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Does time-symmetry in quantum theory imply retrocausality?

Matthew Leifer
Chapman University
Joint work with Matt Pusey (Perimeter)

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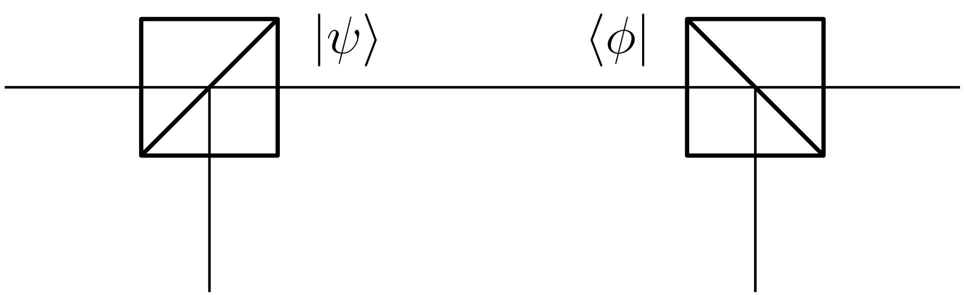
Price's Argument

- Huw Price has argued that a time-symmetric realist account of quantum theory should be retrocausal[1].
- Time symmetry in question is (a refinement of) $|\langle\phi|\psi\rangle|^2 = |\langle\psi|\phi\rangle|^2$.
- His argument is based on an experiment in which a single photon passes through two polarizing beam-splitters.



- Assuming that $|\psi\rangle$ is a beable, he argues that $|\phi\rangle$ must also be real.
- This is an assumption of the reality of the quantum state (ψ-ontology).

[1] H. Price, Stud. Hist. Phil. Mod. Phys. 43:75–83 (2012).

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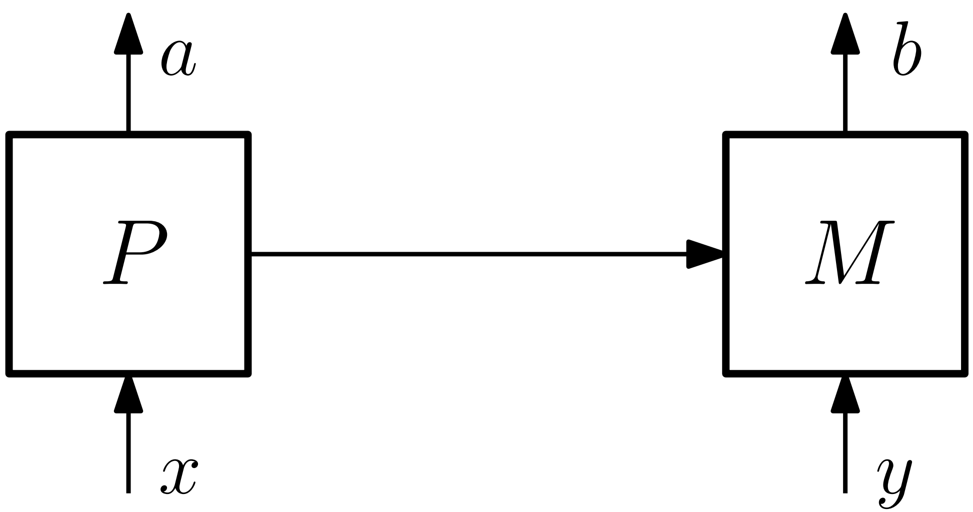
- Consider experiments involving a preparation P, followed by a measurement M in a definite time order.



- An *operational theory* consists of a set of possible *experiments* (P, M) and, for each experiment, a prediction

$$p_{PM}(a, b|x, y).$$

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- A preparation P is associated with:
  - A Hilbert space $\mathcal{H}_A$.
  - A set of subnormalized density operators $\rho_{a|x}$ on $\mathcal{H}_A$.
- A measurement M is associated with:
  - A Hilbert space $\mathcal{H}_B$.
  - A set of POVMs $E_{b|y}$ on $\mathcal{H}_B$.
- (P, M) is an experiment if $\mathcal{H}_A = \mathcal{H}_B$.
- Quantum theory then predicts:

$$p_{PM}(a, b|x, y) = \text{Tr}\left(E_{b|y}\rho_{a|x}\right).$$

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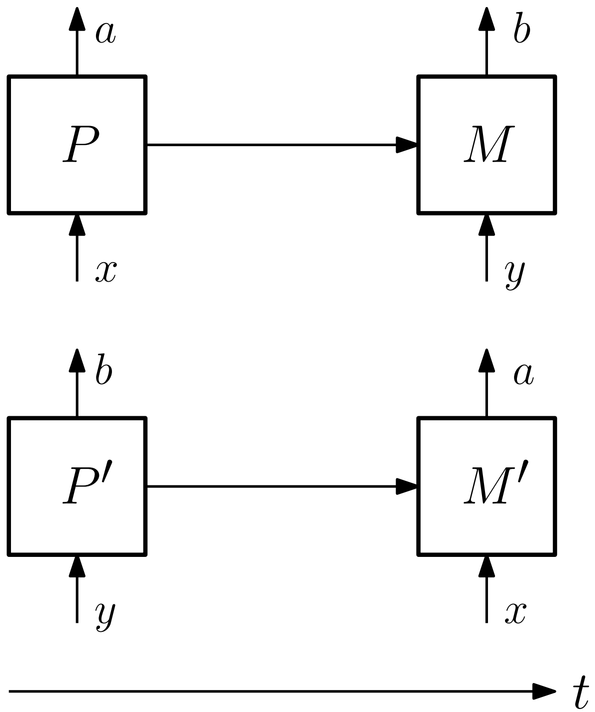
- An experiment (P, M) has an *operational time reverse* if there exists (P', M') such that

$$p_{PM}(a, b|x, y) = p_{P'M'}(b, a|y, x).$$



Operational Time Symmetry

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- A theory is *operationally time symmetric* if every experiment has an operational time reverse.
- Most operational theories are not operationally time-symmetric because we can signal into the future but not into the past.

$$p_{PM}(a|x,y) = p_{PM}(a|x,y')$$
$$p_{PM}(b|x,y) \neq p_{PM}(b|x',y)$$

- We can, however, artificially restrict attention to the *no-signaling sector* of a theory i.e. only consider experiments for which

$$p_{PM}(a|x,y) = p_{PM}(a|x,y')$$
$$p_{PM}(b|x,y) = p_{PM}(b|x',y)$$

Operational Time Symmetry: Quantum Case

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- In quantum theory, no-signaling into the future corresponds to

$$\sum_a \rho_{a|x} = \sum_a \rho_{a|x'} = \rho,$$

  i.e. x is the choice of an ensemble decomposition of a fixed density operator.

- The no-signaling sector of quantum theory is operationally time symmetric[2].

$$E_{a|x} = \rho^{-\frac{1}{2}} \rho_{a|x} \rho^{-\frac{1}{2}}$$
$$\rho_{b|y} = \rho^{\frac{1}{2}} E_{b|y} \rho^{\frac{1}{2}}$$

[2] M. Leifer and R. Spekkens, Phys. Rev. A 88:052130 (2013).

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Ontological Framework

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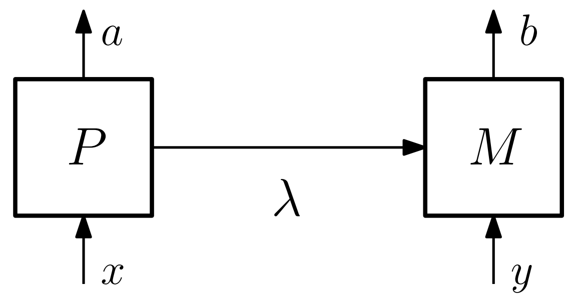
- We now assume that the system has some ontological properties between P and M, denoted by λ, known as the system's *ontic state*.



- An *ontic extension* of an experiment is a joint distribution $p_{PM}(a, b, \lambda | x, y)$ such that
$$\sum_{\lambda} p_{PM}(a, b, \lambda | x, y) = p_{PM}(a, b | x, y).$$
- A *ontic extension* of a theory is an assignment of such a distribution to every experiment.

