Title: Arrows of time and locally mediated toy-models of entanglement

Speakers: Nathan Argaman

Collection: Quantizing Time

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Abstract: "Making progress in quantum gravity requires resolving possible tensions between quantum mechanics and relativity.Â One such tension is revealed by Bell's Theorem, but this relies on relativistic Local Causality, not merely the time-reversal symmetric aspects of relativity.Â Specifically, it depends on an arrow-of-time condition, taken for granted by Bell, which we call No Future-Input Dependence.Â One may replace this condition by the weaker Signal Causality arrow-of-time requirement -- only the latter is necessary, both for empirical viability and in order to avoid paradoxical causal loops.Â There is then no longer any ground to require Local Causality, and Bell's tension disappears.Â The locality condition which is pertinent in this context insteadÂ is called Continuous Action, in analogy with Einstein's ""no action at a distance,"" and the corresponding ""local beables"" are ""spacetime-local"" rather than ""local in space and causal in time.""Â Â That such locally mediated mathematical descriptions of quantum entanglement are possible not only in principle but also in practice is demonstrated by a simple toy-model -- a ""local"" description of Bell correlations.Â Describing general physical phenomena in this manner, including both quantum systems and gravitation, is a grand challenge for the future.
[K.B. Wharton and N. Argaman, ""Colloquium:Â Bell's Theorem and Locally-Mediated Reformulations of Quantum Mechanics,"" Rev. Mod. Phys. 92, 21002 (2020).]"

Arrows of time and locally mediated toy-models of entanglement

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Ken Wharton
Izhar Neder

Wharton and A,
Rev. Mod. Phys. Colloquium
92, 021002 (2020).

Outline

- Introduction: Bell's theorem
- Formalism: a locality condition not involving an arrow of time
- Schulman's Levy-flight model
- Outlook

O. Costa de Beauregard (1953), H. Price (1997) ...

Introduction

- A conservative route to revolution: follow Feynman!

- (re)formulations of QM:
  - Heisenberg
  - Schroedinger
  - path integrals
  - de Broglie-Bohm
  - stochastic mechanics
  - ...

Introduction

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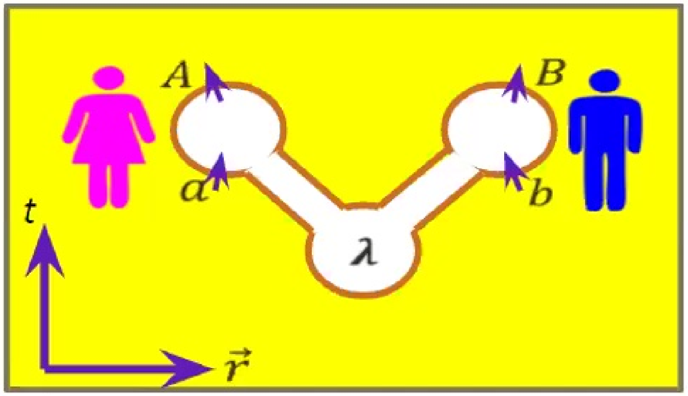
measurement operators
"evolve" back in time

violates
No Future-Input Dependence

Reminder: Bell's Theorem

Locality is not a simple yes/no question:

Local Causality	$\Sigma \langle AB \rangle \leq 2$
Signal Locality	$\Sigma \langle AB \rangle \leq 4$
Quantum Locality	$\Sigma \langle AB \rangle \leq 2^{3/2}$



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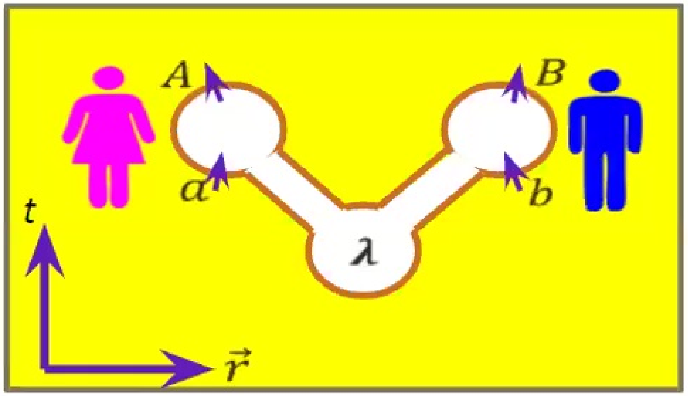

