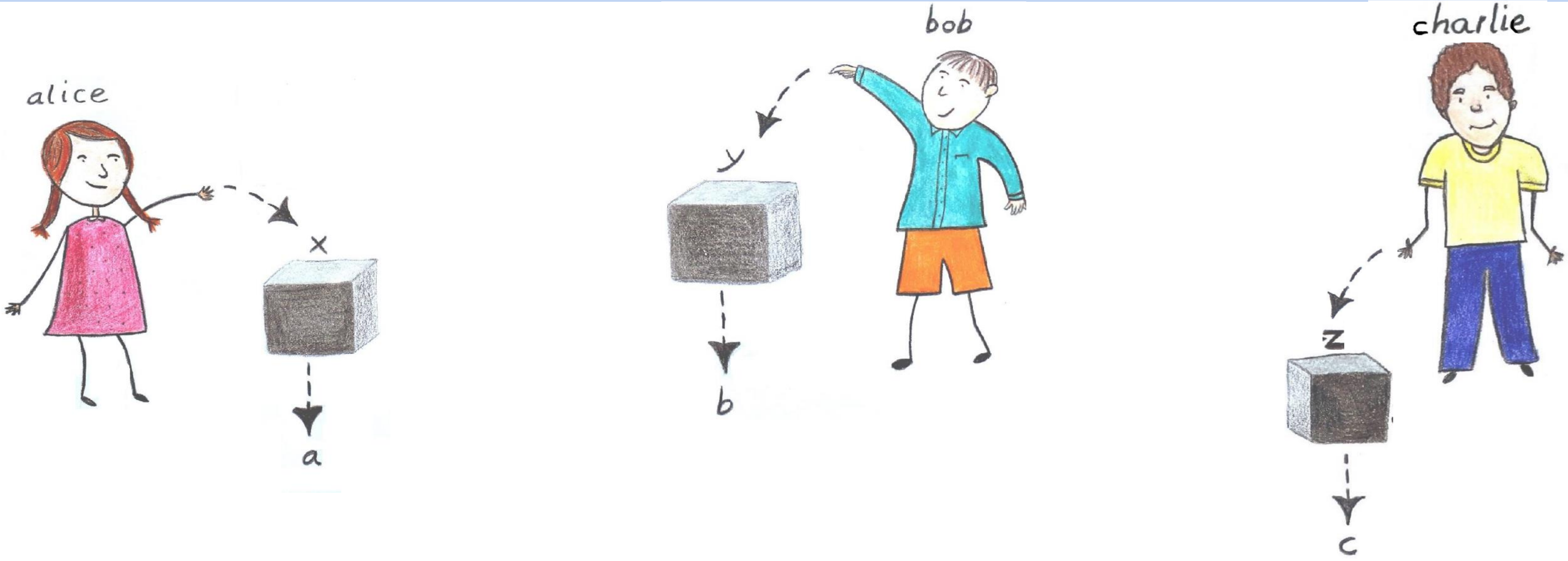




Open question: is there an operational way to test all pure states?

➢ Answer: yes, considering network correlations

I. Šupić, J. Bowles, **M-O. Renou**, A. Acín, M. J. Hoban, Nature Physics, 1745-2481 (2023)


alice
x
a
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z
c

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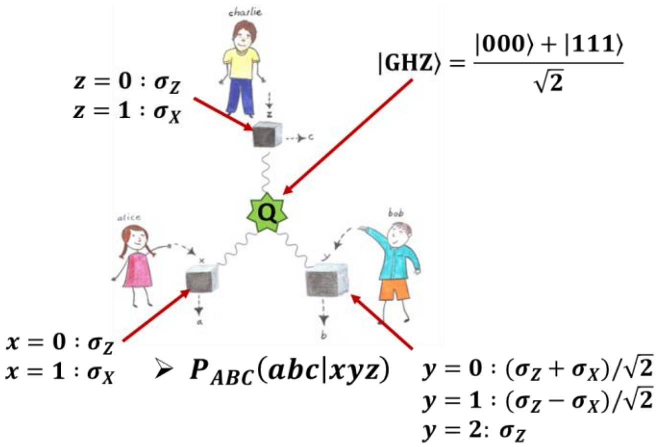

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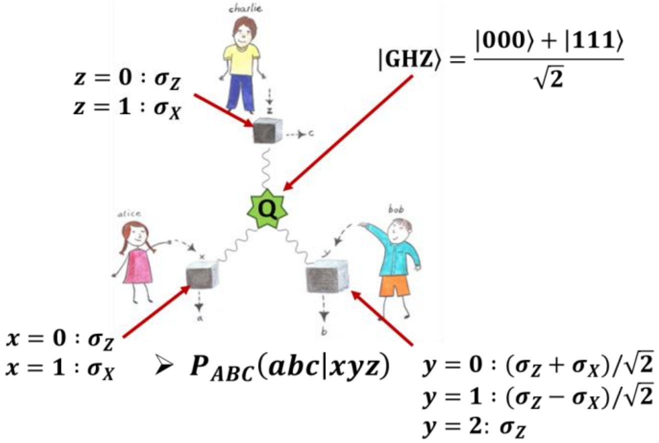

