Title: Exploring alternatives to quantum nonlocality

Speakers: Indrajit Sen

Series: Quantum Foundations

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Abstract: In recent years, it has become increasingly well-known that nearly all the major no-go theorems in quantum foundations can be circumvented by violating a single assumption: the hidden variables (that determine the outcomes) are uncorrelated with the measurement settings. A hidden-variable theory that violates this assumption can be local, separable, non-contextual and have an epistemic quantum state. Such a theory would be particularly well-suited to relativistic contexts. Are such theories actually feasible? In this talk, we discuss some results on the two physical options to violate this assumption: superdeterminism and retrocausality.

Developing an intuitive criticism by Bell, we show that superdeterministic models are conspiratorial in a mathematically well-defined sense in two separate ways. In the first approach, we use the concept of quantum nonequilibrium to show that superdeterministic models require finetuning so that the measurement statistics do not depend on the details of how the measurement settings are chosen. In the second approach, we show (without using quantum non-equilibrium) that an arbitrarily large amount of superdeterministic correlation is needed for such models to be consistent. Along the way, we discuss an apparent paradox involving nonlocal signalling in a local superdeterministic model.

Next, we use retrocausality to build a local, separable, psi-epistemic hidden-variable model of Bell correlations with pilot-waves in physical space. We generalise the model to describe a relativistic Bell scenario where one of the wings experiences time-dilation effects. We show, by discussing the difficulties faced by other hidden-variable approaches in describing this scenario, that the relativistic properties of the model play an important role here (otherwise ornamental in the standard Bell scenario). We also discuss the technical difficulties in applying quantum field theory to recover the model's predictions.

Exploring alternatives to quantum nonlocality

Indrajit Sen

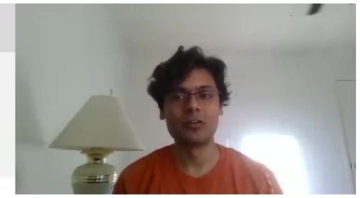
Clemson University

December 9, 2020

Prelude

"..quantum theory would... take an approximately analogous position to the statistical mechanics within the framework of classical mechanics. I am rather firmly convinced that the development of theoretical physics will be of this type; but the path will be lengthy and difficult." – *A. Einstein*[1]

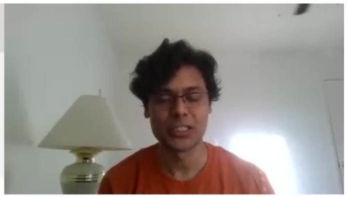
[1] A. Einstein, *Albert Einstein: philosopher-scientist*, section "Reply to criticisms", page 672, Library of Living Philosophers, Chicago, USA, **1949**.



Prelude

"...quantum theory would... take an approximately analogous position to the statistical mechanics within the framework of classical mechanics. I am rather firmly convinced that the development of theoretical physics will be of this type; but the path will be lengthy and difficult." – A. Einstein[1]

Nonlocality, nonseparability, preferred foliation of spacetime, no-signalling, noncontextuality, ψ-onticity, exponential complexity of state space...



The assumption

$$p(k|\psi, M) = \int p(k, \lambda|\psi, M) d\lambda = \int d\lambda p(k|\psi, M, \lambda) \rho(\lambda|\psi, M)$$

The assumption

measurement outcome → k ; measurement setting → M

$$p(k|\psi, M) = \int p(k, \lambda|\psi, M) d\lambda = \int d\lambda \, p(k|\psi, M, \lambda) \rho(\lambda|\psi, M)$$

The assumption

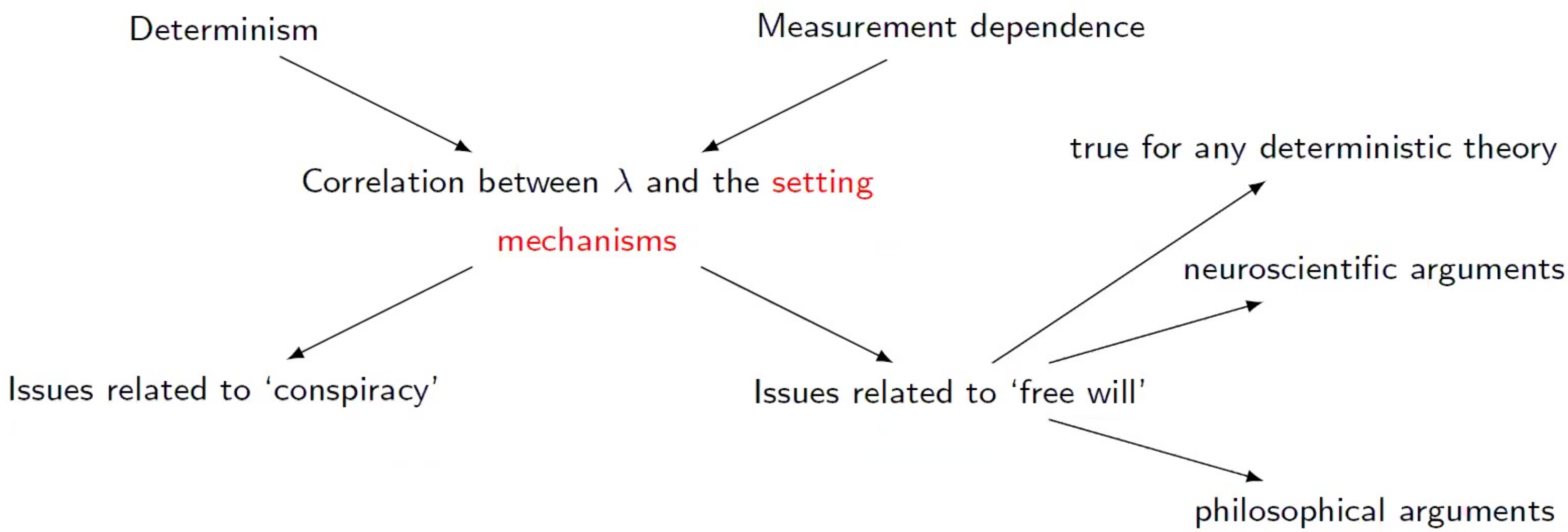
measurement outcome → k measurement setting → M

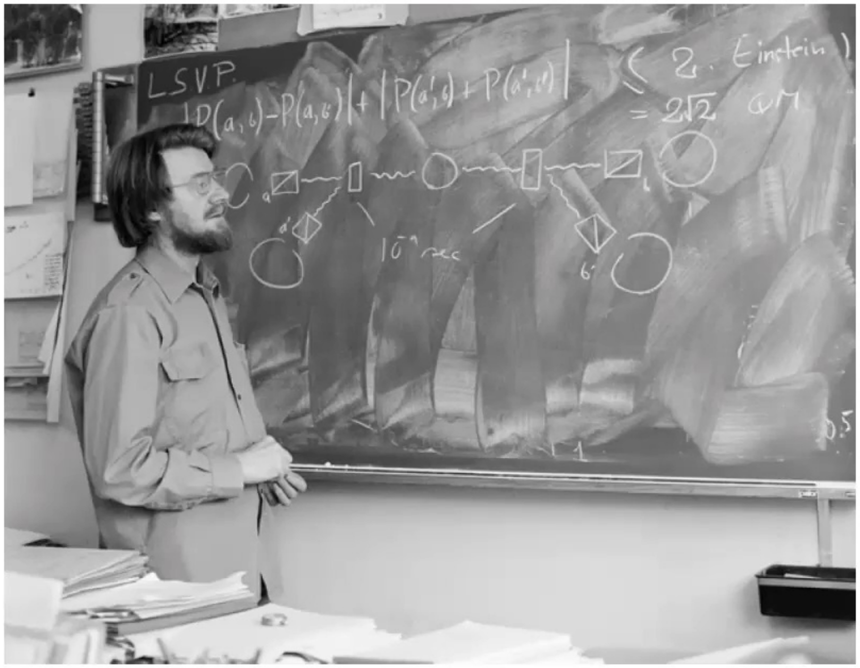
$$p(k|\psi, M) = \int p(k, \lambda|\psi, M) d\lambda = \int d\lambda p(k|\psi, M, \lambda)\rho(\lambda|\psi, M)$$

$$\text{M.I: } \rho(\lambda|\psi, M) = \rho(\lambda|\psi, M').$$

Assumed in nearly all the major no-go theorems in quantum foundations.

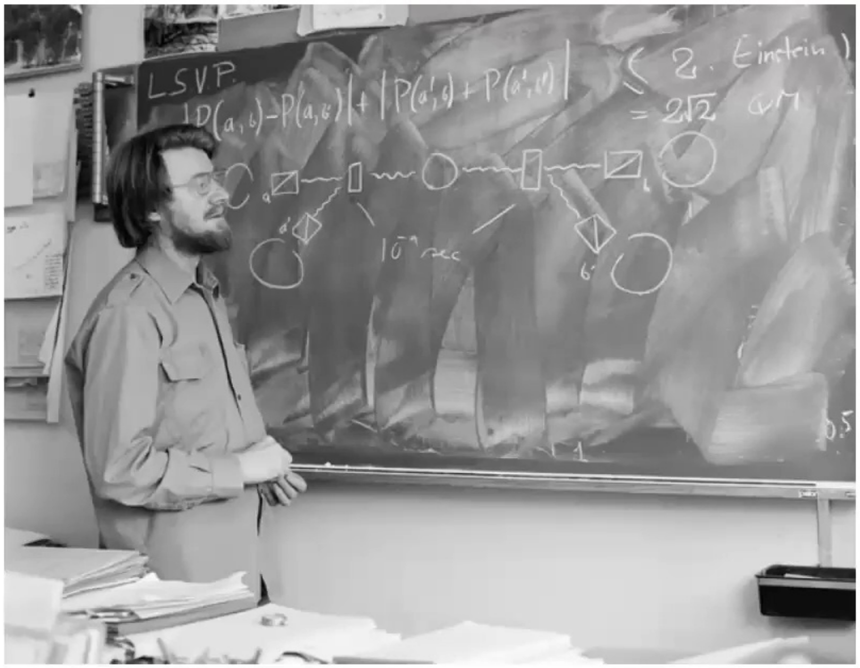
Superdeterminism





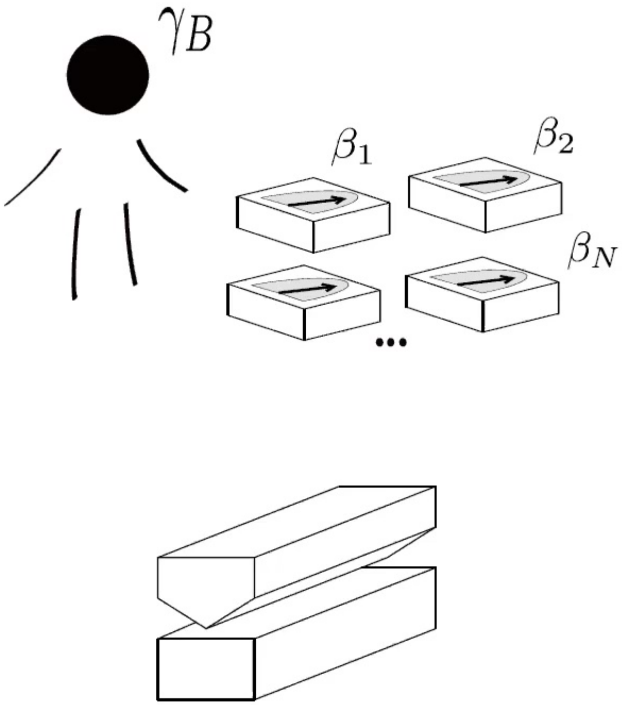
"Now even if we have arranged that [the measurement settings] a and b are generated by apparently random radioactive devices, housed in separate boxes and thickly shielded, or by Swiss national lottery machines, or by elaborate computer programmes, or by apparently free willed experimental physicists, or by some combination of all of these, we cannot be sure that a and b are not significantly influenced by the same factors λ that influence [the measurement results] A and B. But this way of arranging quantum mechanical correlations would be even more mind boggling than one in which causal chains go faster than light. Apparently separate parts of the world would be deeply and conspiratorially entangled..."

