Why Do We Care About Violating Bell Inequalities? Questions and Controversies

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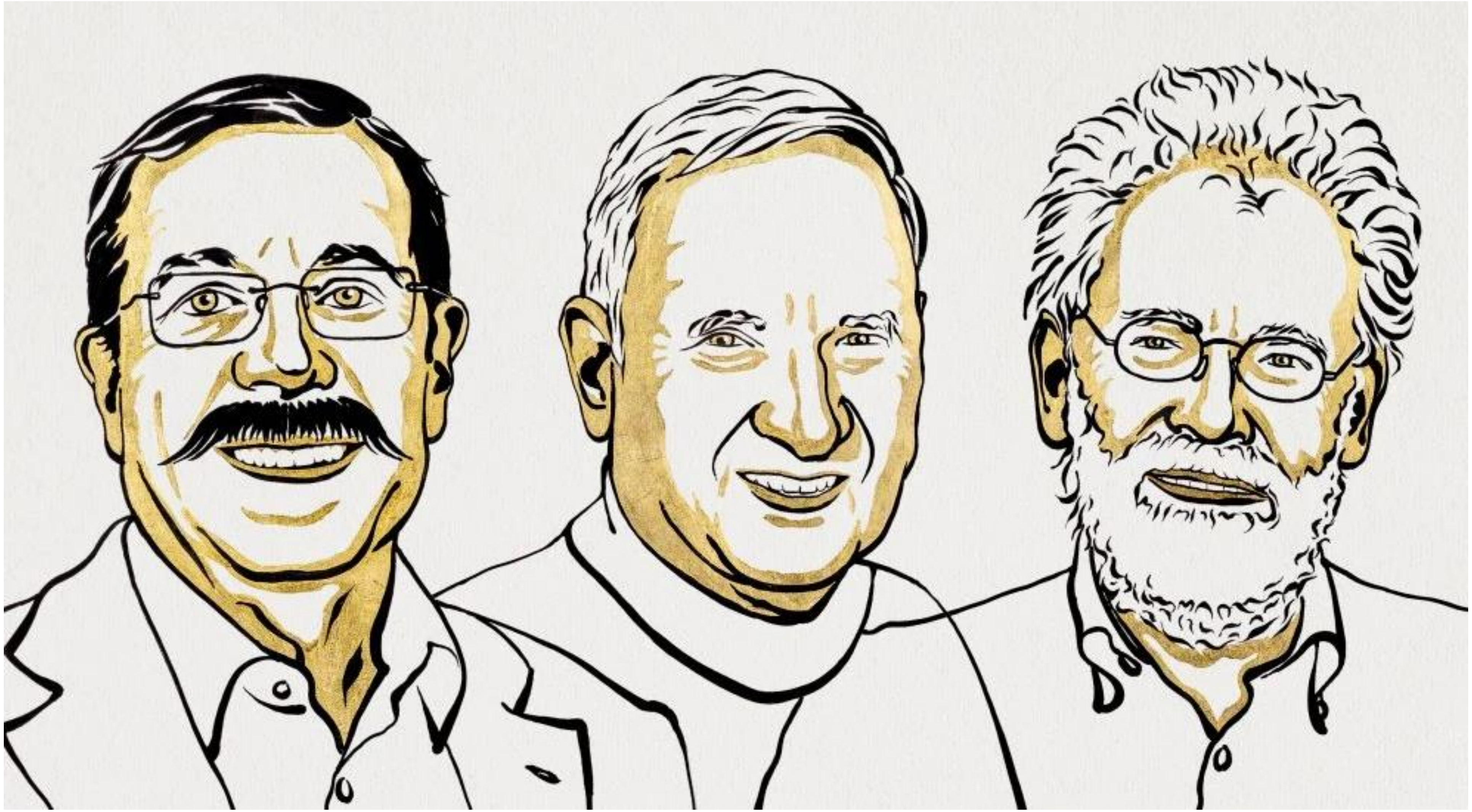
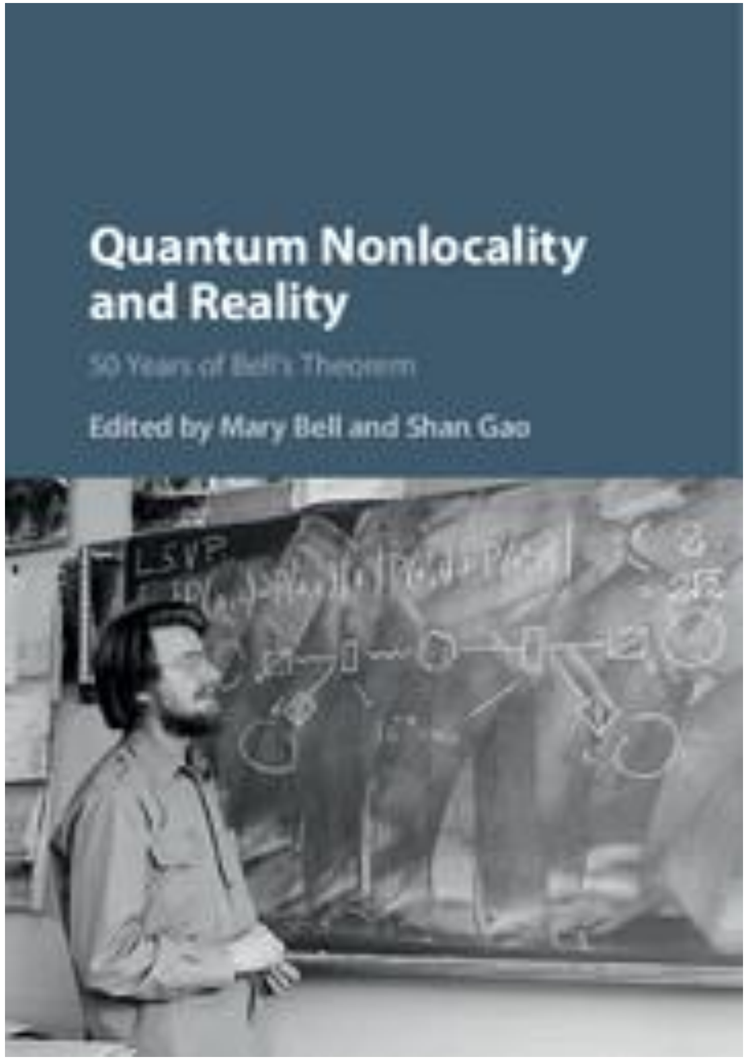


