Constraints on Macrorealism Without Non-Invasive Measurability

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Ronnie Hermens

OxfordMaterials

Outline

1. The Leggett-Garg Inequality

   Macrorealism + Noninvasive Measurability

2. New types of Macrorealism:

   Eigenpreparation Support vs Eigenpreparation Undermining

   Quantum mechanics must be Eigenpreparation Undermining

3. Noise-tolerant definition:

   (α, β)-Support

   Quantum Mechanics poses restrictions on (α, β)

Legget & Garg (1985)

MR: "Macroscopic realism: A macroscopic system with two or more macroscopically distinct states available to it will at all times be in one or the other of these states."

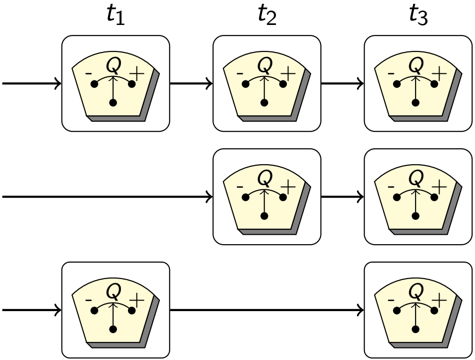
$\rightsquigarrow$ Some observable Q has a definite value at all times.

NIM: "Noninvasive measurability at the macroscopic level: It is possible, in principle, to determine the state of the system with arbitrarily small perturbation on its subsequent dynamics."

$\rightsquigarrow$ There are Q-measurements that do not alter the state of the system.

$$\mathbf{MR} \wedge \mathbf{NIM} \wedge \mathbf{QM} \implies \perp$$

The Leggett-Garg Inequality 2/2



t_1	t_2	t_3	
-1	-1	-1	3
-1	-1	1	-1
-1	1	-1	-1
1	-1	-1	-1
-1	1	1	-1
1	-1	1	-1
1	1	-1	-1
1	1	1	3

MR: $-1 \leq \langle Q_1 Q_2 \rangle_{123} + \langle Q_2 Q_3 \rangle_{123} + \langle Q_1 Q_3 \rangle_{123} \leq 3,$

NIM: $-1 \leq \langle Q_1 Q_2 \rangle_{123} + \langle Q_2 Q_3 \rangle_{23} + \langle Q_1 Q_3 \rangle_{13} \leq 3.$

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Disposing NIM

Eigenstate-Eigenvalue Link

Observable A has a definite value $\iff$
The system is in an eigenstate for A.

MR $\wedge$ E-E Link $\implies$ Superselection Rule

There are no superpositions for the macro-observable Q.

Nature, while known to tolerate linear superpositions at the atomic level, cannot tolerate quantum superpositions of macroscopically distinct states – Leggett 1988

MR $\wedge$ E-E Link $\wedge$ QM $\implies \perp$

- Very strong assumption
- Relies heavily on formalism of quantum mechanics

Operational Models and Ontic Models

Operational model $(\mathcal{P}, \mathcal{T}, \mathcal{M})$

		$P \in \mathcal{P}$	*is a preparation,*
$T \in \mathcal{T}$	*is a transformation,*	$M \in \mathcal{M}$	*is a measurment,*

$\mathbb{P}(m|M,T,P)$ *probability of outcome m for measurement M performed on a system prepared according to P and transformed according to T.*

Ontic model $(\Lambda, \Pi, \Gamma, \Xi)$

$\lambda \in \Lambda$	*is an ontic state,*	$\mu \in \Pi$	*is a probability measure,*
$\gamma \in \Gamma$	*is a Markov kernel from* Λ *to* Λ	$\xi \in \Xi$	*is a Markov kernel from* Λ *to* Ω_ξ*.*

$\forall (P,T,M)$ *there exists* (μ_P, γ_T, ξ_M) *such that*

$$\mathbb{P}(m|M,T,P) = \int_\Lambda \int_\Lambda \xi_M(m|\lambda')\gamma_T(\,\mathrm{d}\lambda'|\lambda)\,\mathrm{d}\mu_P(\lambda).$$

Generalizing the E-E Link

Eigenstate-Eigenvalue Link

Observable A has a definite value $\iff$
The system is in an eigenstate for A.

- Eigenstate $\mapsto$ Eigenpreparation: $\mathbb{P}(q|Q, P_q) = 1$.
- Superselection rule $\mapsto$ all preparations are convex combinations of eigenpreparations.
- MR $\wedge$ QM $\implies$ Superpositions introduce novel preparations.
- Do they also introduce novel ontic states?

Generalized Eigenstate-Eigenvalue Link

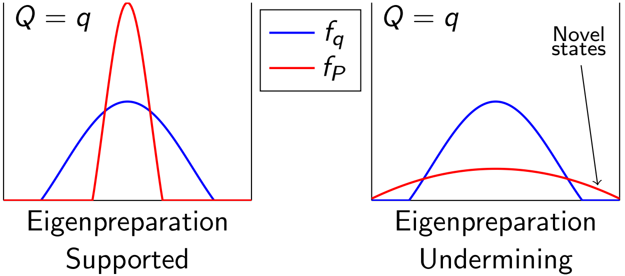
Observable A has a definite value $\iff$
The system is in an ontic state in the support of an eigenpreparation for A.

