Title: Does time-symmetry in quantum theory imply retrocausality?

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Abstract: The two-state vector formalism of Aharonov and collaborators introduces a backwards-evolving state in order to restore time symmetry to quantum measurement theory. The question then arises, does any time-symmetric account of quantum theory necessarily involve retrocausality (influences that travel backwards in time)? In [1], Huw Price argued that, under certain assumptions about the underlying ontology, an interpretation of quantum theory that is both realist and time-symmetric must be retrocausal. Priceâ€™s argument is based on an analysis of a photon travelling between two polarizing beam-splitters. One of his assumptions is that the usual forward-evolving polarization vector of the photon is a beable, i.e. part of the ontology. He argues, on the basis of this and his other assumptions, that a backward-evolving polarization vector must also be a beable.

The assumption that the forward evolving polarization vector is a beable is an assumption of the reality of the quantum state. But one of the reasons for exploring retrocausal interpretations of quantum theory is that they offer the potential for evading the unpleasant conclusions of no-go theorems, such as Bellâ€™s theorem and, in particular, recent proofs of the reality of the quantum state [2]. In this talk, I will show how Priceâ€™s argument can, in fact, be generalized so that it does not assume the reality of the quantum state. I also reformulate the common assumptions of Priceâ€™s and our arguments to make them more generally applicable and to pin down the notion of time-symmetry involved more precisely. The notion of time-symmetry used in the argument is stronger than the notion of time-symmetry usually used in physics, but is still a true symmetry of quantum theory that ought to be taken seriously.

This talk is based on joint work with Matt Pusey.

[1] H. Price. Does time-symmetry imply retrocausality? How the quantum world says â€œmaybeâ€•. Stud. Hist. Phil. Mod. Phys., 43(2):75â€“83, 2012. arXiv:1002.0906

[2] For a review see M. Leifer. Is the quantum state real? An extended review of psi-ontology theorems. Quanta, 3:67-155, 2014. arXiv:1409.1570

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Does time-symmetry in quantum theory imply retrocausality?

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Joint work with Matt Pusey (Perimeter)

June 22, 2016

Collapse and Time-Symmetry

- Is the collapse of the wavefunction ia fundamental time-asymmetry?
- Yakir showed[1] that we can restore time-symmetry by introducing a backwards evolving state that depends on a future measurement choice in addition to the usual forwards evolving state-vector.

$$p(a|\psi, \phi) = \frac{|\langle\phi| P_a |\psi\rangle|^2}{\sum_{a'} |\langle\phi| P_{a'} |\psi\rangle|^2}.$$

- Does this mean we have to accept that there is retrocausality in nature if we want time-symmetry?
- Huw Price has argued that a time-symmetric realist account of quantum theory should be retrocausal[2], but his argument assumes that quantum states are real.

[1] Y. Aharonov, P. Bergmann and J. Lebowitz, Phys. Rev. B 134, 141016 (1964).
[2] H. Price, Stud. Hist. Phil. Mod. Phys. 43:75–83 (2012).