50 + Years of Bell’s Theorem!



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EDITORIAL

Fifty years of Bell's theorem

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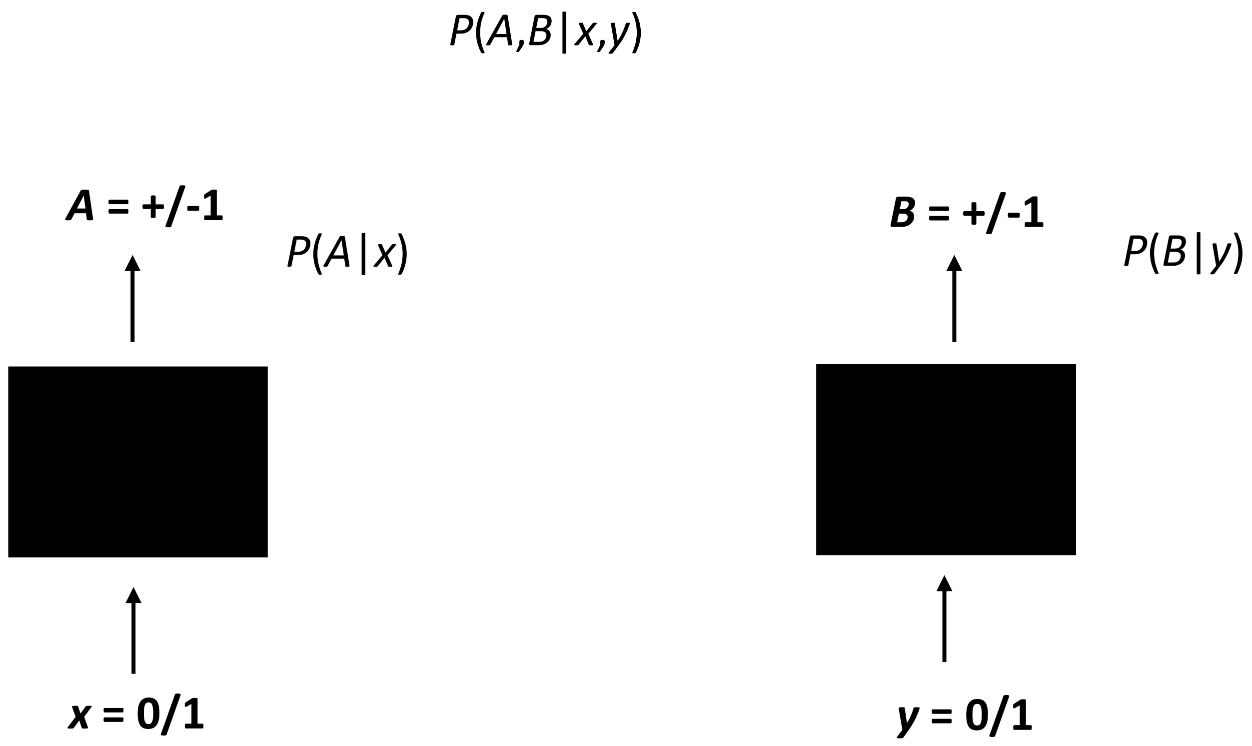
“…*This issue presents recent results on Bell inequalities and entanglement theory, but also topical reviews and personal views on John Bell and his theorem. From the papers it can be seen that there are still ongoing discussions about the assumptions and implications of Bell’s work. At first sight one may be surprised that fifty years later not all issues are settled, but in our opinion this only highlights the importance of Bell’s work…..”*