[2] J. S. Bell, Le Journal de Physique Colloques **1981**, 42

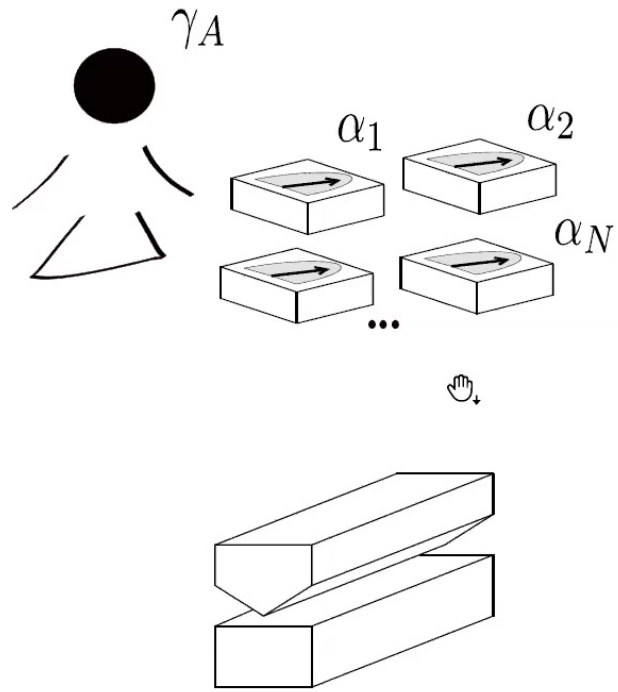


"A theory may appear in which such conspiracies inevitably occur, and these conspiracies may then seem more digestible than the non-localities of other theories. When that theory is announced I will not refuse to listen, either on methodological or other grounds."

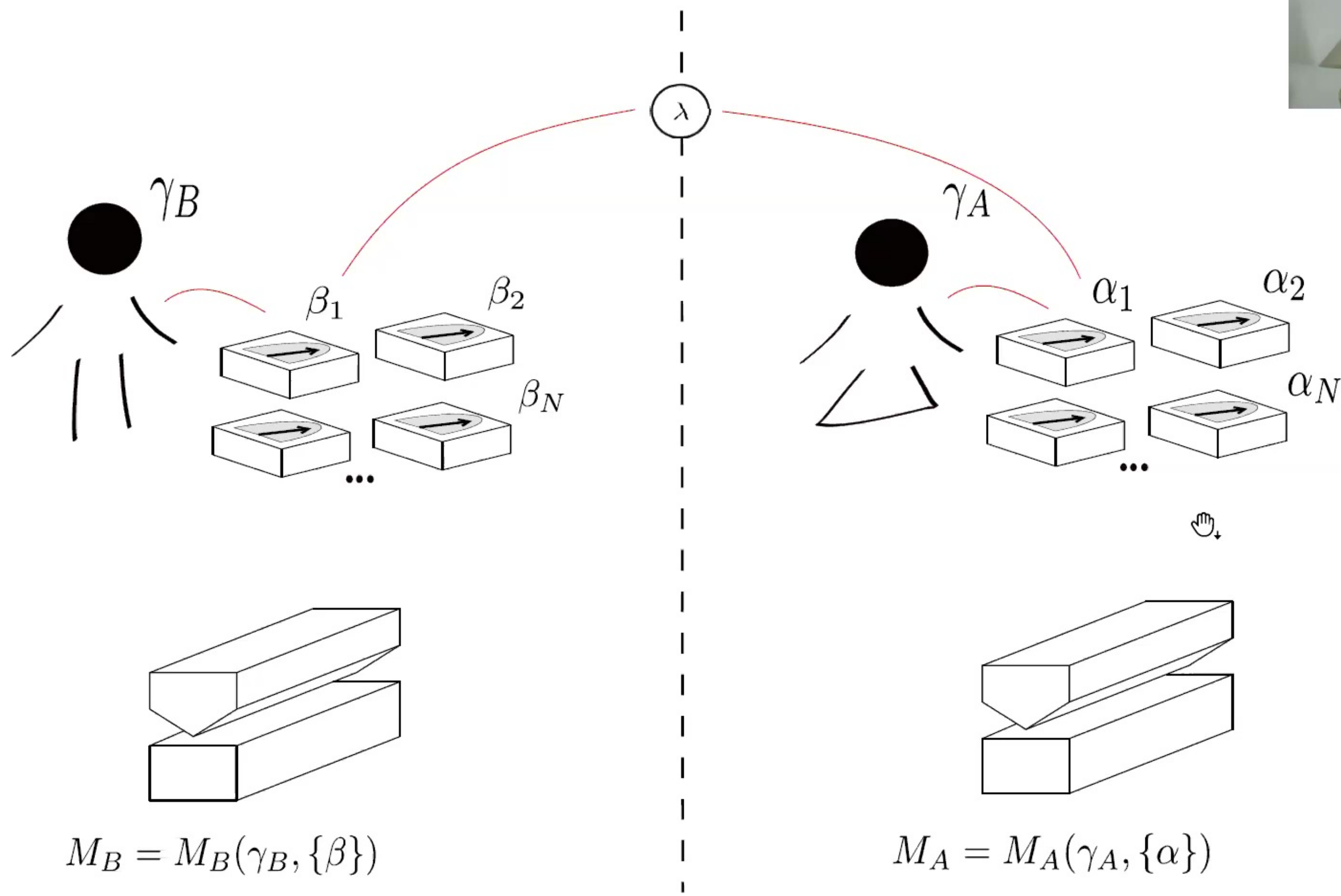
[3] J. S. Bell, Epistemol. Lett. 1977, 15, Republished in Dialectica, 1985, 85-1



