A Hidden Influence inequality for 3 parties

Why quantum correlations are even stranger than we thought

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Overview

Is quantum theory exact?

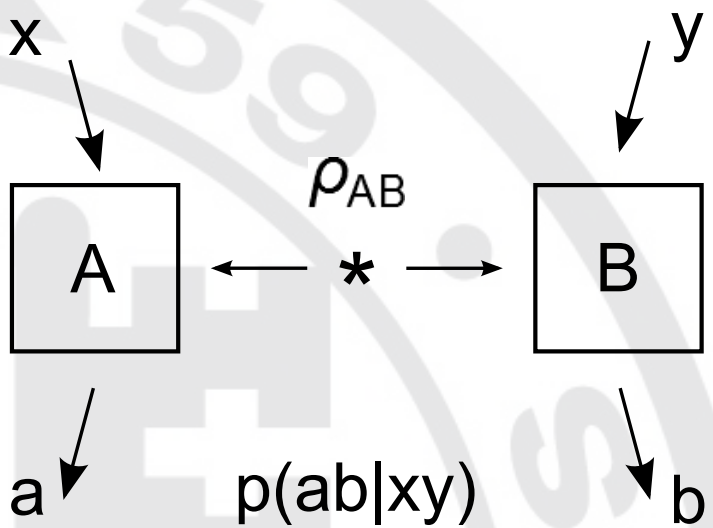
Goal Explain experimentally observable quantum correlations

How Locally and continuously in space and time

- Preliminaries
- Discuss different explanations
- No-go theorems

! Quantum correlations are even more intriguing than expected

Quantum correlations



Measurement settings (inputs): $x, y \in \{0, 1, 2, \dots\}$

Measurement outcomes (outputs): $a, b \in \{0, 1, 2, \dots\}$

$$p(ab|xy) = tr(\rho_{AB} M_x^a \otimes M_y^b)$$

Properties of Quantum correlations

Non-signalling principle

A's output does NOT depend on B's input

A gains no information about B's input

Formal definition

A probability distribution $p(ab|xy)$ is non-signalling iff

$$\sum_b p(ab|xy) = p(a|xy) = p(a|x) \qquad \forall a, x, y$$

$$\sum_a p(ab|xy) = p(b|xy) = p(b|y) \qquad \forall b, x, y$$

The different explanations in more details

Local and continuous explanations in space and time

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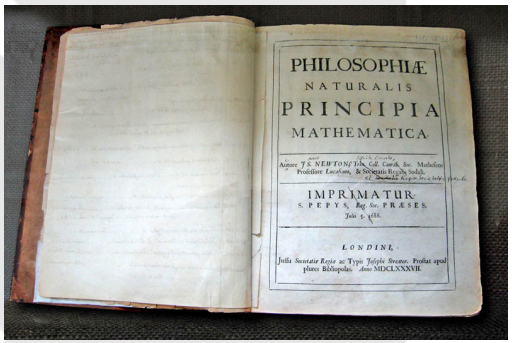
Local and continuous explanations in space and time

Common causes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Local variables
Common past

The different explanations in more details

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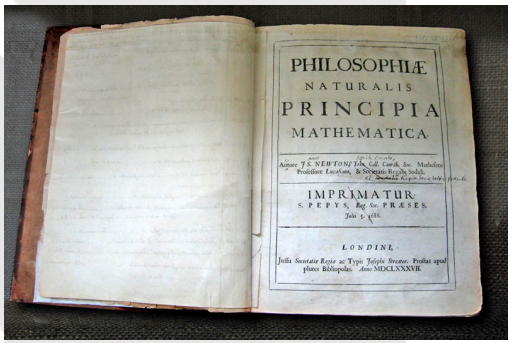
Common causes



Local variables
Common past

Direct causes

Hidden influences
Speed $v > c$

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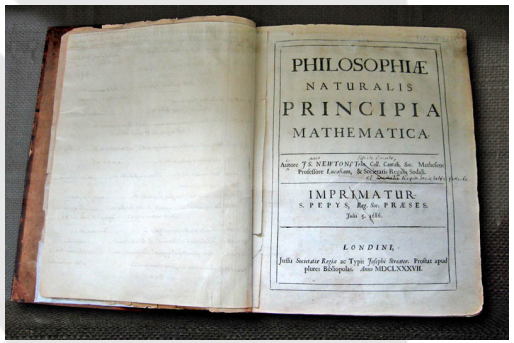