- Does the experimental violation of Bell inequalities indicate the presence of nonlocality in the world, and if so, in what sense?

Can’t we just operationalise the question?

Suppose we start with a pair of boxes, 1 and 2, where

- Box 1 takes an input bit value x = 0,1 and outputs a value A = +/-1 with some probability distribution $P(A|x)$; and
- Box 2 takes an input bit value y =0,1 and outputs a value B = +/-1 with some probability distribution $P(B|y)$.



Suppose, moreover, that the values x and y are chosen independently of one another, and that we find there to be correlations between the outputs of the boxes:

$$P(A,B|x,y) \neq P(A|x)P(B|y)$$

- We explore the idea that these correlations might be due (and due only) to some further variable, λ, connecting the two boxes:

$$P(A,B|x,y,\lambda) = P(A|x,\lambda)\mathrm{P}(B|y,\lambda) \qquad (1)$$

FACTORISABILITY

- If in addition this further variable λ is independent of the input values *x* and *y*:

$$P(x,y|\lambda) = P(x|\lambda)P(y|\lambda) = P(x)P(y), \qquad (2)$$

λ - *INDEPENDENCE*

then certain interesting inequalities follow relating the expectation values for the outputs of these boxes, given various arrangements of the inputs, in particular:

CHSH: <x=0,y=0> + <x=0,y=1> + <x=1, y=0> - <x=1, y=1> ≤ 2

Why do we care about this?

- We care when we embed the boxes in a relativistic spacetime, and the choice of *x* and the outcome *A* occur at spacelike separation from the choice of *y* and the outcome *B.*
- Start with the idea that correlations should be explicable, and start with the idea that:

"The direct causes (and effects) [of events] are nearby, and even the indirect causes (and effects) are no further away than permitted by the velocity of light" (Bell 1990)