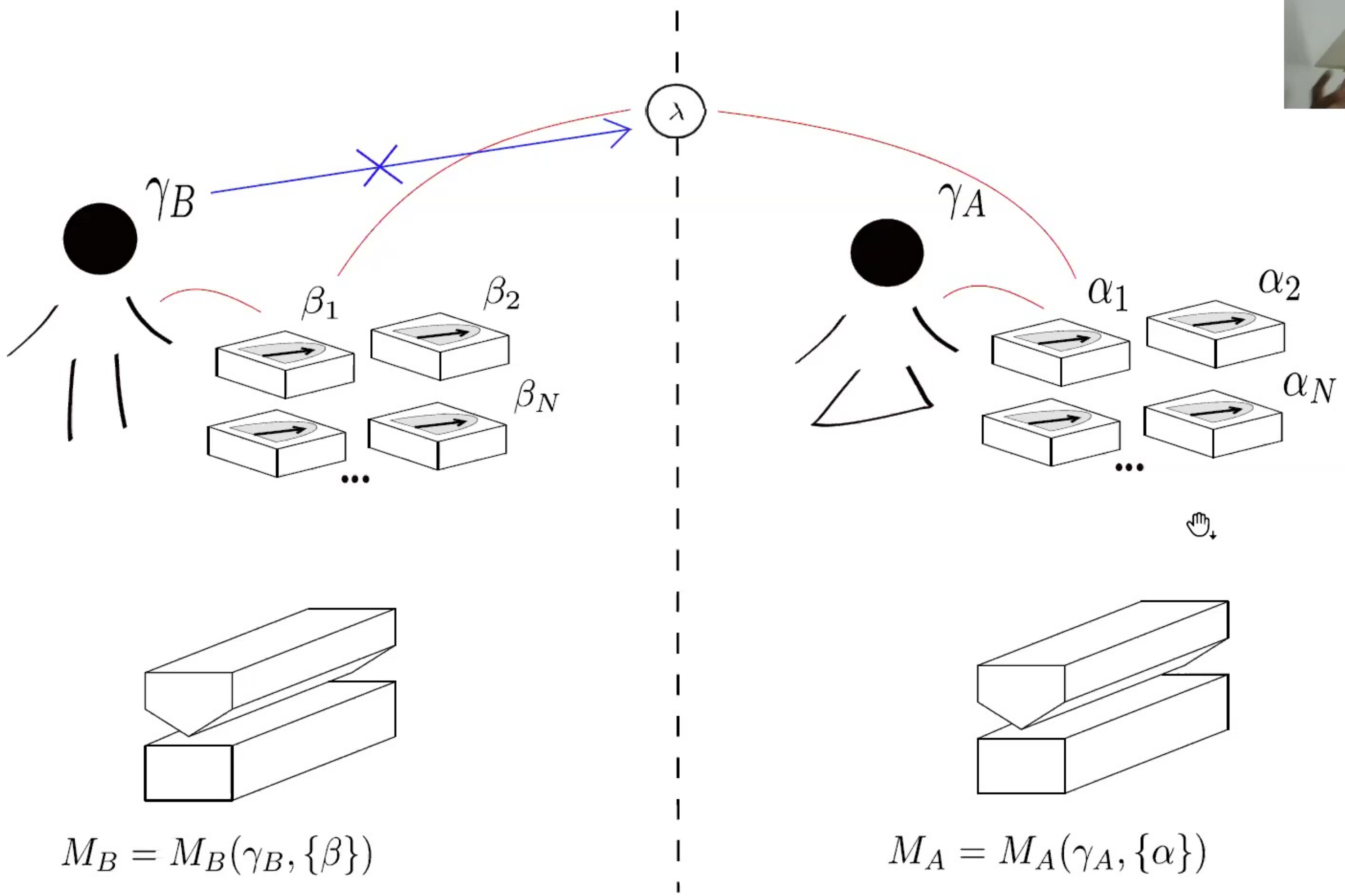
$$M_B = M_B(\gamma_B, \{\beta\})$$



$$M_A = M_A(\gamma_A, \{\alpha\})$$



$M_B = M_B(\gamma_B, \{\beta\})$ $\qquad$ $M_A = M_A(\gamma_A, \{\alpha\})$


λ
γ_B
γ_A
β_1
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α_2
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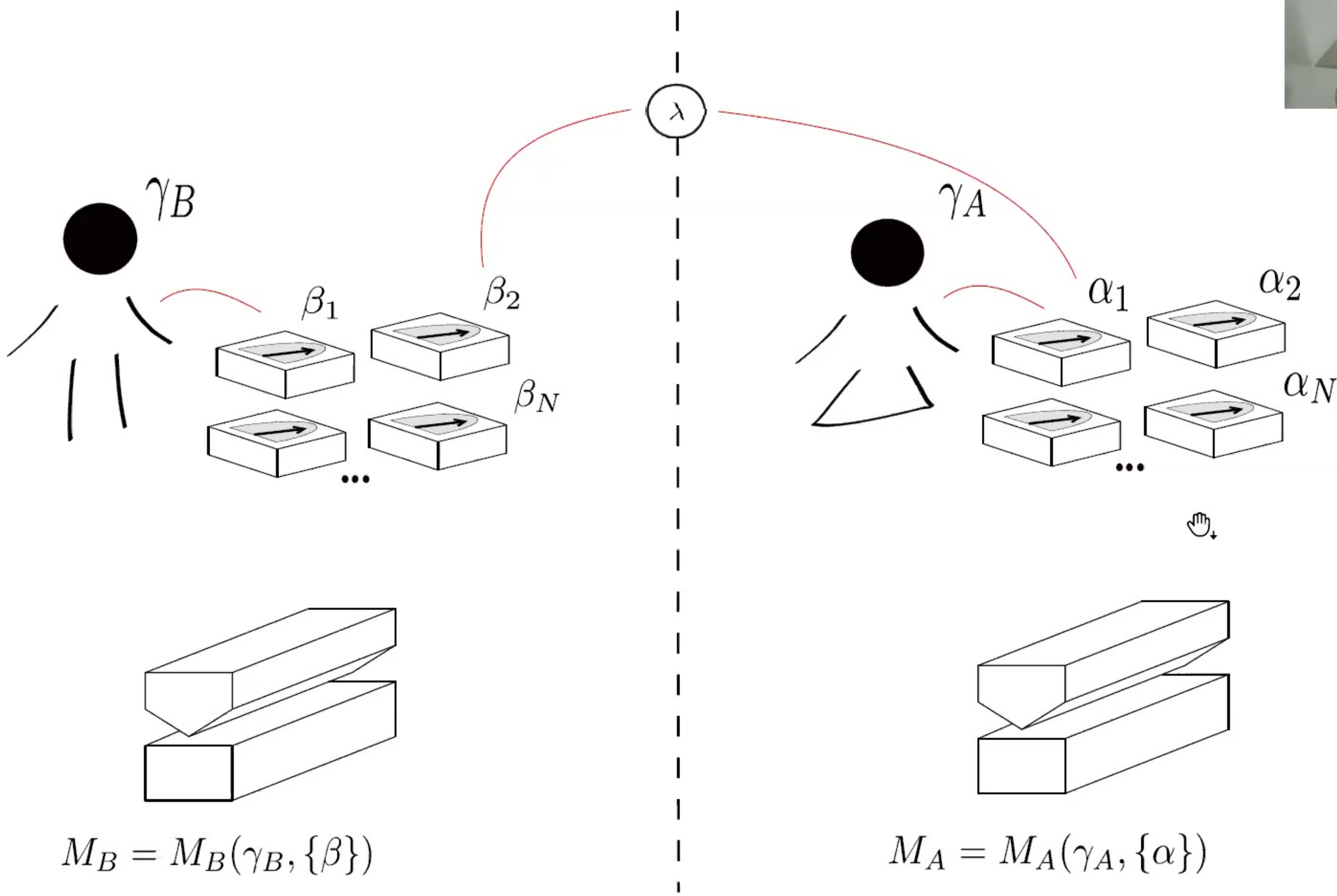
$M_B = M_B(\gamma_B, \{\beta\})$
$M_A = M_A(\gamma_A, \{\alpha\})$



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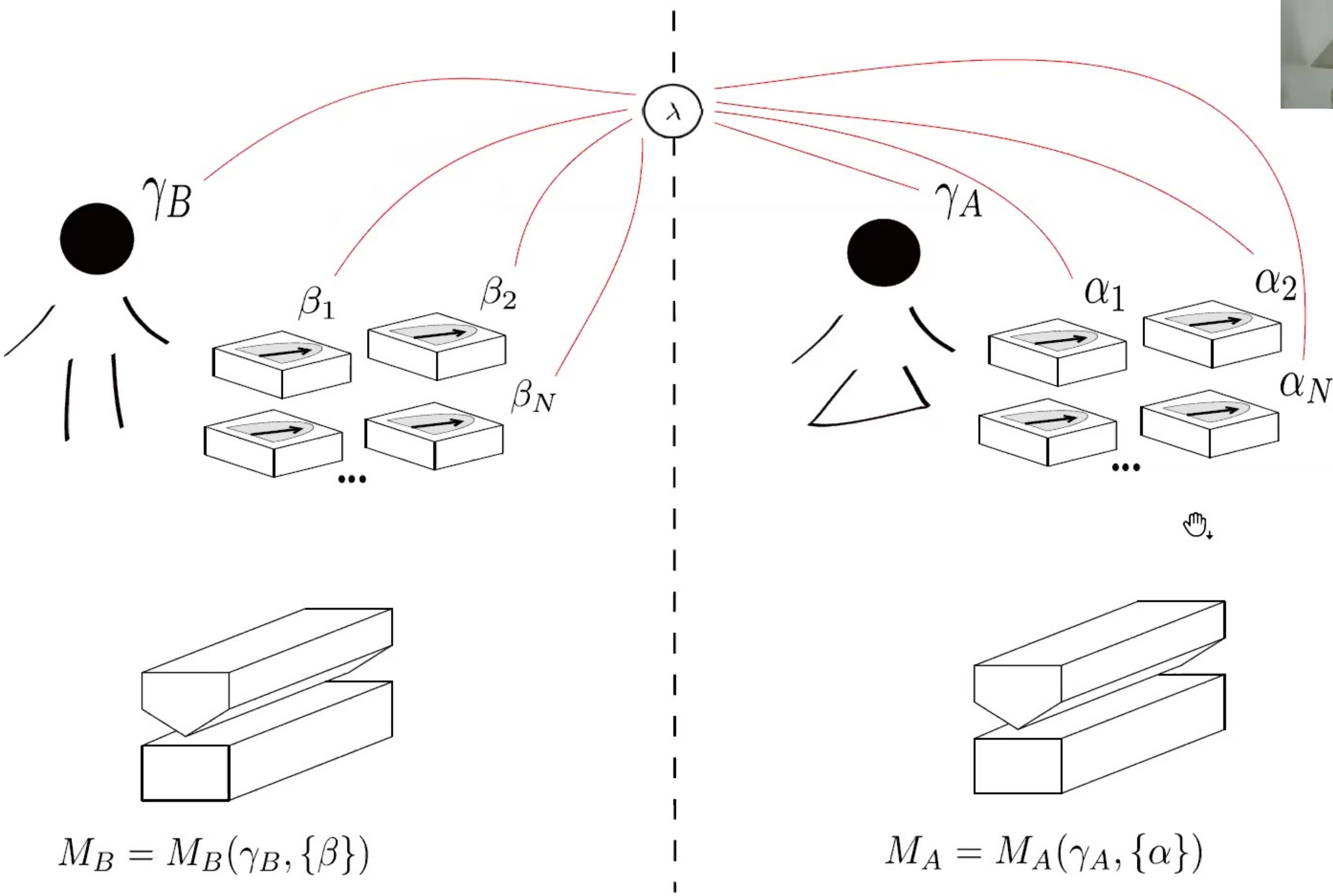

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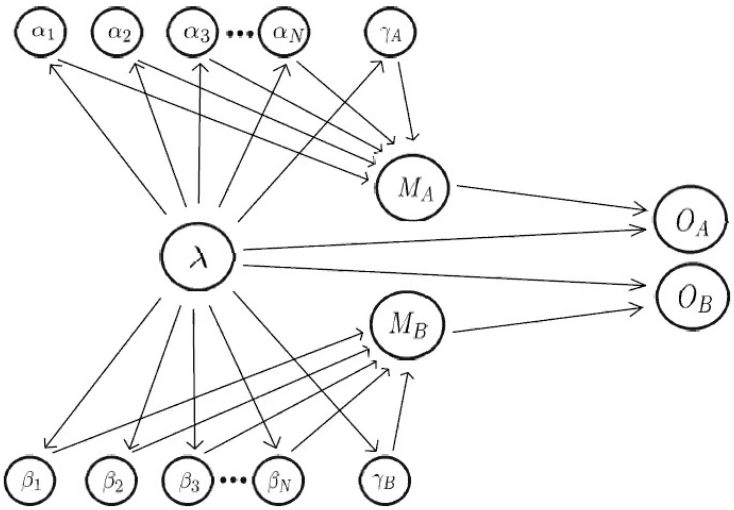
α_1
α_2
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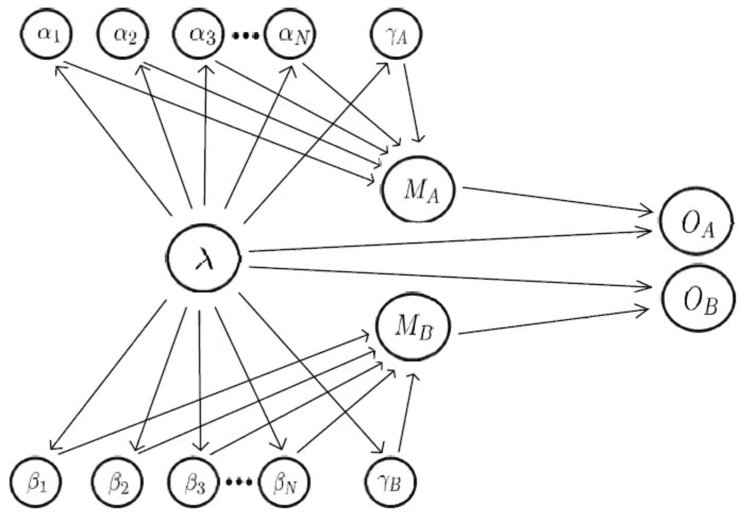
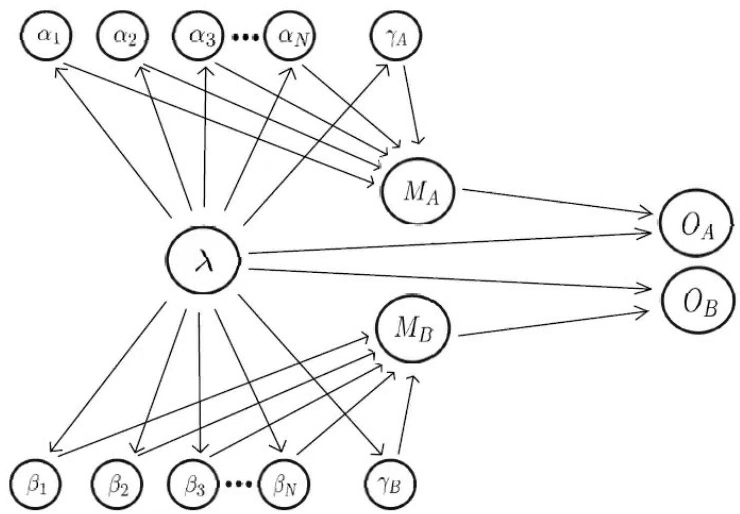


$$p(\lambda|M_A, M_B) = \sum_{\{\alpha\},\gamma_A} \sum_{\{\beta\},\gamma_B} p(\lambda|M_A, M_B, \{\alpha\}, \gamma_A, \{\beta\}, \gamma_B)\ p(\{\alpha\}, \gamma_A, \{\beta\}, \gamma_B|M_A, M_B)$$