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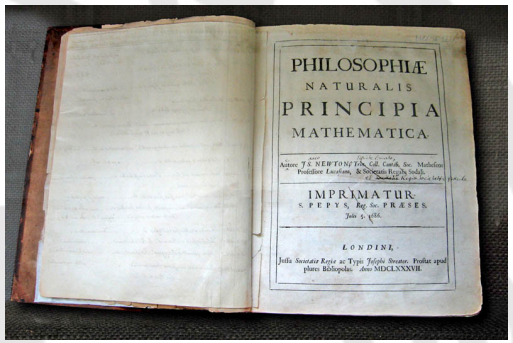

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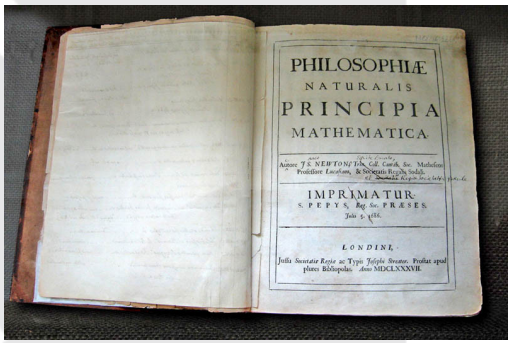
Approach I: Common causes

Local and continuous explanations in space and time

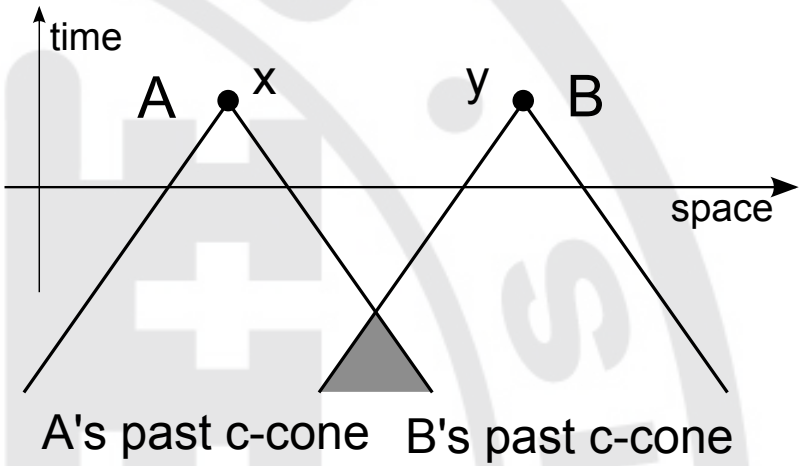
Common causes



Local variables
Common past

Approach I: Locally causal theories

- We agree on *Strategies* before the measurements



- Locality assumption: $p(ab|xy) = \sum_{\lambda} q(\lambda)p(a|x\lambda)p(b|y\lambda)$
- λ in the shaded region

Approach I: Quantum example

- Measuring quantum state $\rho_{AB} \Rightarrow p(ab|xy)$

$$|\Psi^-\rangle = \rho_{AB} = \frac{1}{\sqrt{2}}(|0\rangle_A \otimes |1\rangle_B - |1\rangle_A \otimes |0\rangle_B) \in \mathcal{H}_A \otimes \mathcal{H}_B$$

Theorem (Bell)