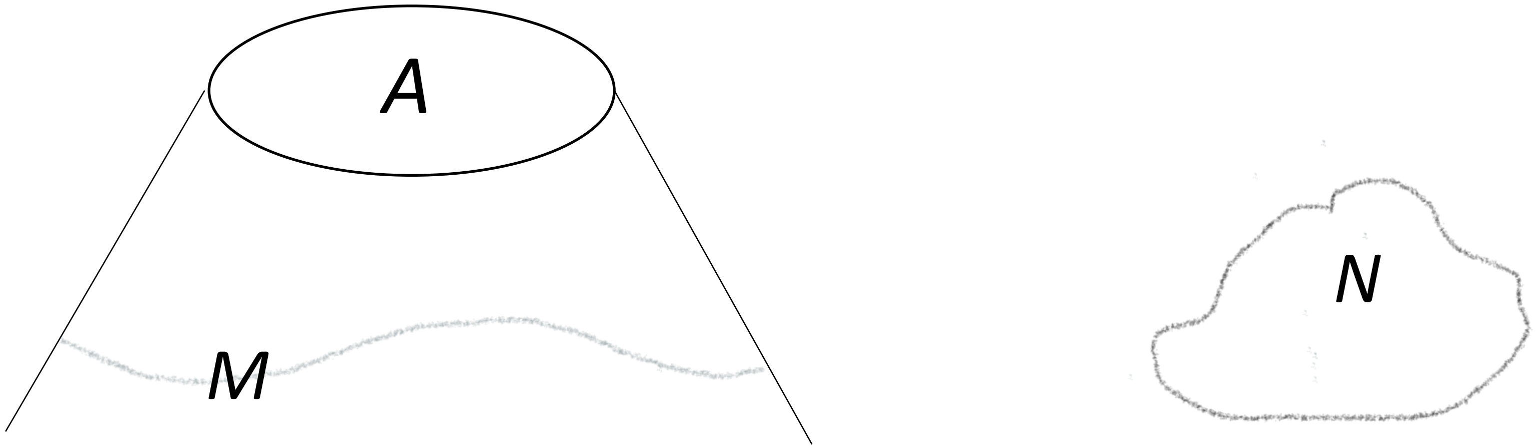
LOCAL CAUSALITY (informal version)

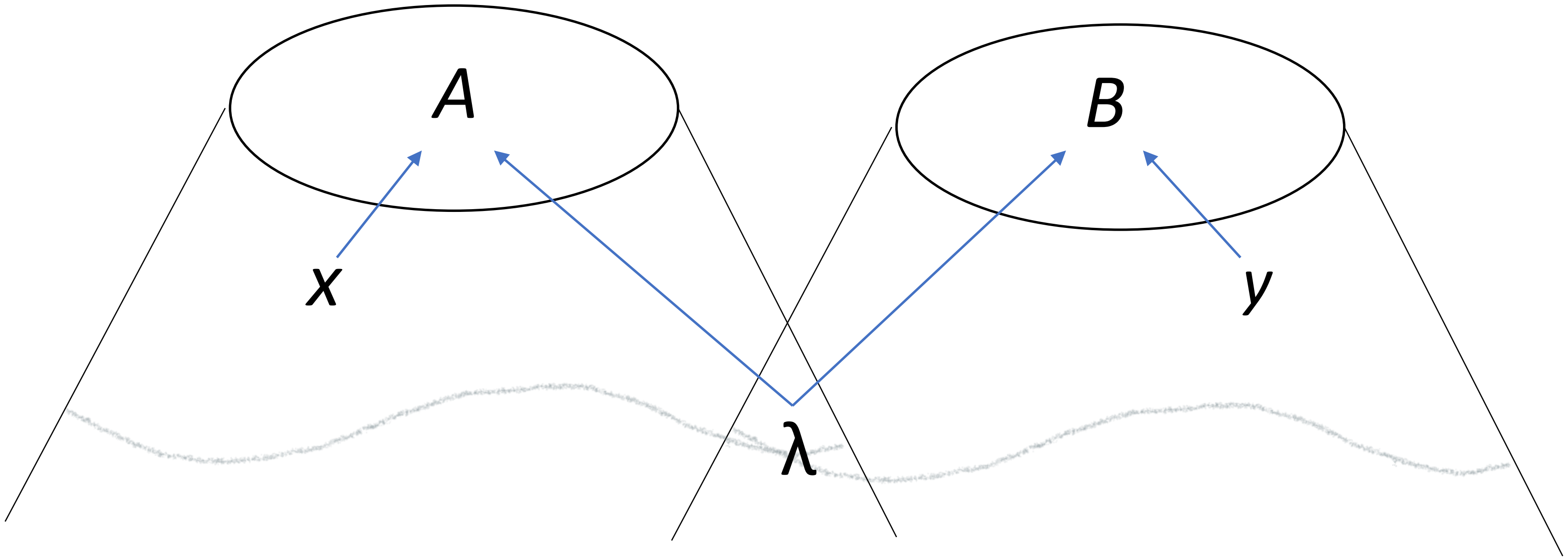
Local Causality *formal version*

- For an event *A,* for a full specification (or a sufficient specification) *M* of facts in the past light cone of *A,*

$$P(A|M,N) = P(A|M),$$

  - Where *N* is a specification of facts in any region spacelike to *A*





Bell experiment in standard configuration

Pro tem conclusion:

- Since we violate the CHSH inequality (etc.), and there's no funny business (λ-dependence), **local causality must fail**.
- Often taken to lead to two further conclusions, viz.,

1. Quantum mechanics is nonlocal, and
2. *The world* is nonlocal.

Is that right?

- There seem to exist clear counter-examples (operationalist/anti-realist QM, Everett) ;
- Moreover, question:
  - How does the failure of the specific condition of *Local Causality* relate to the presence of non-locality, and especially to the presence of any form of nonlocality we might find worrying?
- Distinguish:
  - Dynamical nonlocality (action at a distance) from
  - Kinematical nonlocality (nonseparability)

- Dynamical nonlocality:
  - There are changes in *locally defined* properties due to spacelike goings-on
- Kinematical nonlocality:
  - The states assigned to unions of spacetime regions are not determined by the states assigned to the individual regions.

- Perhaps all that is going on is a failure of kinematical locality?
- But puzzles remain:
  1. What went wrong with Bell's reasoning?
  2. Grant there to be non-separability – how does that help violate a Bell inequality? Grant there to be non-separable features in the joint past of Alice and Bob's experiment, but just condition on these and include in λ. (Henson 2013)

Turn to the counterexamples:

- Operationalist/anti-realist QM: Denies much descriptive content to the theory; locality is just the operational notion of *no-signalling*
  - E.g. Peres;
  - E.g.(?) QBism of Fuchs, Schack, Mermin;

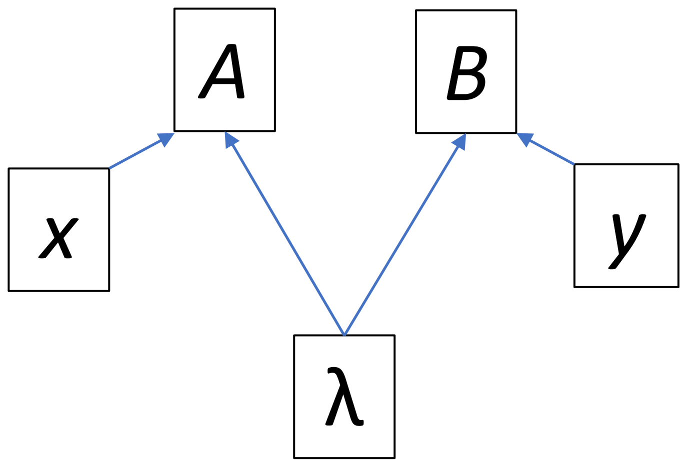
- Intermediate views – Healey, Friederich – where probabilities are not univocal localisable physical facts

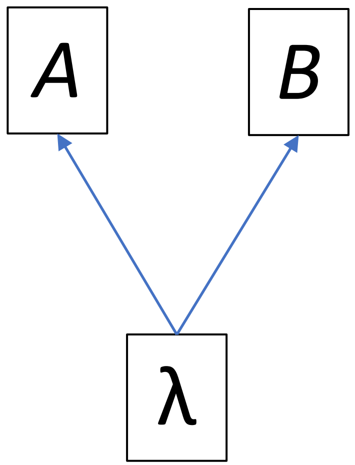
- Everett (Many Worlds). Four (interrelated) factors:
  - Explicitly local dynamics for the q state (plus idea that all the ontology supervenes on the q state and its evln);
  - The *absence* of collapse;
  - The *presence* of non-separability;
  - Non-uniqueness of measurement outcomes.

    Cf. Brown and Timpson (2016)

Back to λ-independence

- Without this condition, factorisable theories can display any correlation you like: e.g. any quantum correlation; e.g. maximal no-signalling correlations (Popescu-Rohrlich boxes).
- *Minimally*, to believe this condition holds, we need the choice of measurement settings *x* and y to be outside the future light cone of the preparation of the systems to be experimented on.