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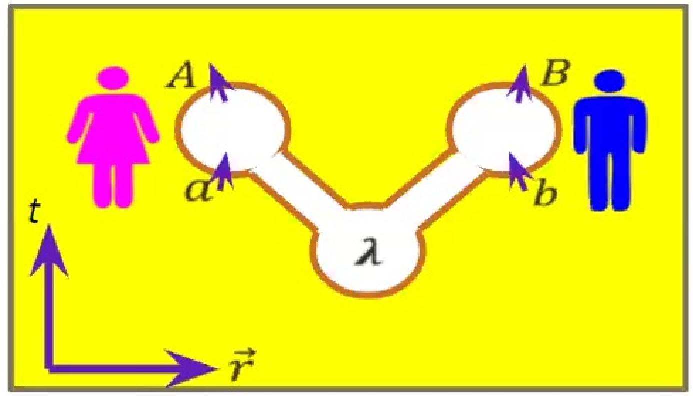


Causality is not a yes/no question either!

No Future-Input Dependence $\neq$ Signal Causality

Formalism

Physical models: $P_I(Q)$

~~Hilbert-space states~~

Example:
Bell singlet correlations

$$p_{a,b}(A,B) = \tfrac{1}{4}[1 + AB\cos(2a - 2b)]$$

Formalism

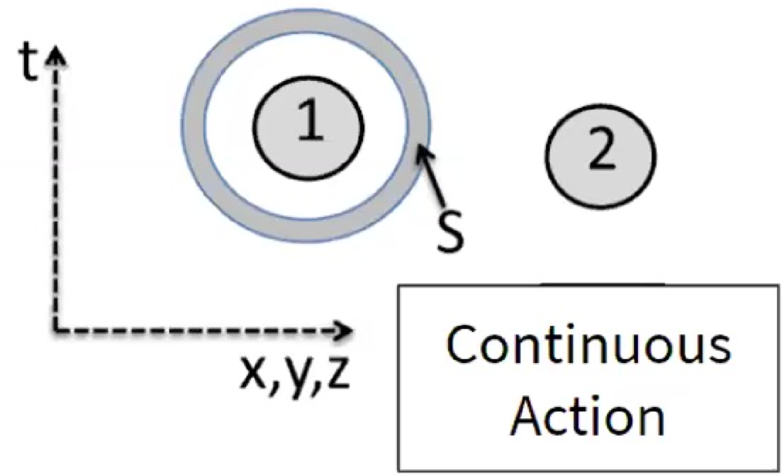
Physical models: $P_I(Q)$

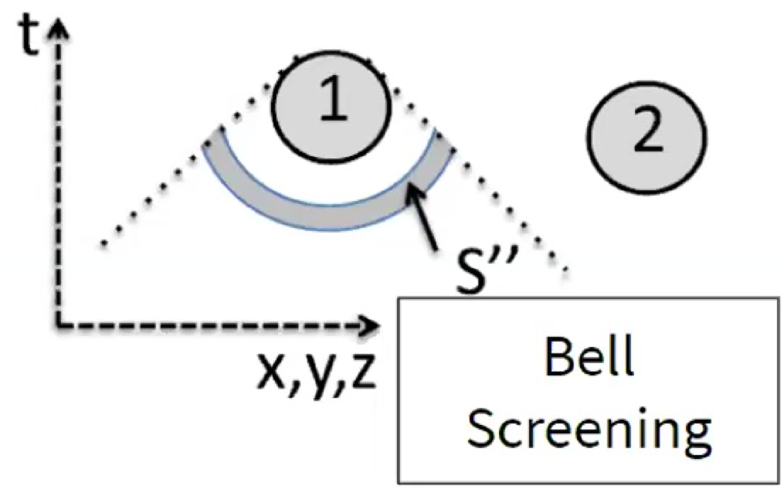
~~Hilbert-space states~~

No Future-Input Dependence

Continuous Action (nothing spooky)