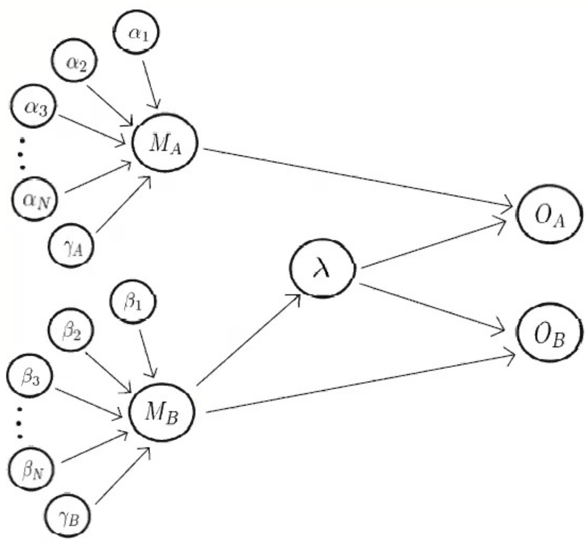
$$p(\lambda|M_A, M_B) = \sum_{\{\alpha\},\gamma_A} \sum_{\{\beta\},\gamma_B} p(\lambda|M_A, M_B, \{\alpha\}, \gamma_A, \{\beta\}, \gamma_B)\ p(\{\alpha\}, \gamma_A, \{\beta\}, \gamma_B|M_A, M_B)$$

cannot be arbitrary

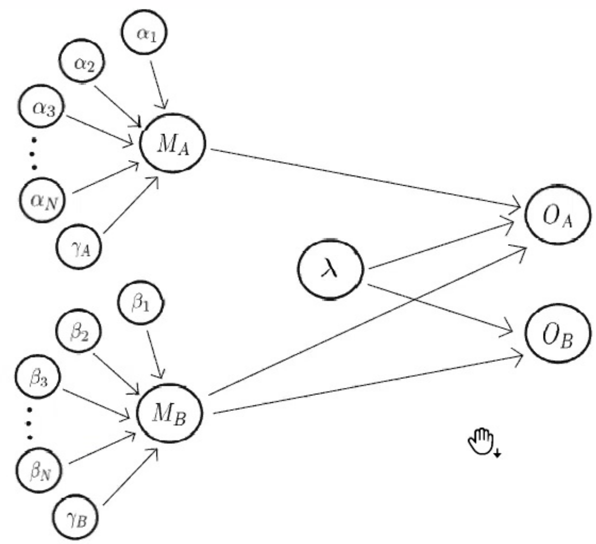
Measurement statistics do not depend on how the settings are chosen:

$$\sum_{\lambda} p(O_A, O_B|\lambda, M_A, M_B) p(\lambda|M_A, M_B, \{\alpha\}', \gamma'_A, \{\beta\}', \gamma'_B) = \sum_{\lambda} p(O_A, O_B|\lambda, M_A, M_B) p(\lambda|M_A, M_B, \{\alpha\}'', \gamma''_A, \{\beta\}'', \gamma''_B)$$

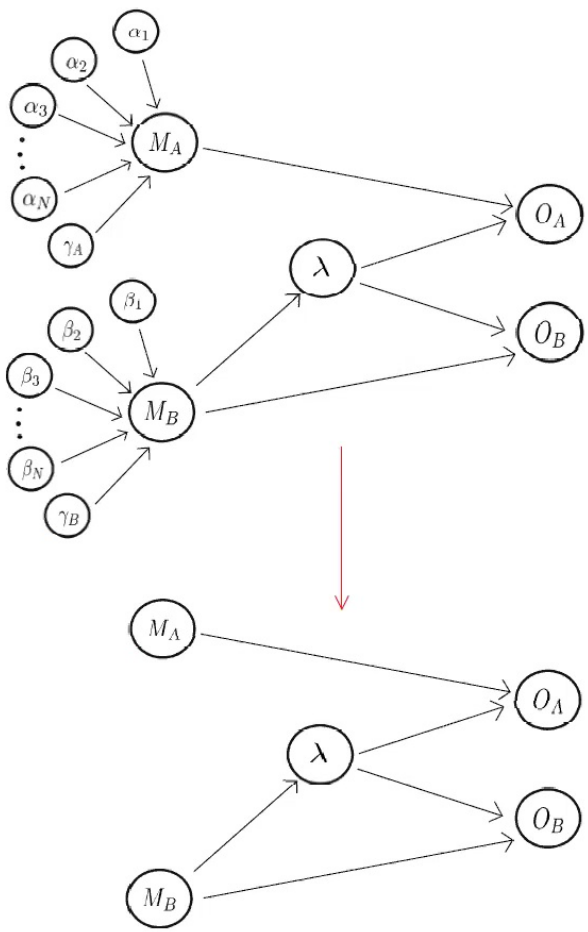
$M_A(\{\alpha\}', \gamma'_A) = M_A(\{\alpha\}'', \gamma''_A)$ and $M_B(\{\beta\}', \gamma'_B) = M_B(\{\beta\}'', \gamma''_B)$.



a) Retrocausal model



b) Nonlocal model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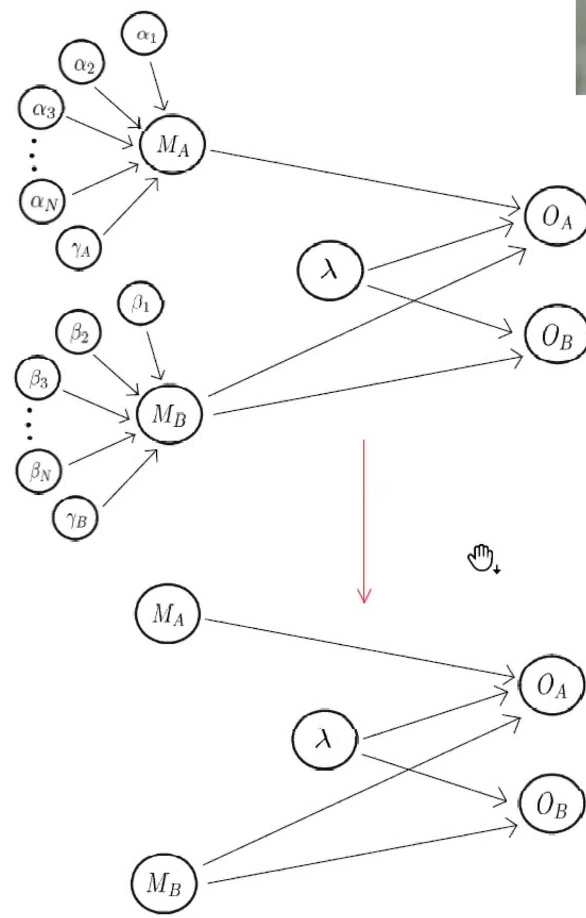
O_B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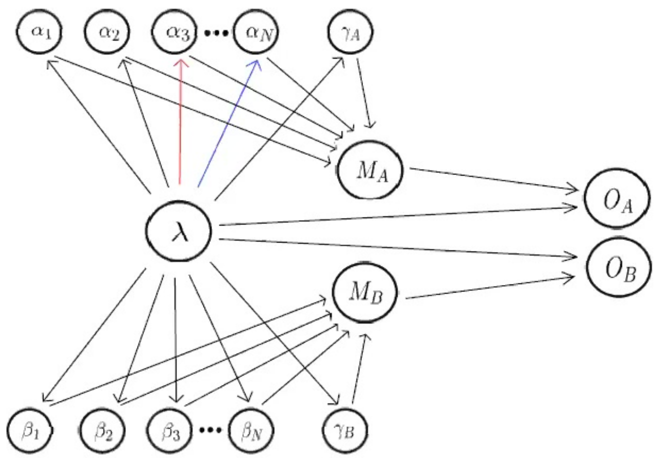
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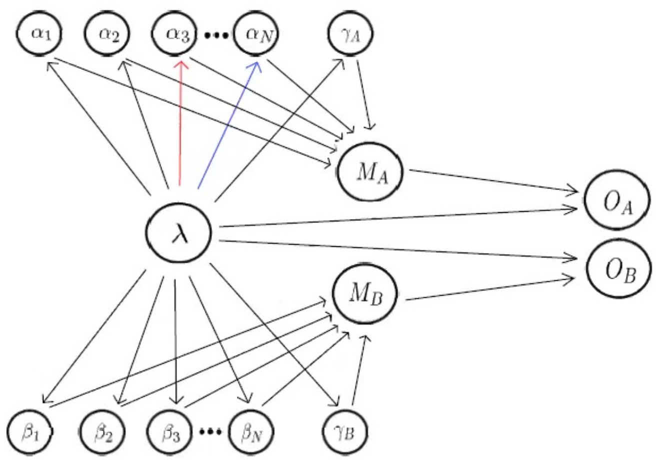


No features of quantum statistics used

Quantification of finetuning

$$F = 1 - \frac{N_f}{V(\Lambda, L)^{\Omega}}$$

Total number of final configurations

overhead fine-tuning parameter

Total number of initial distributions

Total number of configurations for a single distribution

Discretisation parameter, $p(\lambda|\ldots) = l/L$

Size of ontic-space

For a superdeterministic model with only a single distribution $p(\lambda|M_A, M_B)$,

$$F = 1 - \frac{V(\Lambda, L)^4}{V(\Lambda, L)^{\Omega}}$$
$$= 1 - V(\Lambda, L)^{4-N^2 2^{2N}}$$

In this case, $F = 1$ for any $N > 1$ (given[3] $V(\Lambda, L) \to \infty$).

j^{th} configuration of the 'constrained distribution'

