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
“..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

---

"...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

Nonlocality, nonseparability, preferred foliation of spacetime, no-signalling, noncontextuality, \(\psi\)-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

\[ p(k|\psi, M) = \int p(k, \lambda|\psi, M) d\lambda = \int d\lambda p(k|\psi, M, \lambda) \rho(\lambda|\psi, M) \]
The assumption

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

M.I: \( \rho(\lambda|\psi, M) = \rho(\lambda|\psi, M') \).

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

- Determinism
  - Correlation between \( \lambda \) and the setting
  - Issues related to 'conspiracy'

- Measurement dependence
  - true for any deterministic theory
  - neuroscientific arguments
  - philosophical arguments

- Issues related to 'free will'

Indrajit Sen (Clemson University)   Exploring alternatives to quantum nonlocality   December 9, 2020
“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 \( \lambda \) 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...”
“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

Indrajit Sen (Clemson University) Exploring alternatives to quantum nonlocality December 9, 2020
\[ M_B = M_B(\gamma_B, \{\beta\}) \]

\[ M_A = M_A(\gamma_A, \{\alpha\}) \]
Superdeterministic conspiracy

\[ M_B = M_B(\gamma_B, \{\beta\}) \]

\[ M_A = M_A(\gamma_A, \{\alpha\}) \]
\[ M_B = M_B(\gamma_B, \{\beta}\} \]
\[ M_A = M_A(\gamma_A, \{\alpha\} \]

Superdeterministic conspiracy
Superdeterministic conspiracy

\[ M_B = M_B(\gamma_B, \{\beta\}) \]

\[ M_A = M_A(\gamma_A, \{\alpha\}) \]
Superdeterministic conspiracy

\[ M_B = M_B(\gamma_B, \{\beta\}) \]

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

cannot be arbitrary

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

\[ \sum_{\lambda} p(O_A, O_B|\lambda, M_A, M_B)p(\lambda|M_A, M_B, \{\alpha\}', \gamma_A', \{\beta\}', \gamma_B') = \sum_{\lambda} p(O_A, O_B|\lambda, M_A, M_B)p(\lambda|M_A, M_B, \{\alpha\}'', \gamma_A'', \{\beta\}'', \gamma_B'') \]

\[ M_A(\{\alpha\}', \gamma_A') = M_A(\{\alpha\}'', \gamma_A'') \text{ and } M_B(\{\beta\}', \gamma_B') = M_B(\{\beta\}'', \gamma_B'') \]
a) Retrocausal model

b) Nonlocal model
Superdeterministic conspiracy

\[
\begin{align*}
\alpha_1 & \to \lambda \to \gamma_1 \\
\alpha_2 & \to \lambda \to \gamma_2 \\
\vdots & \to \lambda \to \gamma_N \\
\beta_1 & \to \lambda \to \gamma_1 \\
\beta_2 & \to \lambda \to \gamma_2 \\
\vdots & \to \lambda \to \gamma_N \\
M_A & \to O_A \\
M_B & \to O_B
\end{align*}
\]
No features of quantum statistics used
Quantification of finetuning

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

- Overhead fine-tuning parameter
- Total number of final configurations
- Total number of initial distributions
- Discretisation parameter, \( p(\lambda|\ldots) = 1/L \)
- Size of ontic-space

Indrajit Sen  (Clemson University)  
Exploring alternatives to quantum nonlocality  
December 9, 2020
For a superdeterministic model with only a single distribution \( p(\lambda|M_A, M_B) \),

\[
F = 1 - \frac{V(\Lambda, L)^4}{V(\Lambda, L)^\Omega}
= 1 - V(\Lambda, L)^{4-N2^{2N}}
\]

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

For more general superdeterministic models, the minimum finetuning is

\[
F = 1 - \prod_{A,B} \left( \sum_{j=1}^{V(\Lambda,L)} \left( \frac{V^{j}_{AB}(\Lambda, L)/V(\Lambda, L)}{V(\Lambda, L)} \right)^{\Omega-1} \right)
= 1 - \prod_{A,B} \left( \sum_{j=1}^{V(\Lambda,L)} \left( \frac{V^{j}_{AB}(\Lambda, L)/V(\Lambda, L)}{V(\Lambda, L)} \right)^{N2^{2N-2}-1} \right)
\]

In this case, \( 0 < F < 1 \) for any \( N > 1 \).