$$P_{I_1,I_2}(Q_1|Q_2,Q_S) = P_{I_1}(Q_1|Q_S)$$





Schulman's Lévy-flight model

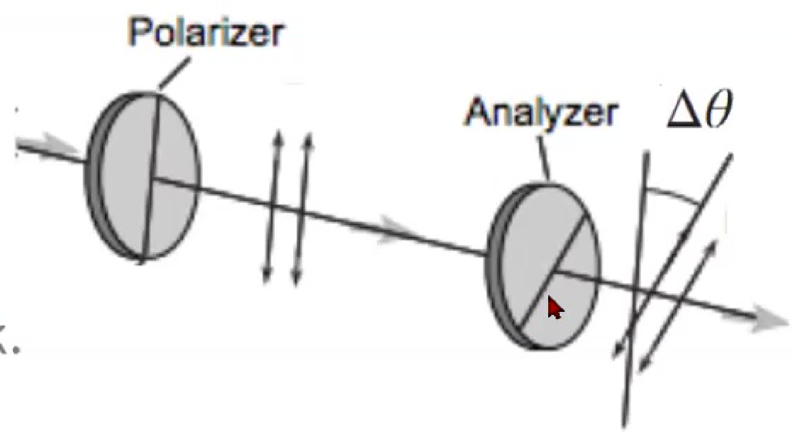
Postulate a random walk

$$\Delta q \equiv \int_{t_1}^{t_2} \frac{dq(t)}{dt}\, dt$$

with a Lorentzian distribution for each kick.

Then

$$P(\Delta q) \propto \frac{1}{(\Delta q)^2 + \gamma^2}$$



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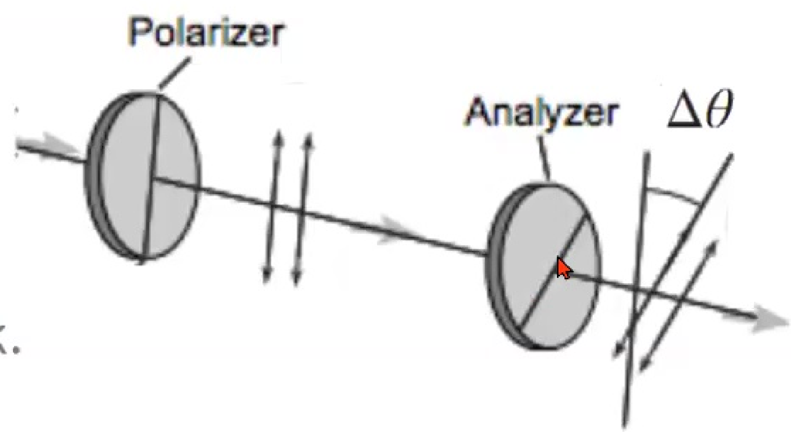


with a Lorentzian distribution for each kick.

Then

$$P(\Delta q) \propto \frac{1}{(\Delta q)^2 + \gamma^2}$$

Impose the constraint $\Delta q = \Delta\theta + n\pi$.

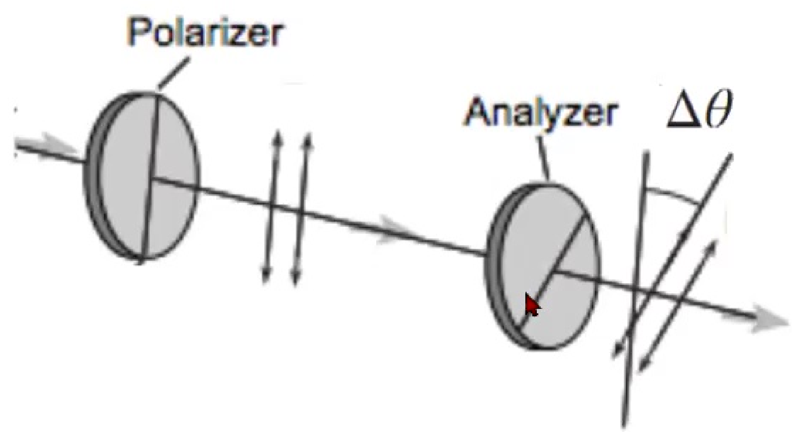
➪ A time-symmetric description. $\gamma \to 0$