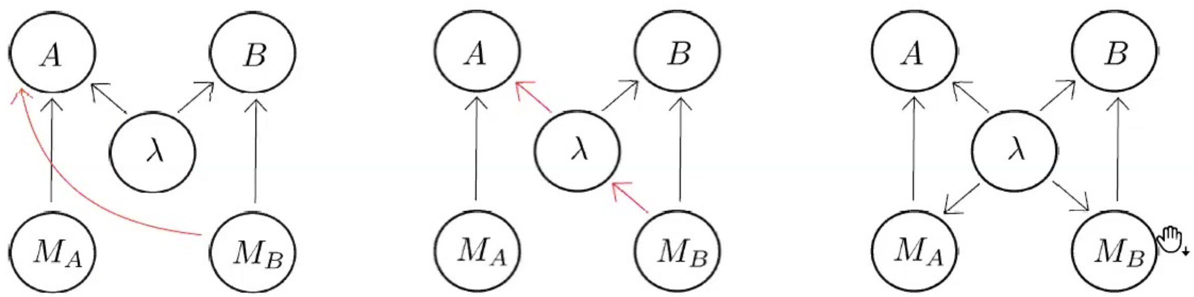
For more general superdeterministic models, the minimum finetuning is

$$F = 1 - \prod_{A,B} \frac{\sum_{j=1}^{V(\Lambda,L)} \left(v_{AB}^{j}(\Lambda, L)/V(\Lambda, L)\right)^{\frac{\Omega}{4}-1}}{V(\Lambda, L)}$$
$$= 1 - \prod_{A,B} \frac{\sum_{j=1}^{V(\Lambda,L)} \left(v_{AB}^{j}(\Lambda, L)/V(\Lambda, L)\right)^{N^2 2^{2N-2}-1}}{V(\Lambda, L)}$$

In this case, $0 < F < 1$ for any $N > 1$.

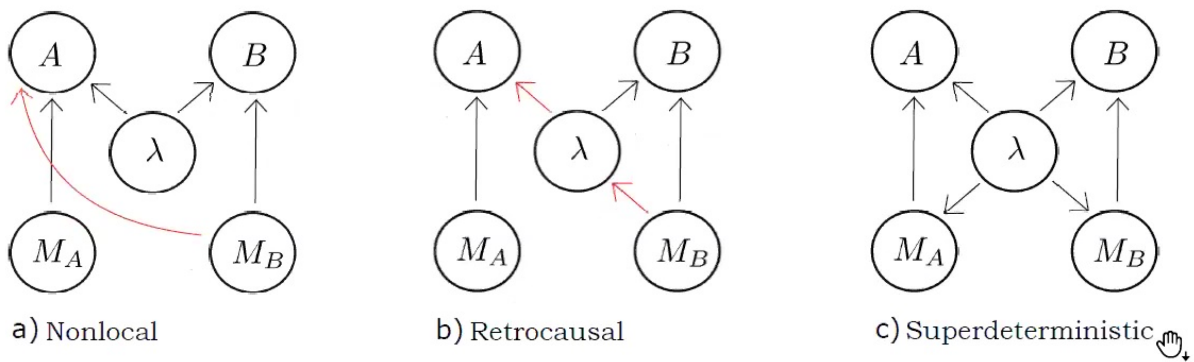
[3] L. Hardy, *Stud. Hist. Phil. Sci. B* **2004**, *35*.

Does superdeterministic signalling constitute an actual signal?



a) Nonlocal b) Retrocausal c) Superdeterministic

Does superdeterministic signalling constitute an actual signal?



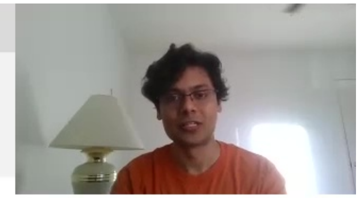
Conditions for actual signalling (from $M_B \to A$):

1. Violation of formal no-signalling constraints.
2. Causal relationship from $M_B \to A$.

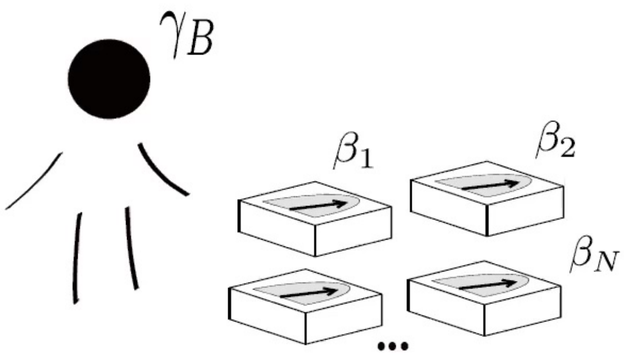
'No-signalling' $\to$ Marginal-independence

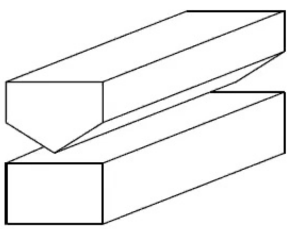
Is there a conversation?

Is there a conversation?



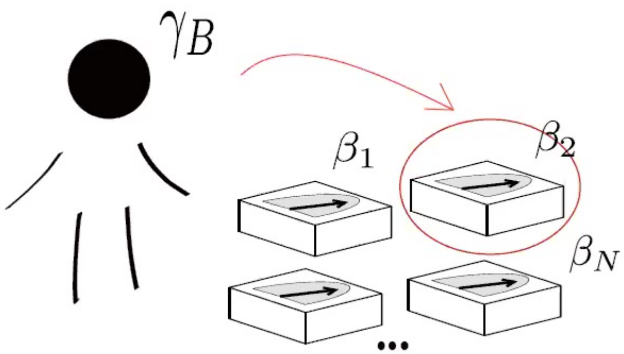
A series of coincidences mimicking an actual conversation...

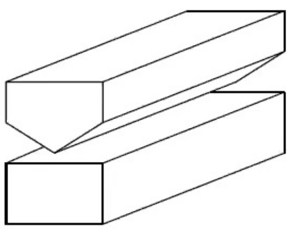




$$M_B = M_B(\gamma_B, \{\beta\})$$

$$p(\lambda | M_A, M_B, \{\alpha\}, \{\beta\}, \gamma_A = i, \gamma_B = j) = p(\lambda | M_A, M_B, \alpha_i, \beta_j, \gamma_A = i, \gamma_B = j)$$





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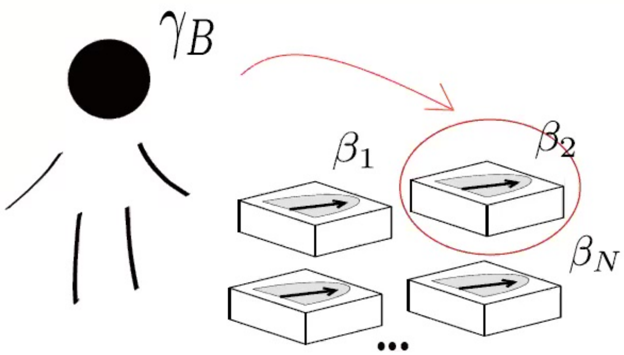
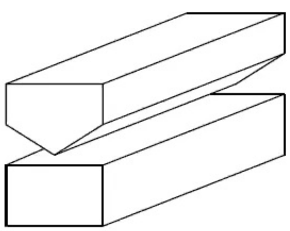
Each run belongs to a particular sub-ensemble $E = (i, j)$ out of N^2 possibilities.

$$E = (\gamma_A, \gamma_B)$$





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Each run belongs to a particular sub-ensemble $E = (i, j)$ out of N^2 possibilities.

$$E = (\gamma_A, \gamma_B)$$

$$W = N^{2N_0}$$

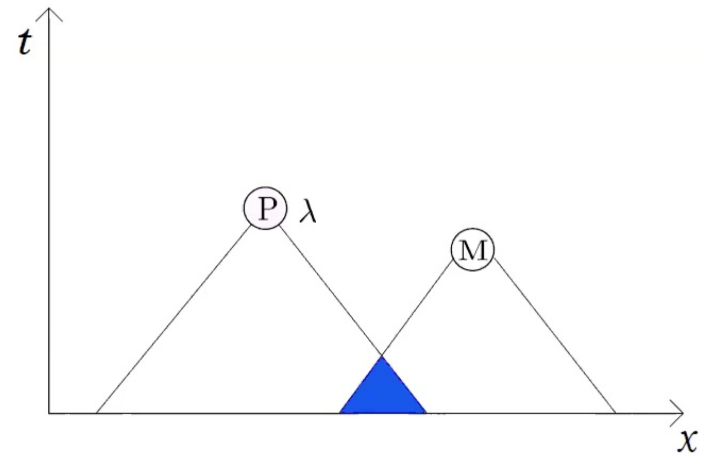
number of runs

$k \in \{1, 2, \ldots W\}$

$$S = -\sum_{k=1}^{W} p(k) \log_2 p(k)$$

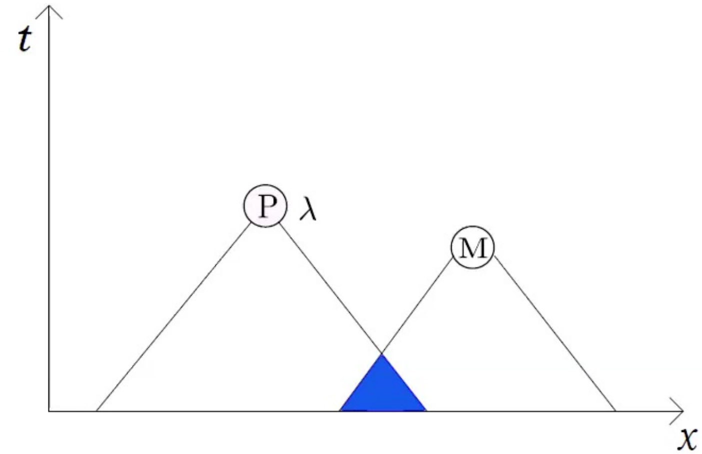
Afterwards,

$$\Delta S = -H(k : \{\gamma_A, \gamma_B\}) = \sum_{k=1}^{W} p(k) \log_2 p(k)$$



In a recent M.D model[4], $H(\lambda : M_A, M_B) \sim 0.08$ bits

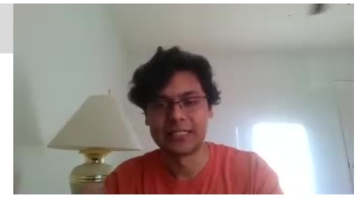
[4] M. J. Hall, C. Branciard, *arXiv: 2007.11903* **2020**.