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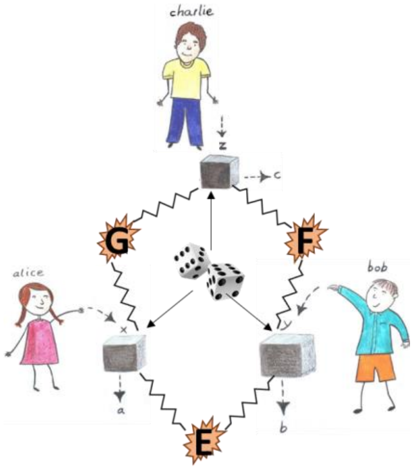

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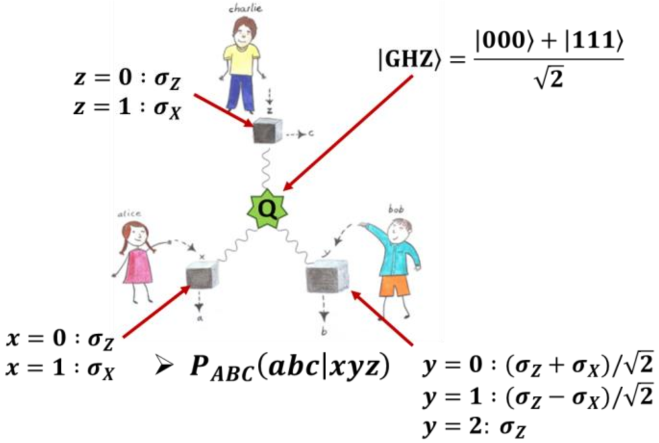

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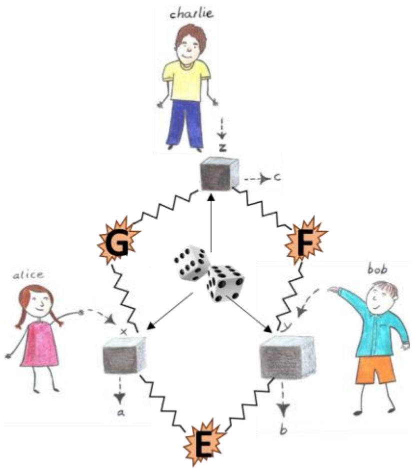

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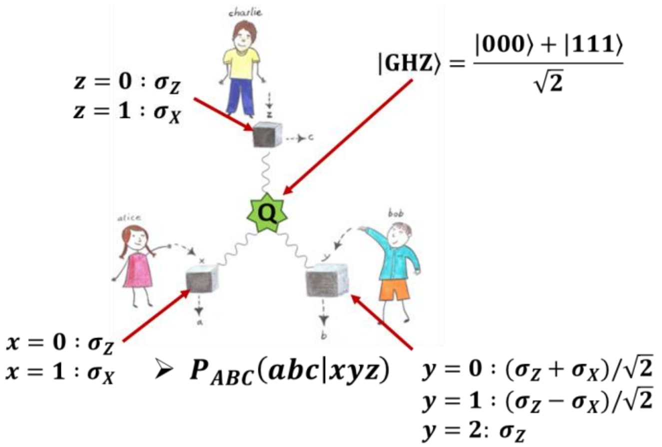

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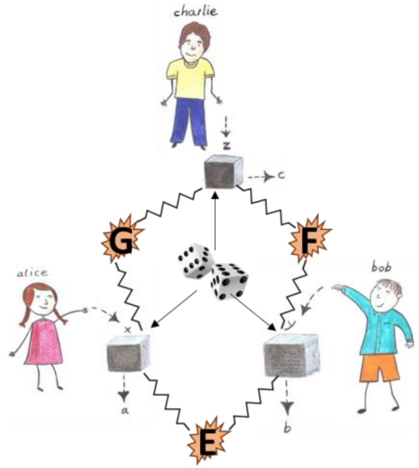