Schulman's Lévy-flight model

Quantitative prediction:

Impose either $\Delta q = \Delta\theta + n\pi$

or $\Delta q = \Delta\theta + n\pi + \frac{\pi}{2}$



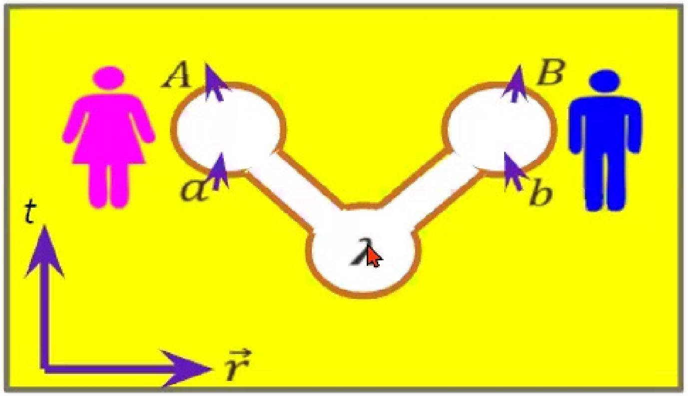
Use $$\sum_{n=-\infty}^{\infty} \frac{1}{(\Delta\theta + n\pi)^2} = \frac{1}{\sin^2(\Delta\theta)}$$

Malus' law, $P = \cos^2(\Delta\theta)$, follows by normalization.

Bell's scenario:

Both photons have the same initial polarization λ

$$P_{a,b}(\lambda) = \frac{1}{4}\left[\delta(a-\lambda) + \delta\left(a + \frac{\pi}{2} - \lambda\right) + \delta(b-\lambda) + \delta\left(b + \frac{\pi}{2} - \lambda\right)\right]$$



Malus' law:

$$P_a(A=1|\lambda) = \cos^2(a-\lambda)$$

Bell correlations:

$$p_{a,b}(A,B) = \tfrac{1}{4}[1 + AB\cos(2a-2b)]$$

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Schulman's Lévy-flight model

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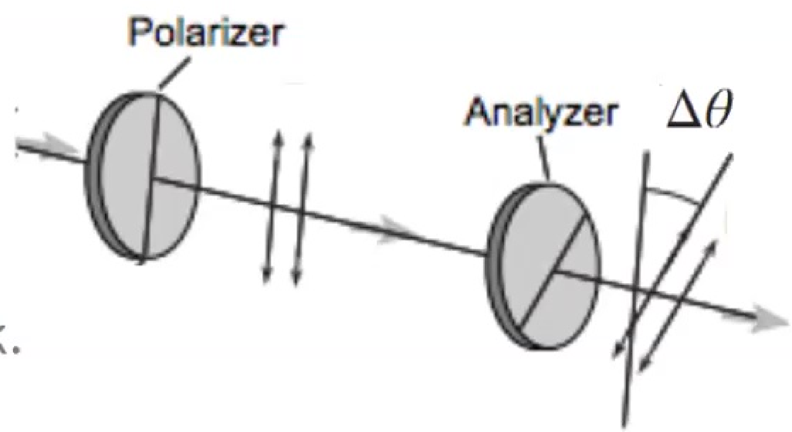

with a Lorentzian distribution for each kick.

Then

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Impose the constraint $\Delta q = \Delta\theta + n\pi$.

⇨ A time-symmetric description. $\gamma \to 0$

Features

Stochastic variables, standard probabilities.

Time symmetry, broken (initial conditions, Feynman-Vernon, etc.).

No tension with relativity. A **locally mediated** model.

Entanglement can be blocked along the photon world lines.

Measuring λ at the source destroys the entanglement (which path).

No tension with the PBR theorem, with Leggett inequalities, etc.

ψ is a state of knowledge, analogous to diffusive p.d.f. for random walk.

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Summary

Models allowing “beables” to have Future-Input Dependence can provide a locally mediated description of entanglement.

Puzzles:

- Generalize to all of QM? to QFT?
- The measurement problem?
- Relate no signaling to the flow of entropy?