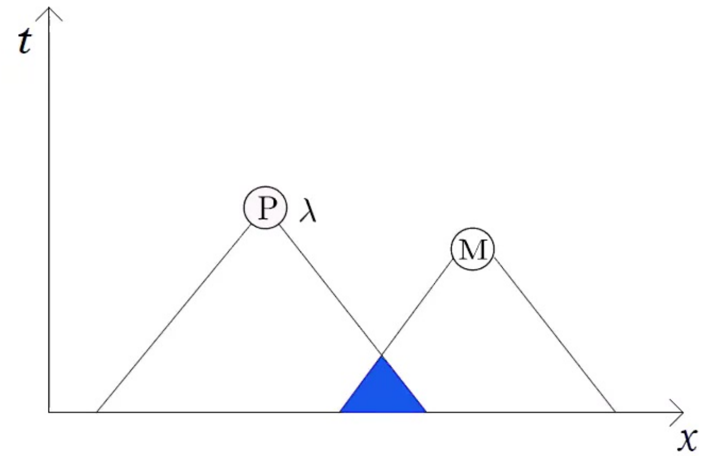


In a recent M.D model[4], $H(\lambda : M_A, M_B) \sim 0.08$ bits

If $p(k) = 1/W \ \forall \ k$, $H(E : \gamma_A, \gamma_B) = 2 \log_2 N$.

For $N = 16$, $H(E : \gamma_A, \gamma_B) = 8$ bits, which is $\sim 100 H(\lambda : M_A, M_B)$.





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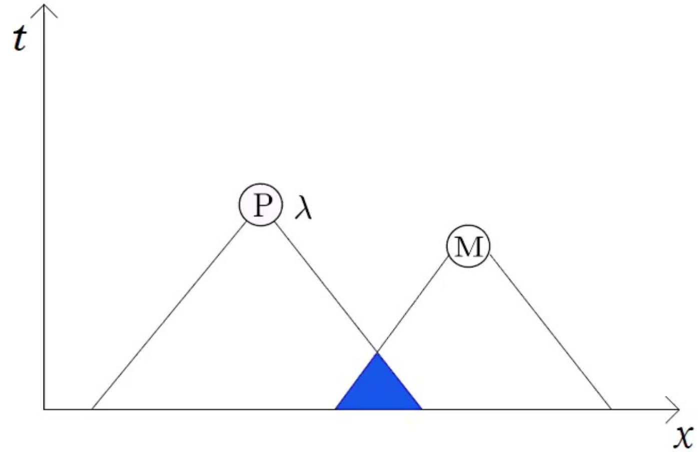
This approach does not use arbitrary initial distributions.



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This approach does not use arbitrary initial distributions.

Verdict: Superdeterminism is conspiratorial and we can quantitatively discuss this in two separate ways.

Retrocausality

Abraham-Lorentz equation: $m(\dot{v} - \tau \ddot{v}) = F_{ext}$, where $\tau = \frac{2e^2}{3c^3}$.

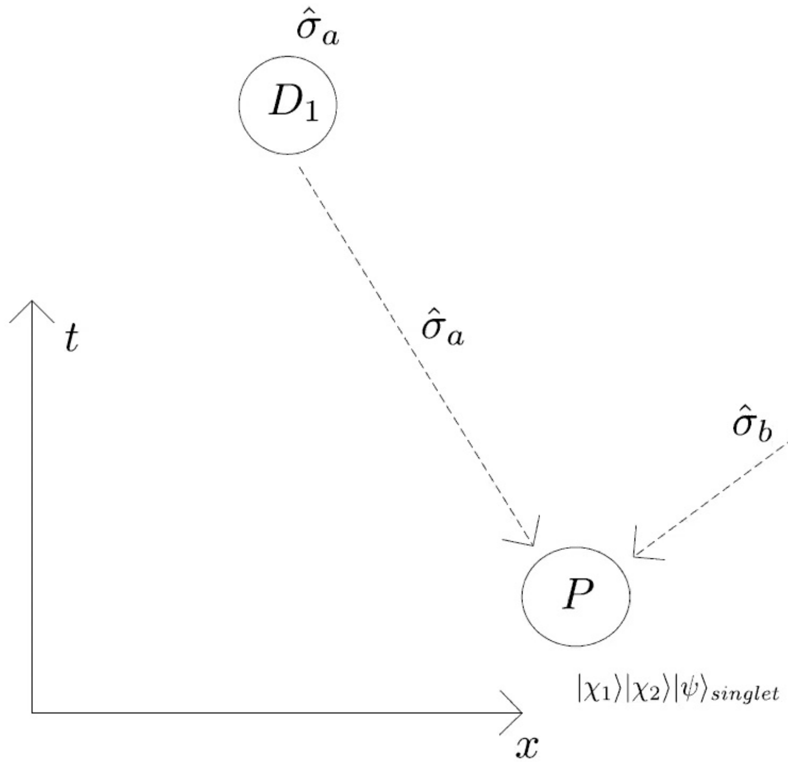
Retrocausality

Abraham-Lorentz equation: $m(\dot{v} - \tau \ddot{v}) = F_{ext}$, where $\tau = \frac{2e^2}{3c^3}$.

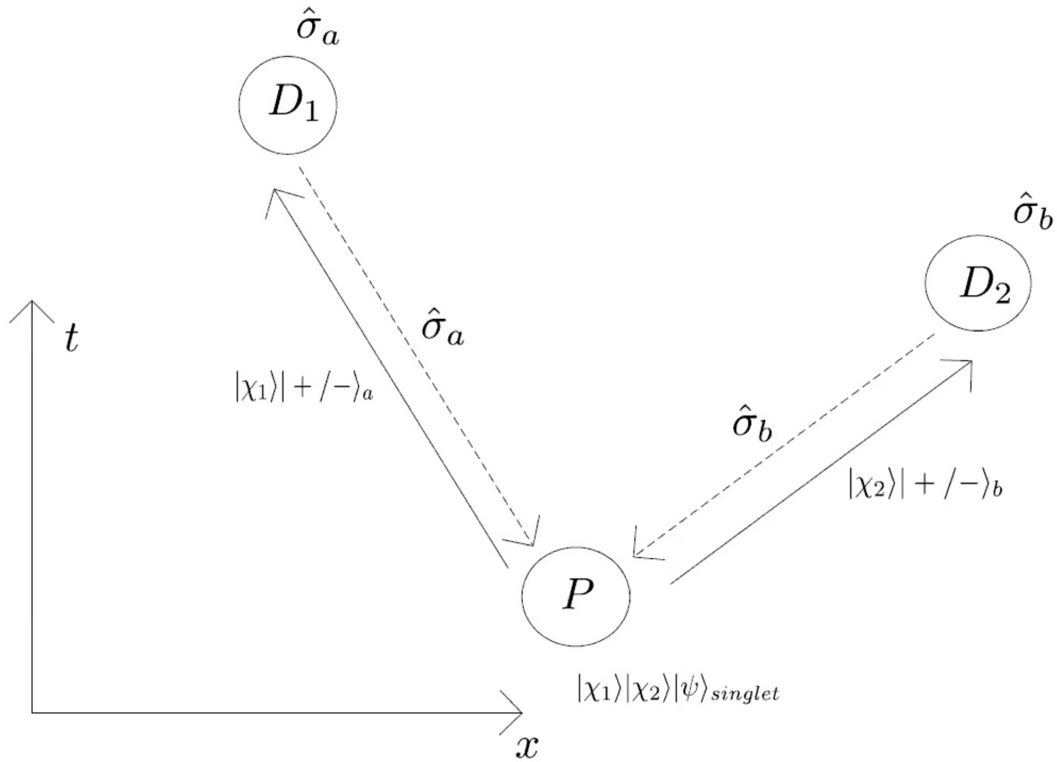
$$\dot{v}/m = \frac{e^{t/\tau}}{\tau} \int_t^{\infty} e^{-t'/\tau} F(t') dt'$$

The acceleration of the particle at time t depends on the force applied after time t.

Retrocausal Brans model



Retrocausal Brans model



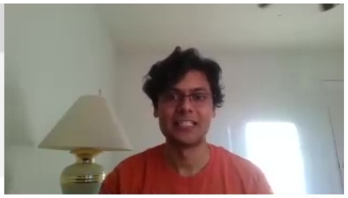
Mathematical formulation

Ontology

Joint ontic quantum state: $\langle \vec{r}_1 | \langle \vec{r}_2 | \psi_o(t) \rangle \rangle = \chi_1(\vec{r}_1, t) | i_1 \rangle_a \otimes \chi_2(\vec{r}_2, t) | i_2 \rangle_b$. Evolves via the Schrodinger equation.

Position of each particle: $\vec{r}_1(t)$, $\vec{r}_2(t)$. Evolves via $\vec{v} = \frac{\vec{\nabla} S(\vec{r}, t)}{m}$.

Mathematical formulation



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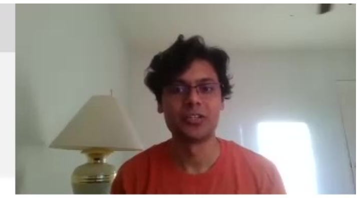
Local, Separable, 3D pilot-waves.

Mathematical formulation



Ontology

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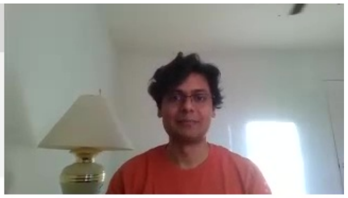
Local, Separable, 3D pilot-waves.

Initial conditions

The ensemble-proportions $|c_{++}|^2$, $|c_{+-}|^2$, $|c_{-+}|^2$, $|c_{--}|^2$ of the joint ontic quantum states determined by $|\psi\rangle_{singlet} = c_{++}|+\rangle_a|+\rangle_b + c_{+-}|+\rangle_a|-\rangle_b + c_{-+}|-\rangle_a|+\rangle_b + c_{--}|-\rangle_a|-\rangle_b$.

The initial distribution of positions $\rho(\vec{r}_1, \vec{r}_2, 0) = |\chi_1(\vec{r}_1, 0)|^2 |\chi_2(\vec{r}_2, 0)|^2$.

Mathematical formulation



Ontology

Joint ontic quantum state: $\langle \vec{r}_1 | \langle \vec{r}_2 | \psi_o(t) \rangle = \chi_1(\vec{r}_1, t) | i_1 \rangle_a \otimes \chi_2(\vec{r}_2, t) | i_2 \rangle_b$. Evolves via the Schrodinger equation.

Position of each particle: $\vec{r}_1(t)$, $\vec{r}_2(t)$. Evolves via $\vec{v} = \frac{\vec{\nabla} S(\vec{r}, t)}{m}$.

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Bell correlations reproduced.