Eigenpreparation Support vs Eigenpreparation Undermining

- Superpositions introduce novel preparations.
- Do they also introduce novel ontic states?

Generalized Eigenstate-Eigenvalue Link

Observable A has a definite value $\iff$
The system is in an ontic state in the support of an eigenpreparation for A.

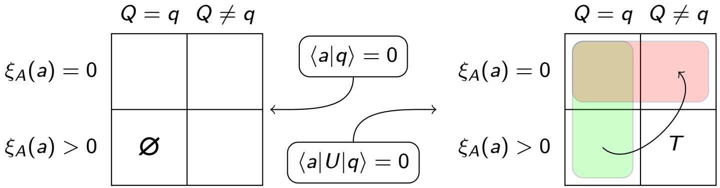


Maroney & Timspon (2016) arXiv:1412.6139

Quantum Mechanics is Eigenpreparation Undermining

Eigenpreparation support $\implies$ All ontic states behave like eigenpreparations:

- $\mathbb{P}(a|A, P_q) = 0$, then $\mathbb{P}(a|A, P) \leq 1 - \mathbb{P}(q|Q, P)\ \forall P$.
- $\mathbb{P}(a|A, T, P_q) = 0$, then $\mathbb{P}(a|A, T, P) \leq 1 - \mathbb{P}(q|Q, P)\ \forall P$.



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Theorem

Q and A 3-valued observables, Q a macro-observale, eigenpreparation support, and

$$\mathbb{P}(a_2|A, P_{q_1}) = \mathbb{P}(a_3|A, T, P_{q_1}) = \mathbb{P}(q_3|Q, T, P_{q_1}) = 0,$$

then for every P

$$\mathbb{P}(q_1|Q, P) - \mathbb{P}(q_2|Q, T, P) - \mathbb{P}(a_1|A, T, P) \leq 0.$$

$$\textbf{MR} \wedge \textbf{ESupp} \wedge \textbf{QM} \implies \perp$$

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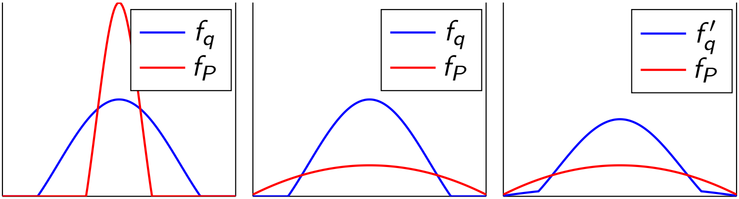
The Problem with Noise 1/2

The distinction between Eigenpreparation Supported and Eigenpreparation Undermining models is not noise-tolerant.



Eigenpreparation Supported | Eigenpreparation Undermining | Eigenpreparation Supported

$$f'_q := (1-\epsilon) f_q + \frac{\epsilon}{\mathbb{P}(q|Q,P)} f_P$$

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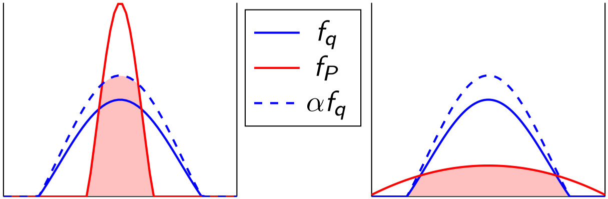
then for every P

$$\mathbb{P}(q_1|Q, P) - \mathbb{P}(q_2|Q, T, P) - \mathbb{P}(a_1|A, T, P) \leq 0.$$

Not Noise-Tolerant

(α, β)-Support



Eigenpreparation Support: $\exists \alpha$ s.t. $\int \min(f_P, \alpha f_q)\, \mathrm{d}\lambda = \mathbb{P}(q|Q,P)$

(α, β)-Support: $\beta + \int \min(f_P, \alpha f_q)\, \mathrm{d}\lambda \geq \mathbb{P}(q|Q,P)$

- Eigenpreparation Support $\iff \beta = 0$,
- (α, β)-Support trivial for $\beta = 1$.

Noise-Tolerant Constraint on Macrorealism

Theorem

Q and A 3-valued observables, Q a macro-observale, eigenpreparation support, and

$$\mathbb{P}(a_2|A, P_{q_1}) = \mathbb{P}(a_3|A, T, P_{q_1}) = \mathbb{P}(q_3|Q, T, P_{q_1}) = 0,$$

then for every P

$$\mathbb{P}(q_1|Q, P) - \mathbb{P}(q_2|Q, T, P) - \mathbb{P}(a_1|A, T, P) \leq 0.$$

Theorem

Q and A 3-valued observables, Q a macro-observale, (α, β)-support, then for every P

$$\mathbb{P}(q_1|Q, P) - \mathbb{P}(q_2|Q, T, P) - \mathbb{P}(a_1|A, T, P) \leq \alpha\left(\mathbb{P}(a_2|A, P_{q_1}) + \mathbb{P}(a_3|A, T, P_{q_1}) + \mathbb{P}(q_3|Q, T, P_{q_1})\right) + 2\beta.$$