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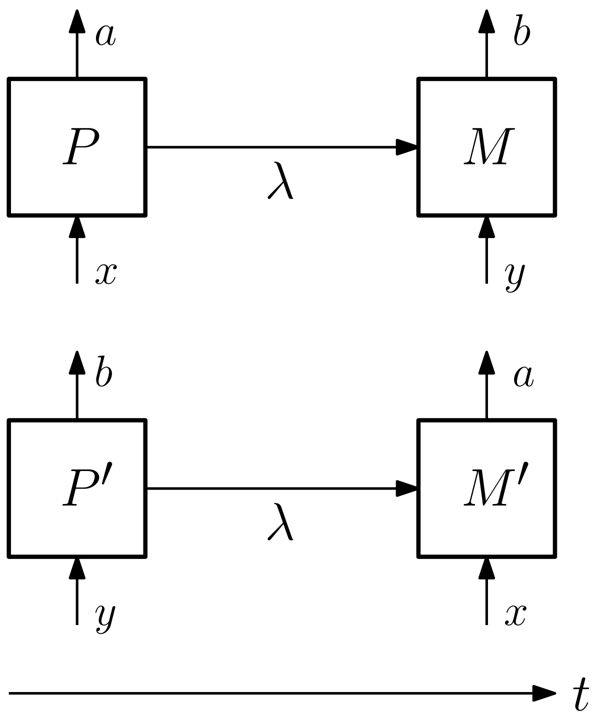
- An experiment (P, M) has an *ontological time reverse* if there exists (P', M') such that

$$p_{PM}(a, b, \lambda | x, y) = p_{P'M'}(b, a, \lambda | y, x).$$



- An ontic extension of a theory is *ontologically time symmetric* if every experiment has an ontological time reverse.

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The Time Symmetry Assumption

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- If a theory is operationally time symmetric then it should have an extension that is ontologically time symmetric.

$$p_{PM}(a, b|x, y) = p_{P'M'}(b, a|y, x)$$

$$\Rightarrow \qquad p_{PM}(a, b, \lambda|x, y) = p_{P'M'}(b, a, \lambda|y, x)$$

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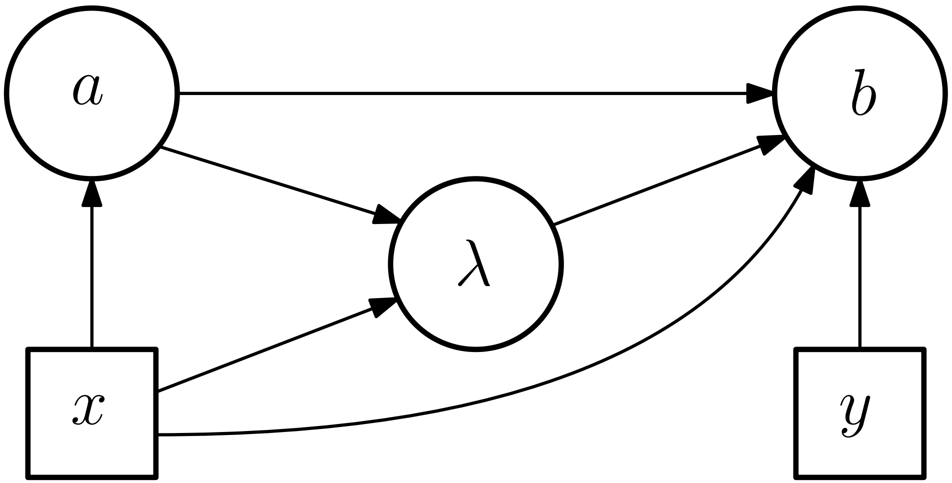
No Retrocausality

- x and y are free choices and the model has the following causal structure:



$$p(a, b, \lambda | x, y) = p(b|\lambda, a, x, y)p(\lambda|a, x)p(a|x)$$

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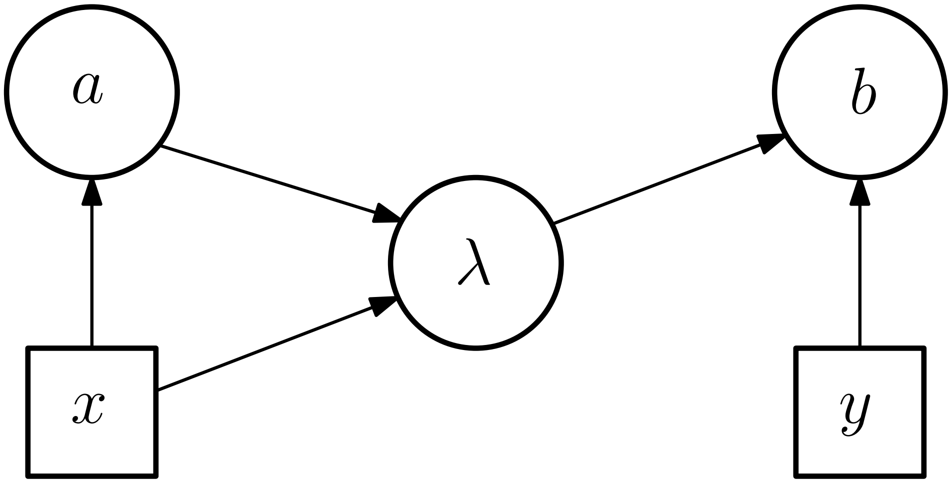
- All correlations between P and M are mediated by λ.