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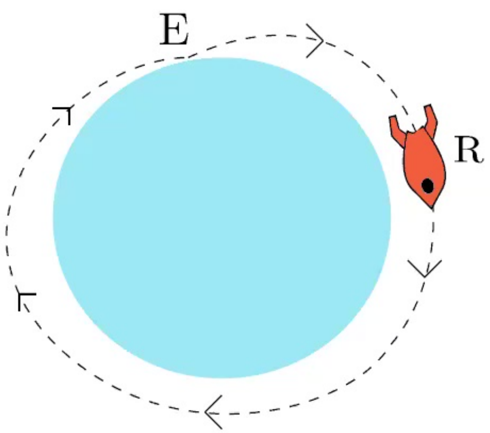
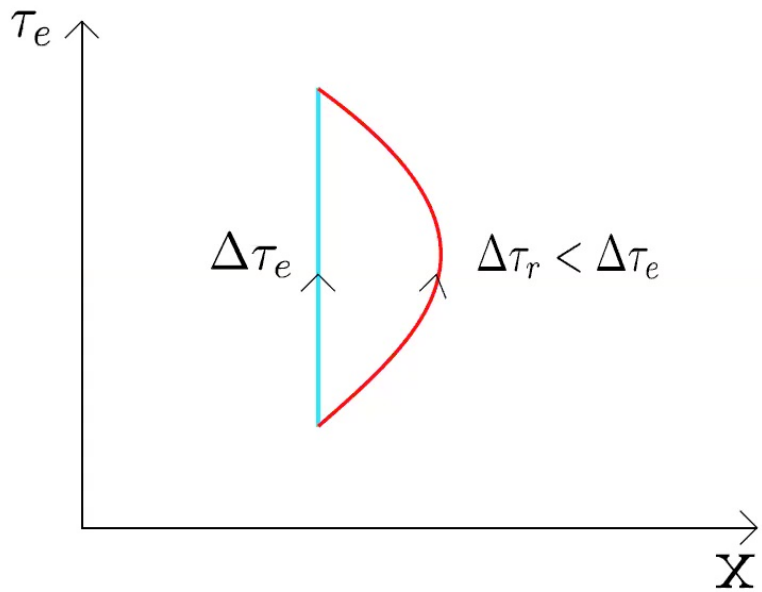
A relativistic Bell scenario





The total Hamiltonian of the systems in non-relativistic quantum mechanics

$$\hat{H} = (\frac{\hat{p}_r^2}{2m} \otimes \hat{I} \otimes \hat{I} \otimes \hat{I} + g\hat{p}_r \otimes \hat{\sigma}_r \otimes \hat{I} \otimes \hat{I}) + (\hat{I} \otimes \hat{I} \otimes \frac{\hat{p}_e^2}{2m} \otimes \hat{I} + g\hat{I} \otimes \hat{I} \otimes \hat{p}_e \otimes \hat{\sigma}_e)$$

valid approximation iff $p_e, p_r \ll mc$

Impossible in any single frame of reference.

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valid in rocket frame — valid approximation iff $p_e, p_r \ll mc$

Impossible in any single frame of reference.

$$|\psi(t)\rangle$$

Description in the retrocausal model

Ontology

$$\chi_r(\vec{x}_r, t) \longrightarrow \chi_r(\vec{x}_r, \tau_r)$$
$$\chi_e(\vec{x}_e, t) \longrightarrow \chi_e(\vec{x}_e, \tau_e)$$

$$\hat{H}\chi_r(\vec{x}_r, t)|i_1\rangle_r \otimes \chi_e(\vec{x}_e, t)|i_2\rangle_e = i\frac{d\chi_r(\vec{x}_r, t)|i_1\rangle_r \otimes \chi_e(\vec{x}_e, t)|i_2\rangle_e}{dt}$$

$$\longrightarrow \hat{H}_e\chi_e(\vec{x}_e, \tau_e)|i_1\rangle_e = i\frac{\partial\chi_e(\vec{x}_e, \tau_e)|i_1\rangle_e}{\partial\tau_e}$$

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$$\frac{\vec{\nabla}S(\vec{x},t)}{m} \longrightarrow \frac{\vec{\nabla}S(\vec{x},\tau)}{m}$$

Distribution

$$|\psi(t)\rangle \longrightarrow |\psi(\tau_e, \tau_r)\rangle$$

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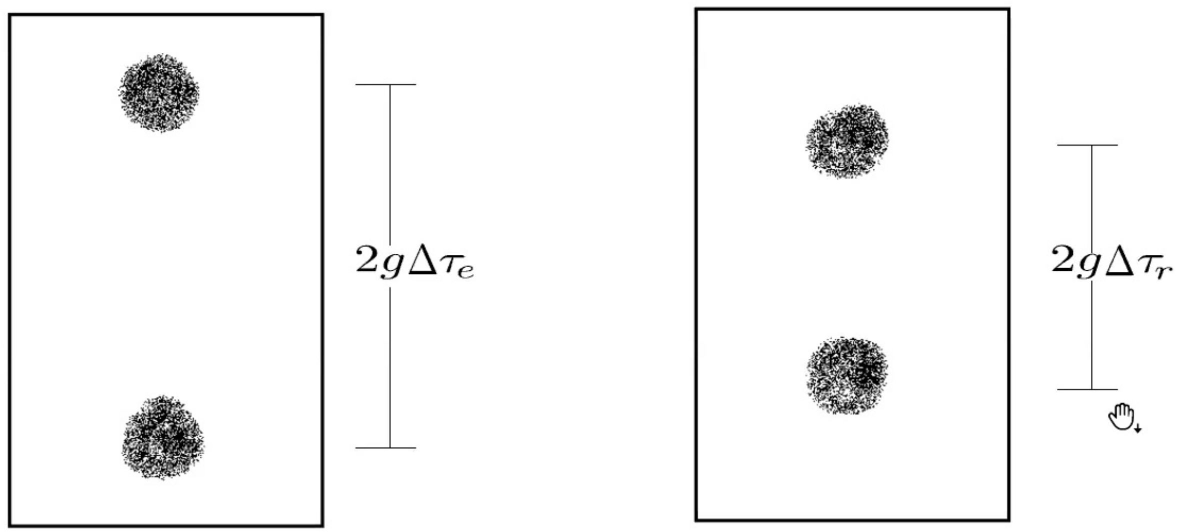

a) Earth lab b) Rocket lab

Description in Quantum field theory

Problems in defining the notion of a particle[6].

[6] G. C. Hegerfeldt, *Phys. Rev. D* **1974**, *10*, G. C. Hegerfeldt, S. N. Ruijsenaars, *Phys. Rev. D* **1980**, *22*, G. C. Hegerfeldt, *Phys. Rev. Lett.* **1985**, *54*, H. Halvorson, R. Clifton in *Ontological aspects of quantum field theory*, World Scientific, **2002**, pp. 181–213, N. Barat, J. Kimball, *Phys. Lett. A* **2003**, *308*, D. Wallace, *arXiv preprint quant-ph/0112149* **2001**, D. Colosi, C. Rovelli, *Class. Quant. Grav.* **2008**, *26*, M. Papageorgiou, J. Pye, *arXiv:1902.10684* **2019**.

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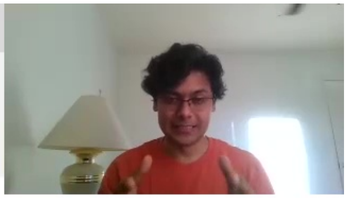

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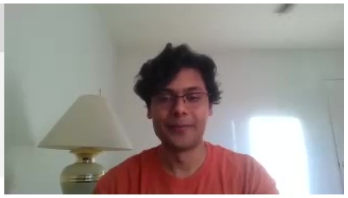

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Description in Pilot-wave theory

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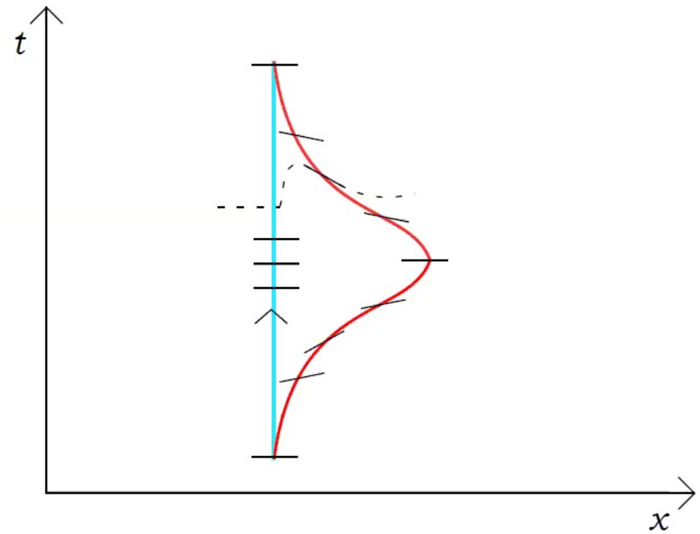

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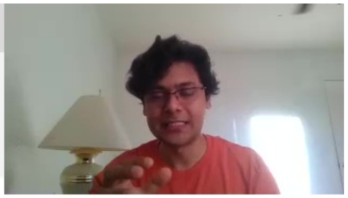

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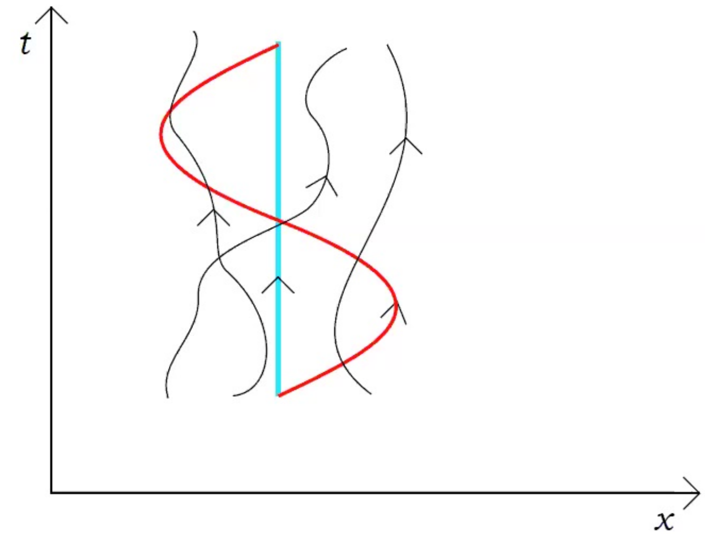

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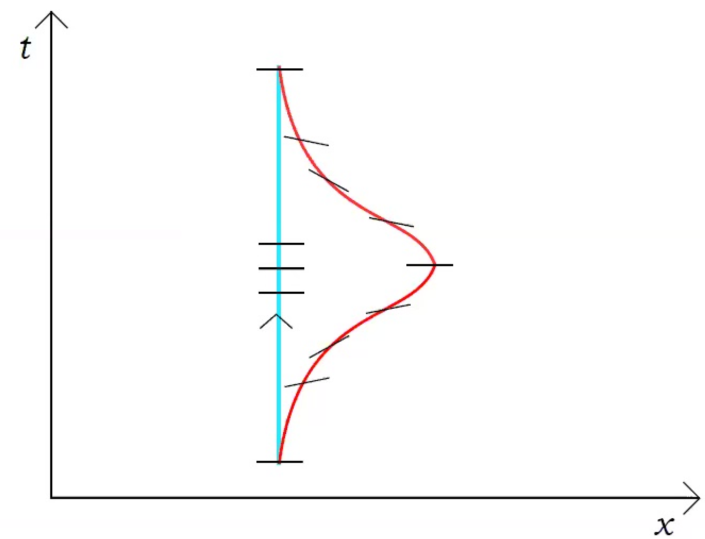