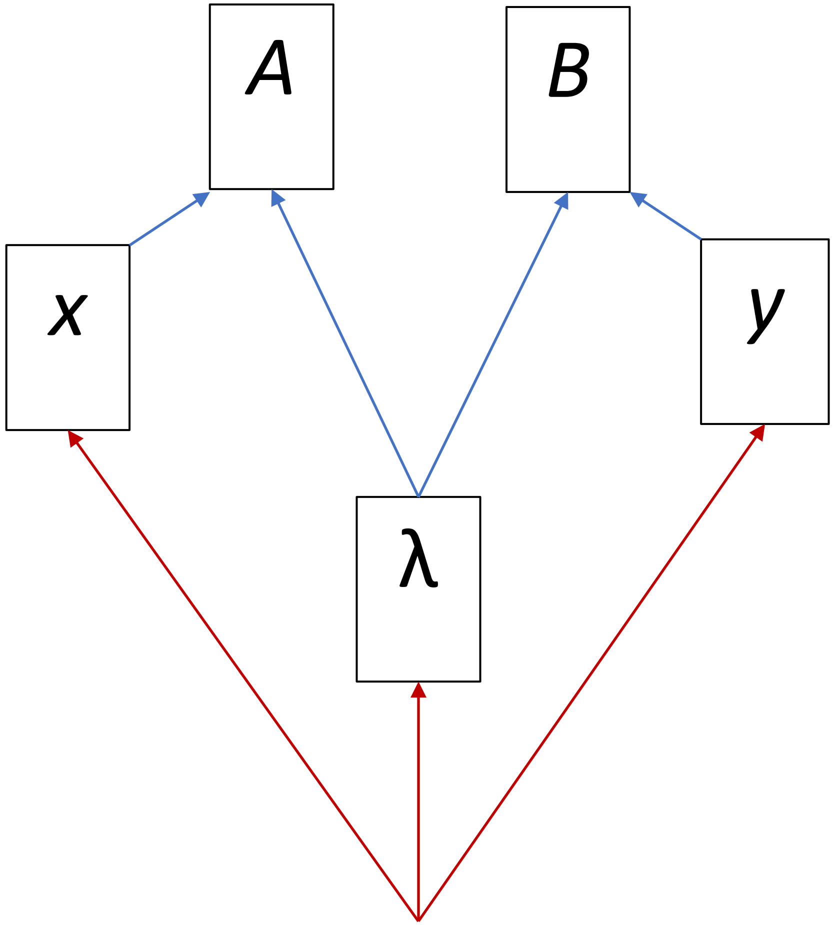




λ independence fails…

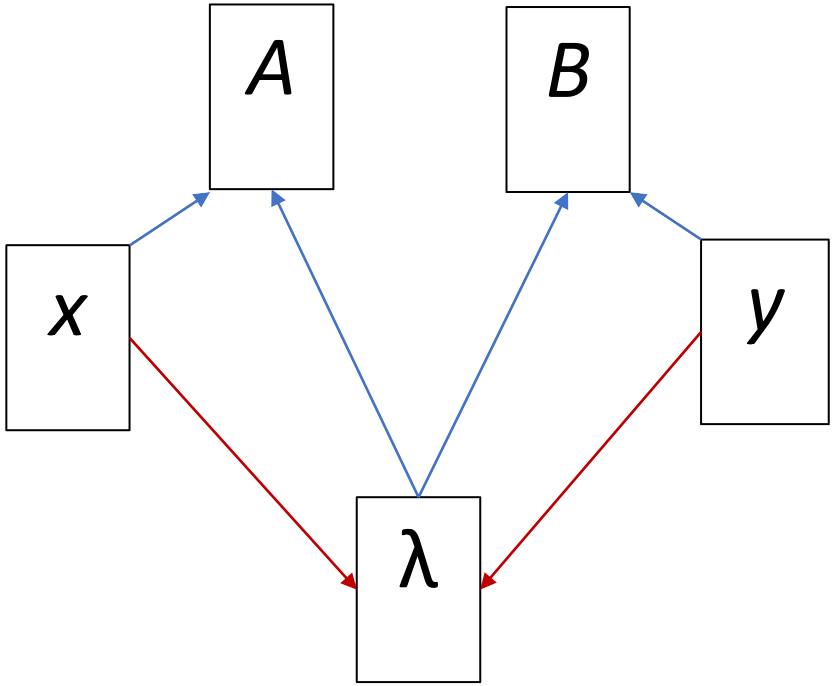
‘Superdeterminism’