No locally causal theory can account for all quantum correlations

J. S. Bell, Physics 1 (3) p. 195-200 (1964)

Approach II: Direct causes

Local and continuous explanations in space and time

Direct causes

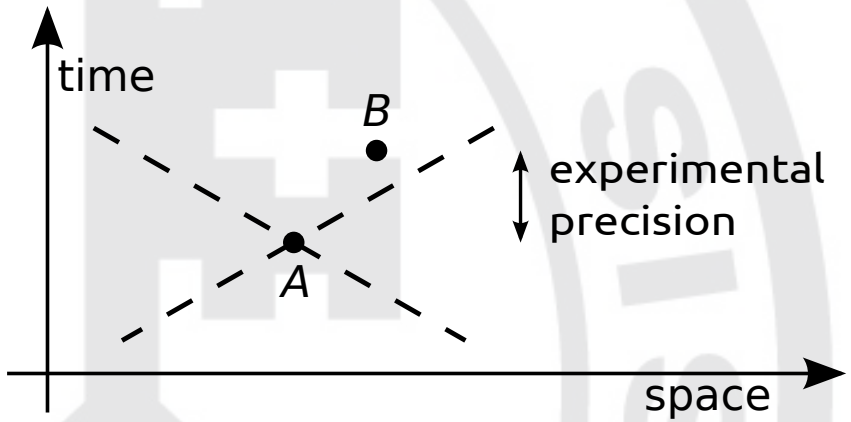
Hidden influences

Speed $v > c$

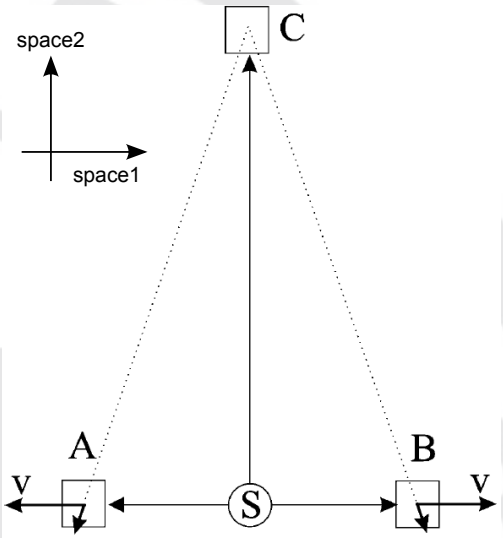
Approach II: Hidden influences (HI)

- Hidden in the sense not having observable consequences

e.g Non-signalling



Approach II: Quantum example



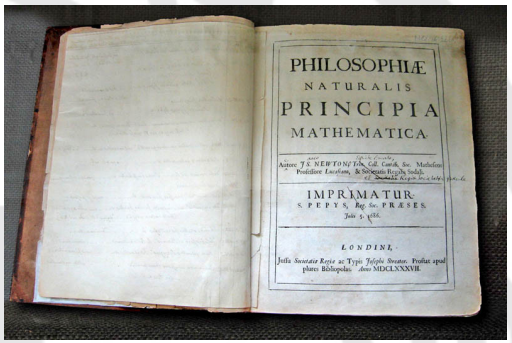
$$|GHZ\rangle = \rho_{ABC} = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle$$

Contradiction by changing the timing of A and B

Valerio Scarani, Nicolas Gisin, Physics Letters A 295 (4) p.167-174, (2002)

Approach III: Combining the two

Local and continuous explanations in space and time



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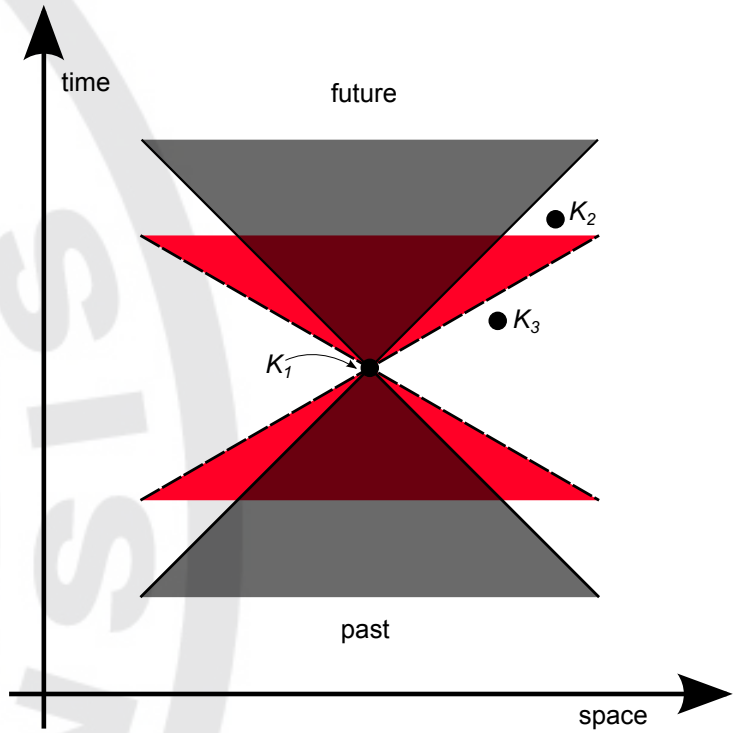
Approach III: *v*-causal models