$$p(a, b, \lambda|x, y) = p(b|\lambda, y)p(\lambda|a, x)p(a|x)$$

- Taken together, the last two assumptions are equivalent to saying that the model is an *ontological model*[3].

[3] N. Harrigan and R. Spekkens, Found. Phys. 40:125 (2010).

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- Theorem: An ontic extension of an operationally time symmetric experiment that satisfies *Time Symmetry* and *No Retrocausality* must satisfy

$$p(\lambda|x,y) = p(\lambda)$$
$$p(a|\lambda,x,y) = p(a|\lambda,x)$$
$$p(b|\lambda,x,y) = p(b|\lambda,y).$$

If it also satisfies *λ-mediation* then,

$$p(a,b|x,y) = \sum_{\lambda} p(a|\lambda,x)p(b|\lambda,y)p(\lambda).$$

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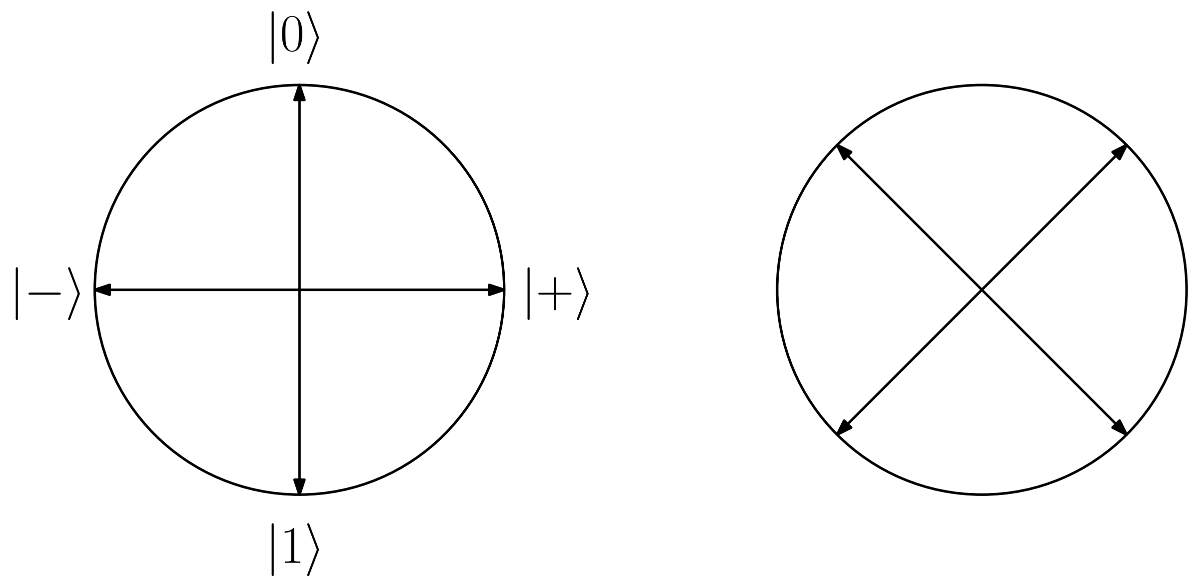
- Does quantum theory violate this for timelike experiments with no signalling into the future?
- Qubit Example:



- Prepare and measure in the optimal bases for CHSH violation, with identity dynamics in between.