- Determinism
- Conspiracy
- No common-common cause



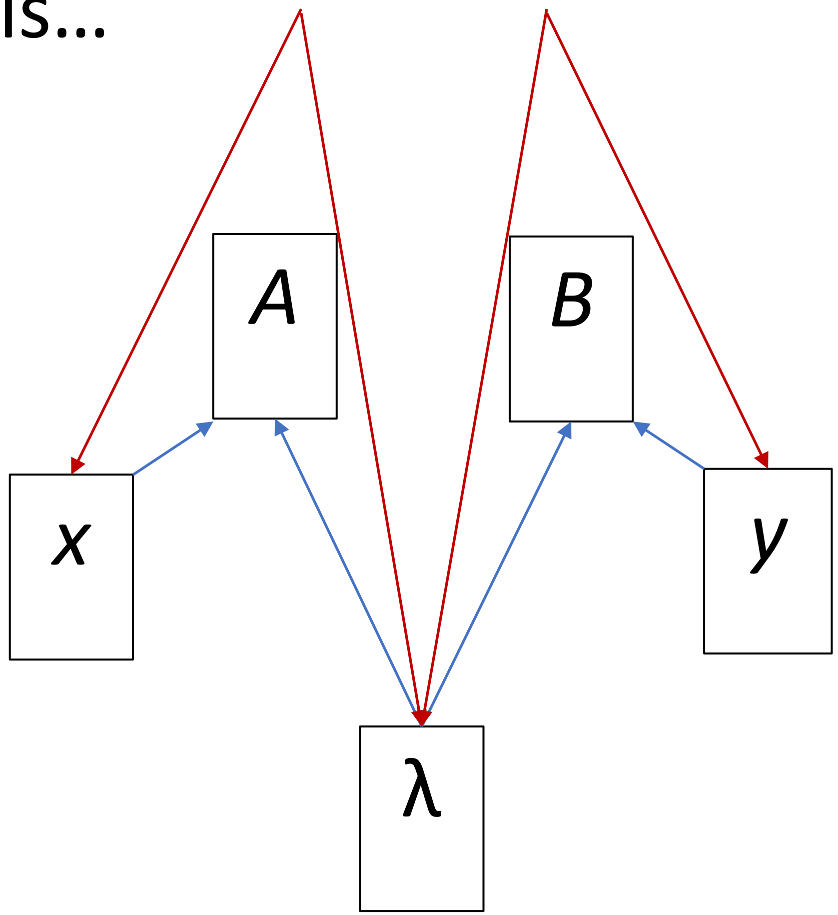
λ independence fails…

Retrocausation

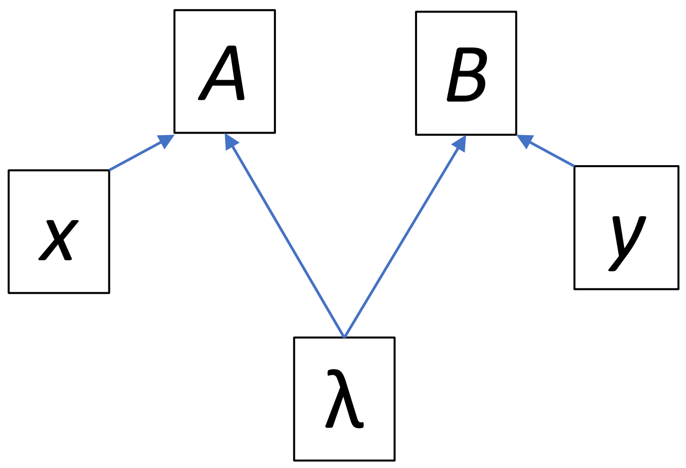


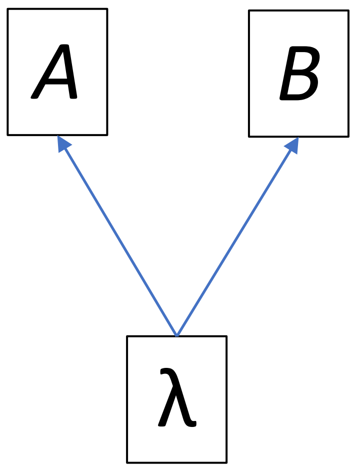
λ independence fails…

Future boundary condition



How seriously do we need to take any of these?