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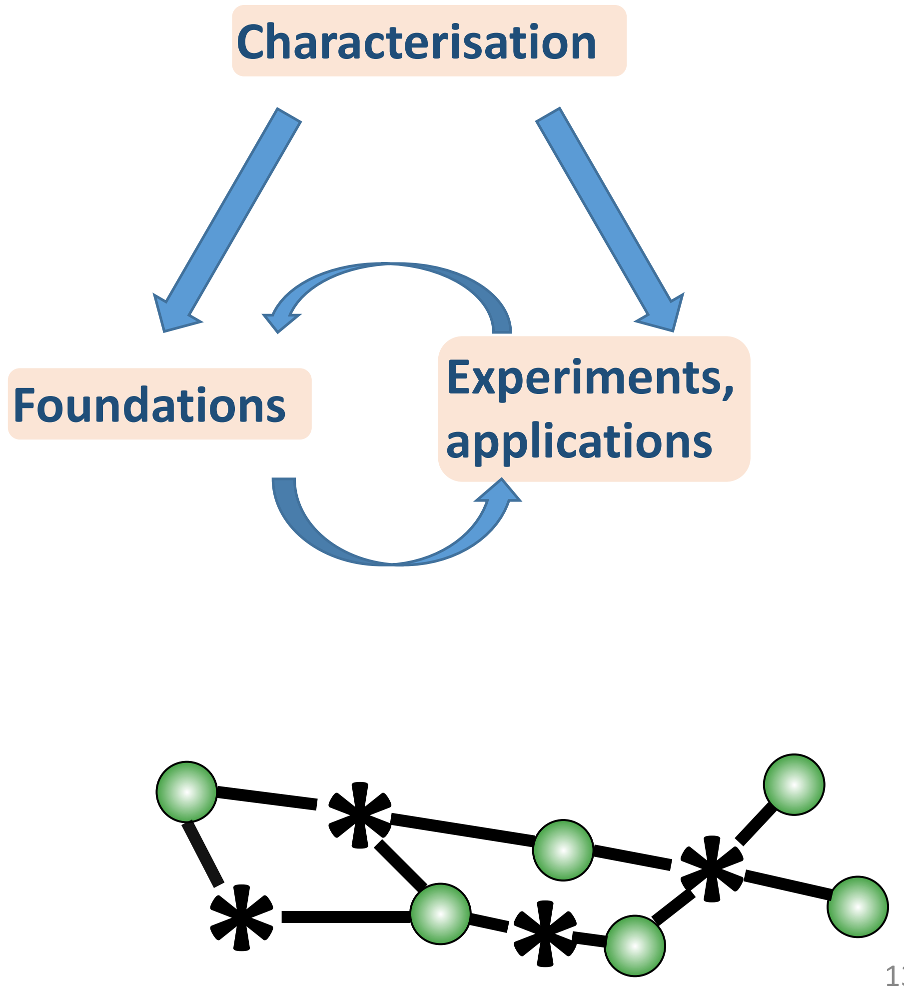
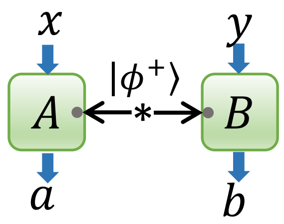
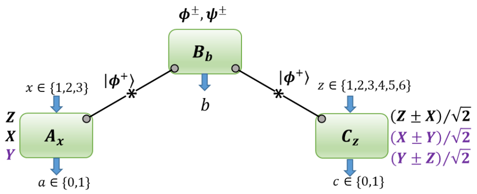
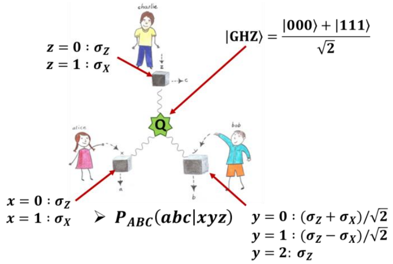
Causal network quantum correlations



Foundations: ongoing and future goals

Alternative Theory	**Incompatibility**
Classical physics	
$\mathbb{R}$ – quantum theory	
Generalised bipartite entanglement	
More?	…

Reconstruct QIT from its correlations?

- Bell theorem excludes LHV models
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Foundations: ongoing and future goals

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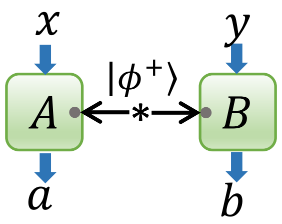
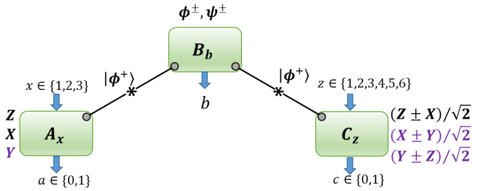
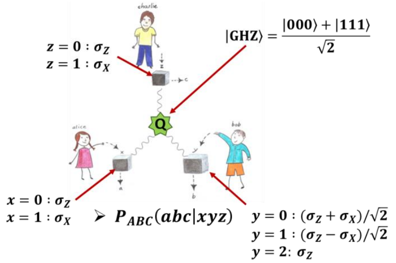
Classical physics	
$\mathbb{R}$ – quantum theory	
Generalised bipartite entanglement	
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Reconstruct QIT from its correlations?

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➢ Exclude more ?

➢ **Characterise** Quantum Information Theory **from its correlations**?