Local causality in the light of the Principal Principle

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Overview

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Quantum non-locality and relativity

Predictions based on entangled quantum states are often regarded as indicating a tension between quantum theory and special relativity:

- John S. Bell (1984): “an apparent incompatibility, at the deepest level, between the two fundamental pillars of contemporary theory”
- Albert and Galchen (2009): “quantum threat to special relativity”
- Michael Seevinck (2010): “a good and fair case can be made that a basic inconsistency exists between quantum theory and relativity.”

For a book-length treatment see “Quantum nonlocality and relativity” (1994) by Tim Maudlin.

But why?

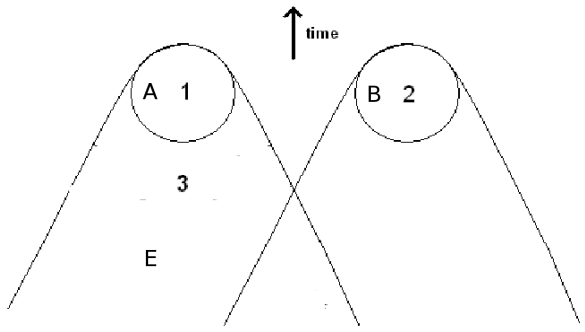
- Some think: wave function collapse must violate Lorentz covariance...,
- ...but this is only problematic on an “ontic” view of the wave function.
- Main argument: Quantum theory violates *local causality*.

J.S. Bell: In a locally causal theory...

> *“[t]he direct causes (and effects) of events are near by, and even the indirect causes (and effects) are no further away than permitted by the velocity of light.” (1990)*

Probabilistic local causality

For probabilistic theories:



A theory will be said to be locally causal if the probabilities attached to the values of local beables in a space-time region 1 are unaltered by specification of values of local beables in a space-like separated region 2, when what happens in the backward light cone of 1 is already sufficiently specified, for example by a full specification of local beables in a space-time region 3. (Bell 1990)

Quantum theory and local causality

- According to Bell: theory is locally causal iff $Pr(A|E) = Pr(A|EB)$, where E fully specifies what happens in 3.
- Quantum theory: Probabilities derived from entangled states violate this equation.
- So quantum theory violates local causality...
- ... just as, according to Bell's theorem, any theory in which quantum theory may be embedded.
- To sum up: For Bell, violation of local causality not only in hidden variable theories, but in quantum theory itself!

Local causality and relativity

Why should the violation of local causality be problematic for special relativity?

- What is cause, what effect? (preferred foliation needed?)
- Superluminal causation is backward causation in some inertial frames.
- Backward causation potentially gives rise to causal loops.
- More qualitatively: completely at odds with everyday picture of causal influences travelling locally.

Two reactions

Two possible reactions for those who think QT and SR are compatible:

- Accept that quantum non-locality requires superluminal causation, but argue that it is harmless.
- Deny that the prescription $P(A|E) = P(A|EB)$ is adequate as a way of spelling out local causality (i.e. absence of superluminal causation).

Let's try the second option!

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Chance and rational credence

But remember David Lewis:

> *Don't call any alleged feature of reality 'chance' unless you've already shown that you have something, knowledge of which could constrain rational credence. (Lewis 1994)*

Let's check whether we are looking at the right "probabilities"!

David Lewis' **Principal Principle**:

- Objective probabilities constrain rational degrees of belief according to:
- $Pr_y(A) = cr(A|E_y T)$,
- Here E_y is "admissible evidence" and T "chance theory", e.g. quantum theory.
- Intuitively: Evidence is inadmissible if using it would be "cheating".

My claim: In a locally causal theory, evidence about B is **inadmissible** for an agent in region 1.

Ought implies can!

- Evidence about chances is always admissible. (“ought implies can”)
- If an agent in 1 **cannot** have any evidence about B at space-like distance in 2, it cannot be **rational** for her to take B into account when forming $cr(A|E_1T)$!
- Therefore, $P(A|E) = P(A|EB)$ matters only if B is *admissible* with respect to region 1. Otherwise, $P(A|EB)$ has nothing to do with the *chance* of A in 1.
- To sum up: Local causality is violated if agents need to take into account evidence that about space-like separated events for their rational credences.

The relevance of no-signalling

But, given quantum theory, *can* an agent in 1 have evidence that B (prior to detecting A)?

- The impossibility of superluminal signalling seems sufficient to exclude that.
- Implemented by “relativistic causality” (operators associated with observables at space-like distance commute)
- $\Rightarrow$ Vindication of standard approach to QFTs.

But note: potentially different for specific interpretations (e.g. de Broglie-Bohm).

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But how do EPR-correlations come about?

An objection:

- Considerations about agents and their rational credences (anthropocentric!!!) have **nothing** to do with superluminal causation!
- One of the probabilities $P(A)$, $P(B)$ must depend on whether the other event occurs.
- Otherwise, EPR-correlations, e.g. perfect anticorrelations, would not come about.
- So, there must be an objective superluminal influence.

The block universe

To answer, consider the least anthropocentric perspective:

- The block universe: “*flow of time*”, and “*becoming*” are anthropocentric concepts.
- The complete spatio-temporal distribution of events assumed as primitively given.
- From this perspective: cannot ask how events “come about” such that EPR-correlations arise.
- They’re simply there!

Becoming

- When we ask how nature is able to evolve in time such that EPR-correlations arise, our perspective is already (partly) anthropocentric.
- Then let's be consistent!
- ... and adopt an anthropocentric approach to quantum probabilities as well...
- ... which is what the Principal Principle does...
- ... without denying that quantum probabilities are objective!

The "quantum threat" to special relativity is a consequence of partial and inconsistent anthropocentricism!

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Summary

- There is widespread belief a tension between quantum theory and special relativity due to the violation of local causality in the first.
- Bell's criterion $P(A|E) = P(A|EB)$ is indeed violated in quantum theory.
- However, this does not spell out local causality correctly if one accepts the Principal Principle.
- If one does, it seems plausible that *no-signalling* is sufficient for local causality.
- There is neither a problem if we adopt the least anthropocentric perspective (block universe) nor if we are consistently anthropocentric.