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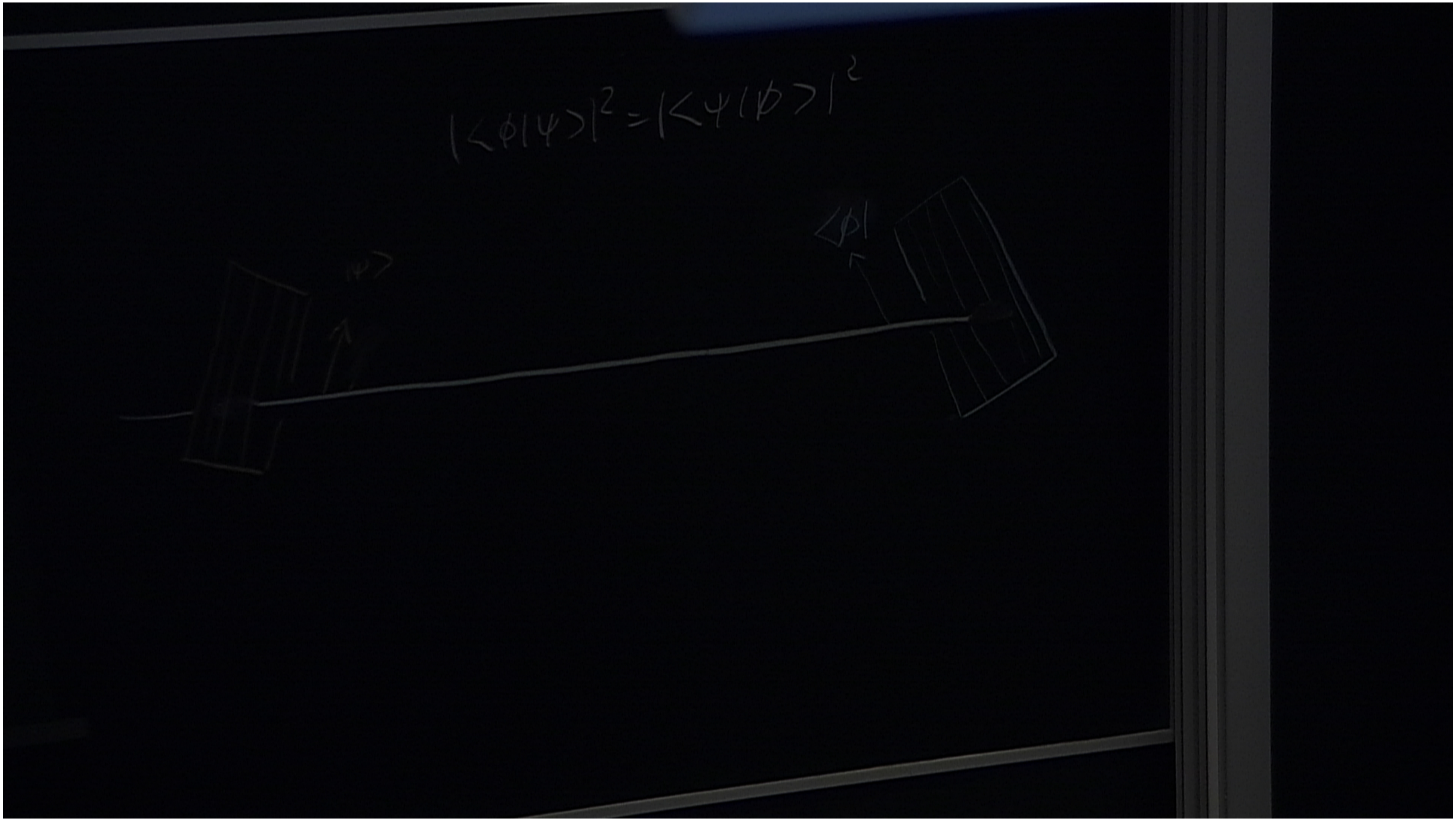
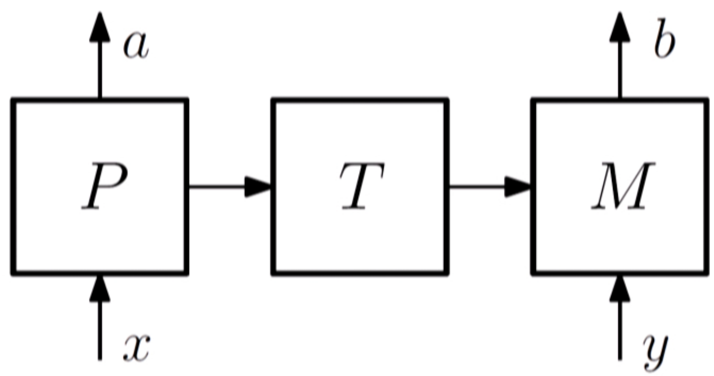

$|\langle\phi|\psi\rangle|^2 = |\langle\psi|\phi\rangle|^2$
$|\psi\rangle$
$\langle\phi|$

PTM Experiments

- Consider experiments involving a preparation P, a transformation T, and a measurement M in a definite time order.



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

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

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Example: Quantum Experiments

- A preparation P is associated with:
  - A Hilbert space $\mathcal{H}_A$.
  - A set of subnormalized density operators $\rho_{aA|x}$ on $\mathcal{H}_A$.
- A transformation T is associated with:
  - An input Hilbert space $\mathcal{H}_{\text{in}}$ and an output Hilbert space $\mathcal{H}_{\text{out}}$.
  - A Completely-Positive, Trace-Preserving map $\mathcal{E}_{\text{out}|\text{in}}$ from the density operators on $\mathcal{H}_{\text{in}}$ to the density operators on $\mathcal{H}_{\text{out}}$.
- A measurement M is associated with:
  - A Hilbert space $\mathcal{H}_B$.
  - A set of POVMs $E_{b|yB}$ on $\mathcal{H}_B$.
- (P, T, M) is an experiment if $\mathcal{H}_{\text{in}} = \mathcal{H}_A$ and $\mathcal{H}_{\text{out}} = \mathcal{H}_B$
- Quantum theory then predicts:

$$p_{PTM}(a, b|x, y) = \mathrm{Tr}\left(E_{b|yB}\mathcal{E}_{B|A}\left(\rho_{aA|x}\right)\right).$$

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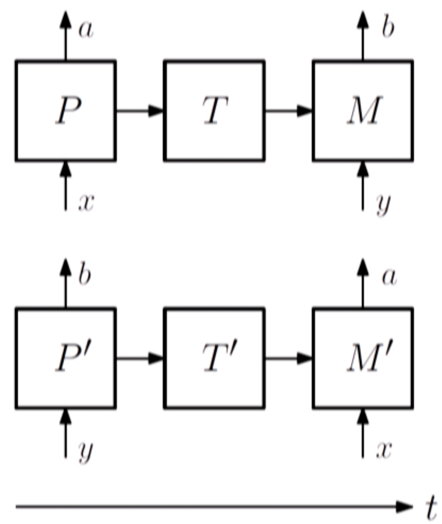
Operational Time Symmetry

- An experiment (P, T, M) has an *operational time reverse* if there exists P', T', M' such that

$$p_{PTM}(a, b|x, y) = p_{P'T'M'}(b, a|y, x).$$



Operational Time Symmetry

- 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.