Proof of $p(\lambda|x,y) = p(\lambda)$

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- By *No Retrocasality*:

$$p(a,b,\lambda|x,y) = p(b|a,\lambda,x,y)p(\lambda|a,x)p(a|x).$$

- Using Bayes' rule on $p(\lambda|a,x)$ gives:

$$p(a,b,\lambda|x,y) = p(b|a,\lambda,x,y)p(a|\lambda,x)p(\lambda|x).$$

- Sum over a and b to get: $p(\lambda|x,y) = p(\lambda|x)$.
- By *Time Symmetry*:

$$p(a,b,\lambda|x,y) = p(a|b,\lambda,x,y)p(\lambda|b,y)p(b|y).$$

- Applying the same argument gives: $p(\lambda|x,y) = p(\lambda|y)$.
- Both these conditions together imply: $p(\lambda|x,y) = p(\lambda)$.

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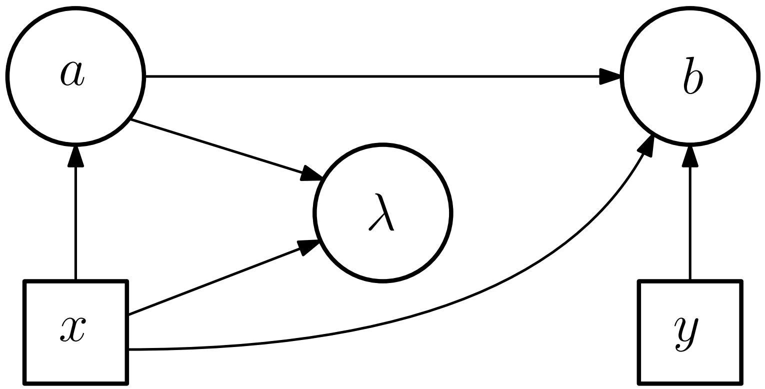
- If we drop λ-*mediation* then we still have the first part of the theorem.
- We can use the Colbeck-Renner theorem[4] to prove that there is an experiment for which we must have:

$$p(b|a, \lambda, x, y) = p(b|a, x, y)$$



- This would be a fairly pointless ontic extension.

[4] R. Colbeck and R. Renner, Nature Communications 2, 411 (2011)

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Time Symmetry

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- Qualitative notion of time symmetry: If we watch a video of a process we cannot tell whether it is playing forwards or in reverse.
- In quantum theory it matters if:
  - We really mean a video (operational time symmetry).
  - We actually mean a record of everything that exists (ontological time symmetry).
- Our principle states that if you cannot tell from a video then you cannot tell from a record.

Time Symmetry

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- Ususal notion of time symmetry: If a trajectory is *possible* in the forward direction then the time reverse of that trajectory is also *possible*.
- Our notion: If a joint probability distribution is predicted in the forward direction then there is an experiment with the same probabilities in the reverse direction.
- Our notion is violated in general due to the thermodynamic arrow of time. It would hold, for example, for a classical system in thermodynamic equilibrium.
- We do not assume that the universe satisfies our notion of time symmetry, only that if it already holds operationally then it should hold ontologically as well.

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- Spekkens' noncontextuality[5]: If two experimental procedures are operationally equivalent then they ought to be ontologically equivalent.

- More general principle: If the operational predictions of a theory have a symmetry then the ontological model ought to have the same symmetry.

- Why? Otherwise there is a fine-tuning — correlations with λ have to be just right so that marginalizing over λ washes out the asymmetry.

[5] R. Spekkens, Phys. Rev. A 71:052108 (2005).

No Retrocausality

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- No-Retrocausality is a common assumption in all no-go theorems. However, the symmetry of the argument is designed to make it the most plausible assumption to give up here.

- However, allowing retrocausality also gives rise to a fine tuning: If there are influences that travel backwards in time then why can't they be used to signal?

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- There is no model of quantum theory in our framework that satisfies our time symmetry assumption, has no retrocausality, and has ontic states mediate the correlations.

- Whether we give up time symmetry or no-retrocausality, there is a fine-tuning in the theory. How should we respond to fine-tunings?

  1. Accept them as brute facts.
  2. Look for a theory that does not have them.
  3. Explain them as emergent (c.f. thermalization).

- 2 or 3 seem preferable, but note that there might be other grounds for preferring theories where certain symmetries (e.g. time-symmetry or Lorentz invariance) are fundamental.

- It does not seem completely implausible that the same processes that are responsible for the thermodynamic arrow of time might explain why retrocausality does not lead to signalling.