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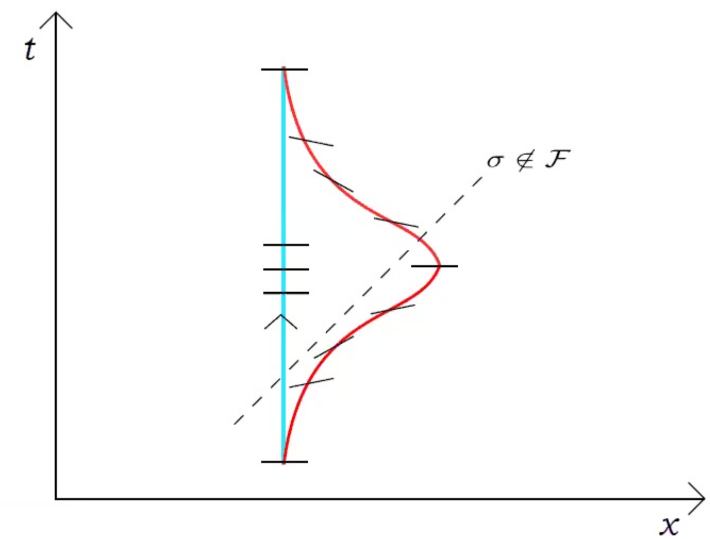

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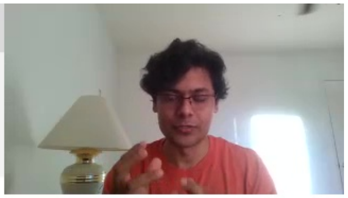

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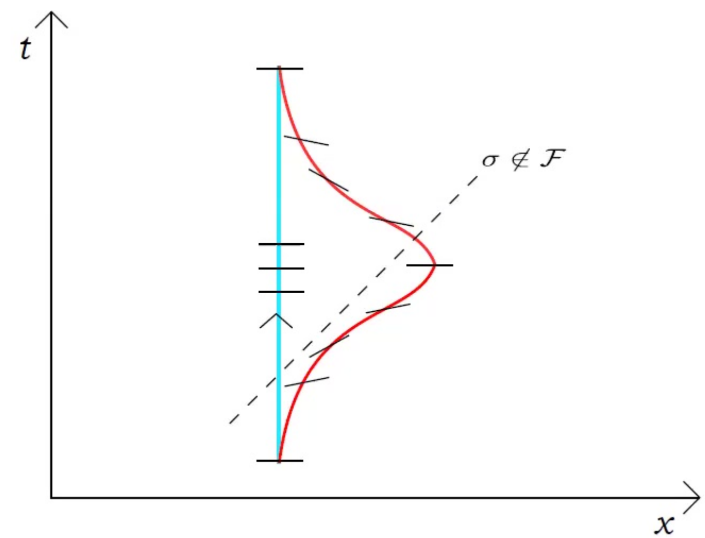

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$|\psi(\tau_e, \tau_r)\rangle$ is ontological.

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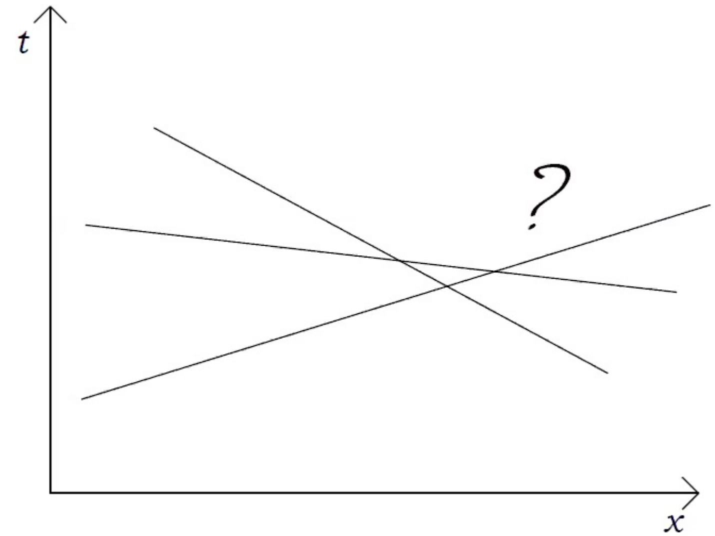

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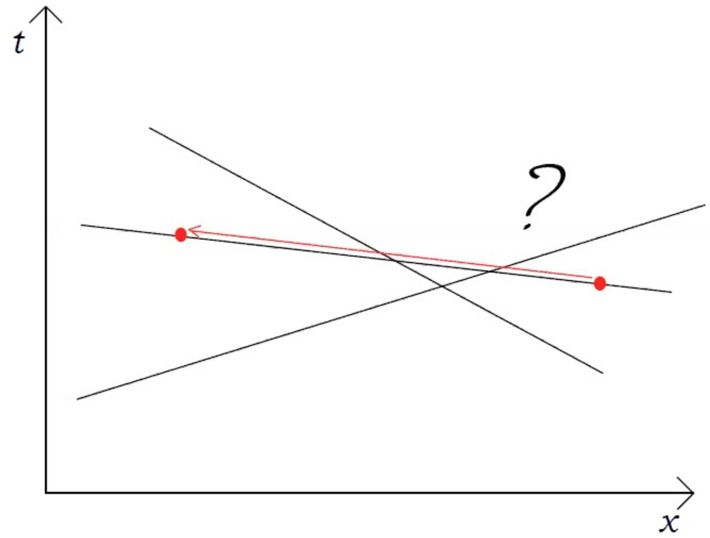

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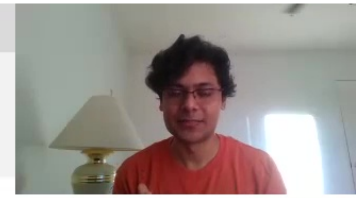

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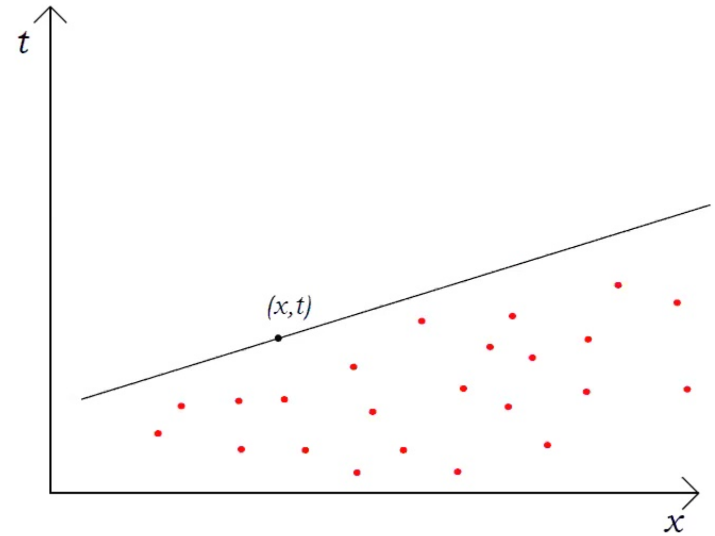

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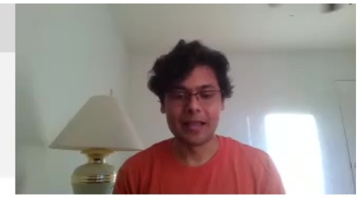

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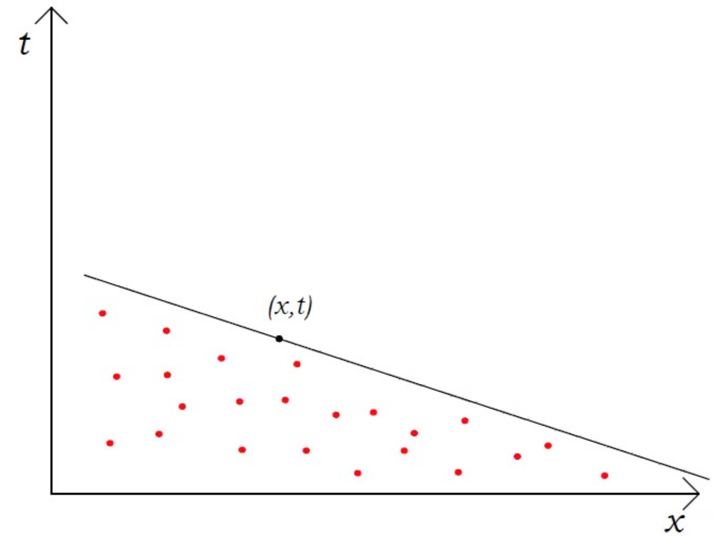

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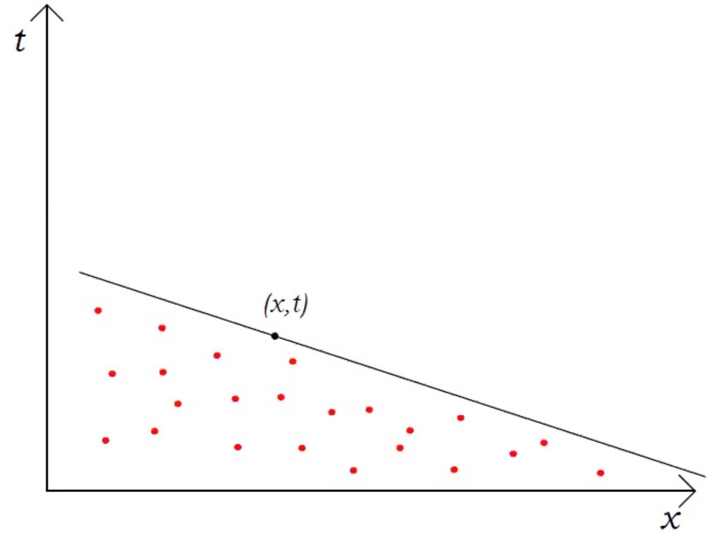

Bottom-line: ψ-epistemicity, locality, separability are useful properties.

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Can violating M.I. provide a credible alternative to quantum nonlocality?

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Which idea does Nature use?

Future work

Near future

- Palmer's superdeterministic proposal[7] $\longrightarrow$ concrete hidden-variable model.
- Non-interventionist causality and retrocausality.
- Pilot-wave theory in quantum-gravity regime.

Further ahead

- Implications of quantum foundations in quantum gravity.

[7] T. Palmer, *Proc. R. Soc. A* **2009**, *465*, 3165–3185, T. Palmer, *Proc. R. Soc. A* **2020**, *476*, 20190350.

Thank you!

Questions?