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

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

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

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Operational Time Symmetry: Quantum Case

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

$$\sum_a \rho_{aA|x} = \sum_a \rho_{aA|x'} = \rho_A,$$

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[3].

$$\begin{aligned} E_{a|xA} &= \rho_A^{-\frac{1}{2}} \rho_{aA|x} \rho_A^{-\frac{1}{2}} \\ \rho_B &= \mathcal{E}_{B|A}(\rho_A) \\ \rho_{bB|y} &= \rho_B^{\frac{1}{2}} E_{b|yB} \rho_B^{\frac{1}{2}} \\ \mathcal{E}_{A|B}(\cdot) &= \rho_A^{\frac{1}{2}} \mathcal{E}^{\dagger}_{B|A} \left(\rho_B^{-\frac{1}{2}} (\cdot) \rho_B^{-\frac{1}{2}} \right) \rho_A^{\frac{1}{2}}. \end{aligned}$$

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

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Ontological Framework

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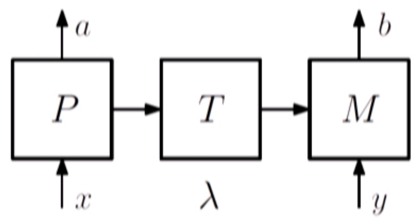
Ontic Extensions

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

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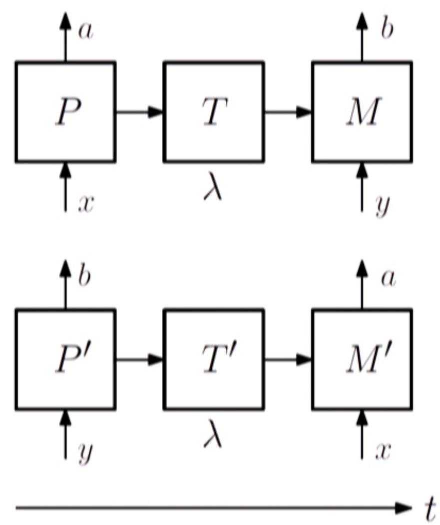
Ontological Time Symmetry

- An experiment (P, T, M) has an *ontological time reverse* if there exists P', T', and M' such that

$$p_{PTM}(a, b, \lambda | x, y) = p_{P'T'M'}(b, a, \lambda | y, x).$$



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

Our Assumptions

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The Time Symmetry Assumption

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

$$p_{PTM}(a,b|x,y) = p_{P'T'M'}(b,a|y,x)$$

$$\Rightarrow \quad p_{PTM}(a,b,\lambda|x,y) = p_{P'T'M'}(b,a,\lambda|y,x)$$

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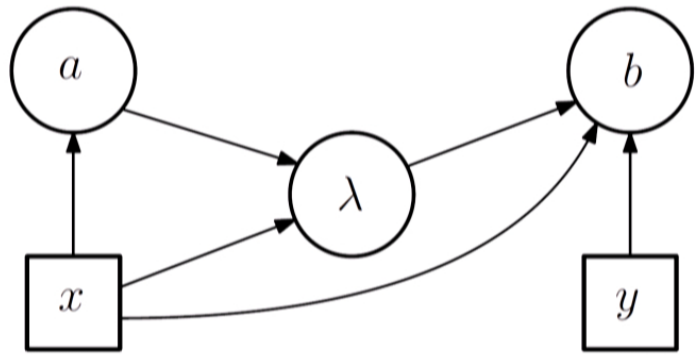

$$p(a,b,\lambda|x,y) = p(b|\lambda,x,y)p(\lambda|a,x)p(a|x)$$

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Main Results

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Main Theorem

- 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 *Weak λ-mediation* then,

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

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

- 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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Main Theorem

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

$$
\begin{aligned}
p(\lambda|x, y) &= p(\lambda) \\
p(a|\lambda, x, y) &= p(a|\lambda, x) \\
p(b|\lambda, x, y) &= p(b|\lambda, y).
\end{aligned}
$$

If it also satisfies *Weak λ-mediation* then,

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

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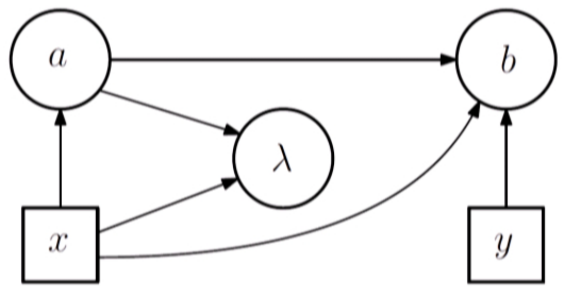
Colbeck-Renner

- If we drop *Weak λ-mediation* then we still have the first part of the theorem.
- We can use the Colbeck-Renner theorem[5] 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.

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

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