So why do we care?

- If we *assume* quantum theory (i.e. $\lambda=|\psi>$), then BI violation (given an experiment in standard configuration) is an *entanglement witness.*
- *If we can assume* λ-independence, then BI violation shows that the world is not locally causal (in its formal statement)
- For experiments in standard configuration, λ-independence is *highly plausible* notwithstanding retrocausation, ‘superdeterminism’ etc.
- Yet we may not have any *dynamical nonlocality* even so:
    - Less - or only partially - realist understandings of QM which embrace limited explanatory demands on physics, avoid it; as do some approaches to probability statements;
    - Everett/Many Worlds avoids it (despite being full-bloodedly realist)
        - The formal statement of local causality may not be apt for theories – like Everett’s - which are realist but fundamentally non-separable

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Open Question:

Suppose one's theory is:

1. Non-separable;
2. Dynamically local;
3. Such that it can violate a Bell inequality (even assuming lambda-independence holds);
4. Not simply an operationalist/instrumentalist theory.

Then must it also be a theory in which *uniqueness for measurement outcomes* fails?

Non Separability, and Reichenbach Redux:

- The factorisability constraint (1) is not automatically satisfactory.
- Where does it come from?
  1. The causal structure imposed by relativity;
  2. The idea from the Principle of the Common Cause that correlations should be causally explicable, either by direct causation between events, or by common cause;
  3. A Reichenbach-style probabilistic formulation of a necessary condition for something's being a common cause (screening-off)

Bell was right…

- In his informal characterisation of local causality:

  "The direct causes (and effects) are nearby, and even the indirect causes (and effects) are no further away than permitted by the velocity of light." (Bell 1990)

- And in his insistence that correlations ought to be apt for causal explanation:

  "Do we then have to fall back on 'no signalling faster than light' as the expression of the fundamental causal structure of contemporary theoretical physics? That is hard for me to accept. For one thing *we have lost the idea that correlations can be explained*, or at least this idea awaits reformulation." (Bell 1990)

But arguably he erred…

- In implementing the (attractive) core of the PCC in Reichenbachian terms.
- Thus: maintain the idea that correlations should be causally explicable, either by direct causation between events, or by common cause, but notice that:
- in *non-separable theories* there are at least **THREE**, not **TWO** routes by which correlations can be explained:
    1. Direct cause,
    2. Reichenbachian common cause (existence of a classical random variable in the past which screens-off the correlation), or
    3. Irreducible relational properties entailed by the non-separable global state.

Summary

- Differences over explanation – over what needs to be explained, and what explanatory resources are available – lie at the heart of longstanding disagreements over Bell inequality violation and nonlocality (in the sense of action-at-a-distance);
- If one is sufficiently operationalist/anti-realist, then one will not need to posit underlying causal mechanisms to account for observed correlations;
- But even full-blooded and explanatorily keen approaches – such as Everett's – need not entail dynamical nonlocality

- Everettian QM is an interesting counter-example to the idea that Bell-inequality violation entails (given lambda-independence) action-at-a-distance (dynamical nonlocality);
- It is also a counter-example showing the inadequacy of Bell’s mathematical formulation of local causality as a satisfactory locality principle, if one wishes to cover theories which may be non-separable. (*Pace* Henson 2013.)
- However, non-factorisable correlations are not (as Bell feared) doomed to be inexplicable in one’s otherwise local theory, once one recognises the significance of the role of non-separability:
    - We can keep the core idea of the PCC that correlations should be explicable either by direct cause or by common cause, but reject the restricted Reichenbachian notion of what common causes have to be like (cf. Cavalcanti and Lal 2014).