- Causal influences propagate at speed $v > c$

$\mathbf{K_1}$ & $\mathbf{K_2}$ are
v-causally connected

$\mathbf{K_1}$ & $\mathbf{K_3}$ are
v-causally disconnected



Approach III: v-causal models

Definition

A v-**causal model** is one that satisfies the equations below

$$P_{A<B}(ab|xy) = \sum_{\lambda} q(\lambda) P(a|x,\lambda) P(b|y, ax\lambda)$$

if A and B are v-causally connected

$$P_{A\sim B}(ab|xy) = \sum_{\lambda} q(\lambda) P(a|x,\lambda) P(b|y,\lambda)$$

if A and B are v-causally disconnected

Approach III: v-causal models for quantum mechanics

all those that explain quantum correlations wherever possible

Note The quantum probability P^Q is independent of the spacetime ordering of the measurements

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$\Rightarrow$ Minimal consistency assumption

- Any v-causal model to reproduce quantum mechanics, satisfies:

$$P^v_{A<B} = P^v_{B<A} = P^Q$$

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$\Rightarrow$ Minimal consistency assumption

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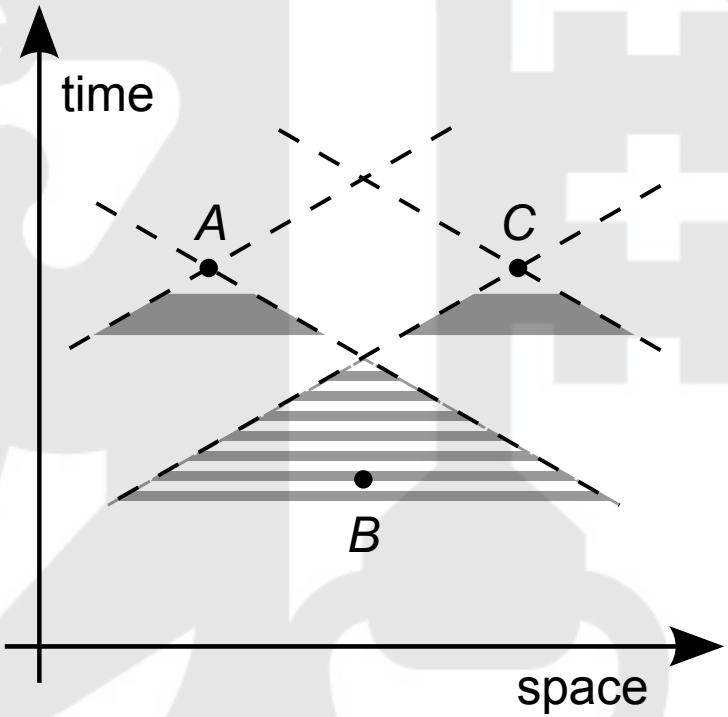
! In certain spacetime configurations not all quantum correlations are reproducable

- e.g if $A \sim B$ and the quantum correlations were nonlocal to begin with

Approach III: How to find a quantum example

1. Local between parties A and C
2. Non-signalling



$\Rightarrow$ Bell-Inequality

Only use $P_A, P_B, P_C, P_{AB}, P_{BC}$

$\rightarrow$ Hidden influence constraints!

Approach III: Quantum example

Predictions of quantum physics & v-causal models $\Rightarrow$ signalling

Experiment?

Approach III: Quantum example

- $\Psi_{ABCD} \in \mathbb{C}^2 \otimes \mathbb{C}^2 \otimes \mathbb{C}^2 \otimes \mathbb{C}^2$

  J-D. Bancal et al., Nature Physics 8, 867 (2012)

- $\Psi_{ABC} \in \mathbb{C}^2 \otimes \mathbb{C}^3 \otimes \mathbb{C}^2$

  T.J. Barnea et al., Phys. Rev. A 88, 022123 (2013)

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  Problems:
  - 3 partite state, visibility needed: 99.9%
- Experimental test still very challenging

The different explanations in more details

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Local and continuous explanations in space and time

Common causes

Both

Direct causes

The different explanations in more details

Local and continuous explanations in space and time

Common causes	Both	Direct causes
✗	✗	✗

The different explanations in more details

Local and continuous explanations in space and time

Common causes	Both	Direct causes
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$\Rightarrow$ Discontinuous explanations in space-time needed

Acknowledgements:

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Thank you for your attention

Questions?

Picture from:

- http://twistedsifter.com/category/history/page/19/
- http://www.houseofsound.ch/monacor-megaphon-tm-22.html
- http://www.hindenburger.de/leser-122/items/wie-bitte.html