Reflections on the PBR Theorem:

Reality Criteria & Preparation Independence

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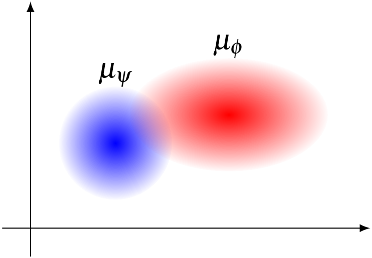
The Quantum State ψ — Real or Phenomenal?

- Assume some space Λ of *ontic states*
- Preparation of *quantum states* $\psi, \phi \in \mathscr{H}$ induce probability distributions μ_ψ, μ_ϕ over Λ, etc.



- If distributions can overlap $\rightarrow$ ψ-epistemic
- If distributions never overlap $\rightarrow$
  Each $\lambda \in \Lambda$ encodes a *unique* quantum state, so ψ-ontic

Harrigan & Spekkens, arXiv:0706.2661 [quant-ph]

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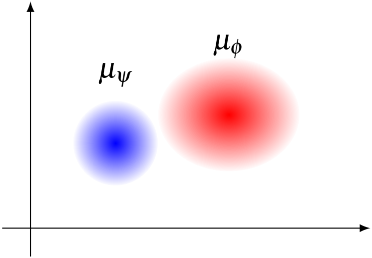

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The PBR Theorem*

The following assumptions

1. systems have an objective physical state
2. quantum predictions are correct
3. *preparation independence*

imply ψ-ontic.

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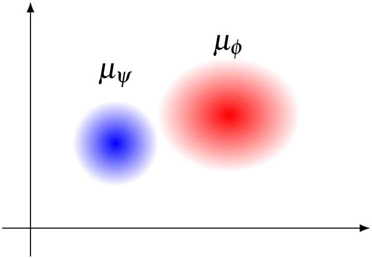

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Preparation Independence

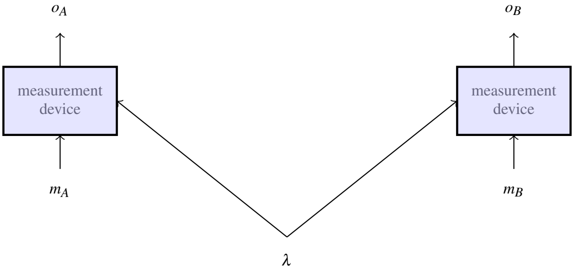
$$\mu(\lambda_A, \lambda_B \mid p_A, p_B) = \mu(\lambda_A \mid p_A) \times \mu(\lambda_B \mid p_B)$$

Causes for suspicion:

- Bell's Theorem becomes trivial (Proceedings)
- Gives rise to alarmingly strong No-Go results*
- Motivated by *local causality* (on shaky ground since Bell)

*Schlosshauer & Fine, arXiv:1306.5805 [quant-ph]

Comparison with Bell Locality



$$p(o_A, o_B \mid m_A, m_B, \lambda) = p(o_A \mid m_A, \lambda) \times p(o_A \mid m_B, \lambda)$$

Ruled out by Bell's Theorem

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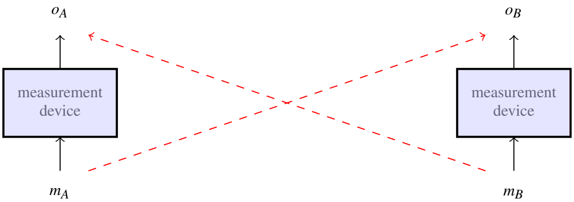
No-signalling

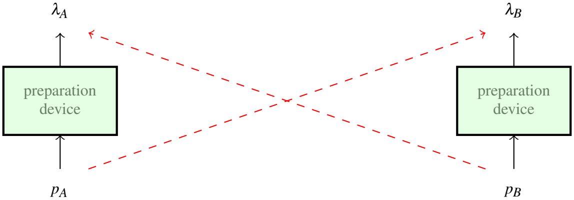


$$p(o_A \mid m_A, m_B) = p(o_A \mid m_A)$$

$$p(o_B \mid m_A, m_B) = p(o_B \mid m_B)$$

An Alternative to Preparation Independence

No-preparation-signalling



$$\mu(\lambda_A \mid p_A, p_B) = \mu(\lambda_A \mid p_A)$$

$$\mu(\lambda_B \mid p_A, p_B) = \mu(\lambda_B \mid p_B)$$

- Preparation Independence $\Longrightarrow$ No-preparation-signalling

Escaping PBR's Conclusion

- Replace *prep. independence* with *no-preparation-signalling*
- Detailed discussion of where PBR argument breaks down (Proceedings)
- A ψ-epistemic model realising PBR statistics:

Define $\mu_{00}, \mu_{0+}, \mu_{+0}, \mu_{++}$ by the table below and measurement response functions as on the right

			System 2			
			$\lvert 0\rangle$		$\lvert +\rangle$	
			λ_δ	λ_0	λ_δ	λ_+
System 1	$\lvert 0\rangle$	λ_δ	0	$1/4$	0	$1/4$
		λ_0	$1/4$	$1/2$	$1/4$	$1/2$
	$\lvert +\rangle$	λ_δ	0	$1/4$	0	$1/4$
		λ_+	$1/4$	$1/2$	$1/4$	$1/2$

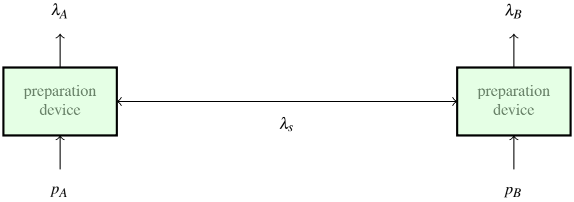
$$\xi_1(\lambda) := \begin{cases} 1/4 & \text{if } \lambda \in \{(\lambda_\delta,\lambda_0),(\lambda_\delta,\lambda_+),(\lambda_0,\lambda_\delta),(\lambda_+,\lambda_\delta)\} \\ 1 & \text{if } \lambda = (\lambda_+,\lambda_+) \\ 0 & \text{otherwise} \end{cases}$$

$$\xi_2(\lambda) := \begin{cases} 1/4 & \text{if } \lambda \in \{(\lambda_\delta,\lambda_0),(\lambda_\delta,\lambda_+),(\lambda_0,\lambda_\delta),(\lambda_+,\lambda_\delta)\} \\ 1 & \text{if } \lambda = (\lambda_+,\lambda_0) \\ 0 & \text{otherwise} \end{cases}$$

$$\xi_3(\lambda) := \begin{cases} 1/4 & \text{if } \lambda \in \{(\lambda_\delta,\lambda_0),(\lambda_\delta,\lambda_+),(\lambda_0,\lambda_\delta),(\lambda_+,\lambda_\delta)\} \\ 1 & \text{if } \lambda = (\lambda_0,\lambda_+) \\ 0 & \text{otherwise} \end{cases}$$

$$\xi_4(\lambda) := \begin{cases} 1/4 & \text{if } \lambda \in \{(\lambda_\delta,\lambda_0),(\lambda_\delta,\lambda_+),(\lambda_0,\lambda_\delta),(\lambda_+,\lambda_\delta)\} \\ 1 & \text{if } \lambda = (\lambda_+,\lambda_+) \\ 0 & \text{otherwise} \end{cases}$$

A Similar Proposal*



$$\int_{\Lambda_s} d\lambda_s \quad \mu(\lambda_A, \lambda_B, \lambda_s \,|\, p_A, p_B) = \mu(\lambda_A \,|\, p_A) \times \mu(\lambda_B \,|\, p_B)$$

Drawbacks:

- λ_s-dependence
- Harder to motivate physically
- Implies no-preparation-signalling

*Emerson, Serbin, Sutherland & Veitch, arXiv:1312.1345 [quant-ph]

Conclusion

Preparation Independence

- An intuition of independence that was invalidated by Bell
- Alarmingly strong no-go results, Bell is trivialised

No-preparation-signalling

- Rules out superluminal *signalling*
- PBR argument no longer holds
- ψ-epistemic interpretation still valid

Proceedings

What if μ_ψ, μ_ϕ overlap on sets of measure zero?

- Dualise to avoid this!

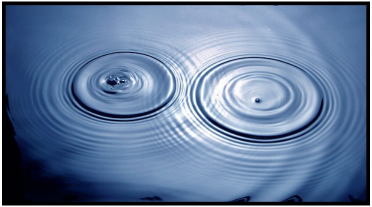
What if ontic/epistemic definitions are applied to things other than ψ?

- *Observable properties* are ontic $\Longleftrightarrow$
  Correlations are *local/non-contextual*

Appendix: The Quantum State ψ — Real or Phenomenal?

ψ-ontic:

- A real physical wave (on configuration space?)
- Easiest way to think about interference
- PBR theorem



ψ-epistemic:

- ψ gives probabilistic information
- Collapse $\rightarrow$ Bayesian updating

- Can't reliably distinguish non-orthogonal ψ, ϕ
- ψ is exponential in the number of systems
- Can't be cloned
- Can be teleported