---

Does superdeterministic signalling constitute an actual signal?

a) Nonlocal

b) Retrocausal

c) Superdeterministic

---

Indrajit Sen  (Clemson University)   Exploring alternatives to quantum nonlocality   December 9, 2020
Does superdeterministic signalling constitute an actual signal?

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

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

‘No-signalling’ $\rightarrow$ Marginal-independence
Is there a conversation?
Is there a conversation?

A series of coincidences mimicking an actual conversation...
\[ p(\lambda|\mathcal{M}_A, \mathcal{M}_B, \{\alpha\}, \{\beta\}, \gamma_A = i, \gamma_B = j) = p(\lambda|\mathcal{M}_A, \mathcal{M}_B, \alpha_i, \beta_j, \gamma_A = i, \gamma_B = j) \]

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

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

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

\[ E = (\gamma_A, \gamma_B) \]
\[ W = N^2 N_0 \]
\[ S = -\sum_{k=1}^{W} p(k) \log_2 p(k) \]

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


Indrajit Sen  (Clemson University)  Exploring alternatives to quantum nonlocality  December 9, 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 \(\sim 100H(\lambda : M_A, M_B)\).
In a recent M.D model, $H(\lambda : M_A, M_B) \sim 0.08$ 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 $\sim 100H(\lambda : M_A, M_B)$.

This approach does not use arbitrary initial distributions.
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 \(\sim 100H(\lambda : M_A, M_B)\).

This approach does not use arbitrary initial distributions.

**Verdict:** Superdeterminism is conspiratorial and we can quantitatively discuss this in two separate ways.
Abraham-Lorentz equation: \( m(\dot{v} - \tau \ddot{v}) = F_{\text{ext}} \), where \( \tau = \frac{2e^2}{3c^3} \).
Retrocausality

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

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

The acceleration of the particle at time \( t \) depends on the force applied after time \( t \).
Retrocausal Brans model
Retrocausal Brans model

\[ |\chi_1\rangle + |\chi_2\rangle \]

\[ |\hat{\chi}_1\rangle + |\hat{\chi}_2\rangle \]

\[ \psi \text{ singlet} \]

\[ D_1 \rightarrow P \rightarrow D_2 \]
Ontology

Joint ontic quantum state: \( \langle \vec{r}_1 | \langle \vec{r}_2 | \psi_0(t) \rangle = \chi_1(\vec{r}_1, t) | i_1 \rangle_a \otimes \chi_2(\vec{r}_2, t) | i_2 \rangle_b \). Evolves via the Schrödinger equation.

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

Ontology

Joint ontic quantum state: $\langle \vec{r}_1 | \langle \vec{r}_2 | \psi_0(t) \rangle = \chi_1(\vec{r}_1, t)|i_1\rangle_a \otimes \chi_2(\vec{r}_2, t)|i_2\rangle_b$. Evolves via the Schrödinger equation.

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

Local, Separable, 3D pilot-waves.
Ontology

Joint ontic quantum state: \( \langle \vec{r}_1 | \langle \vec{r}_2 | \psi_0(t) \rangle = \chi_1(\vec{r}_1, t) |i_1\rangle_a \otimes \chi_2(\vec{r}_2, t) |i_2\rangle_b \). Evolves via the Schrodinger equation.

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

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

\[ |\psi\rangle_{\text{singlet}} = c_{++} |+\rangle_a |+\rangle_b + c_{+-} |+\rangle_a |-\rangle_b + c_{-+} |-\rangle_a |+\rangle_b + c_{--} |-\rangle_a |-\rangle_b. \]

The initial distribution of positions \( \rho(\vec{r}_1, \vec{r}_2, 0) = |\chi_1(\vec{r}_1, 0)|^2 |\chi_2(\vec{r}_2, 0)|^2 \).
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 \( \vec{v} = \frac{\nabla S(\vec{r}, t)}{m} \).

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

\[ |\psi\rangle_{\text{singlet}} = c_{++} |+\rangle_a |+\rangle_b + c_{+-} |+\rangle_a |-\rangle_b + c_{-+} |-\rangle_a |+\rangle_b + c_{--} |-\rangle_a |-\rangle_b \].

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

\( \psi \)-epistemic

Bell correlations reproduced.
Mathematical formulation

Ontology

Joint ontic quantum state: \( \langle \vec{r}_1 | \langle \vec{r}_2 | \psi_0(t) \rangle = \chi_1(\vec{r}_1, t) | \hat{\imath}_1 \rangle_a \otimes \chi_2(\vec{r}_2, t) | \hat{\imath}_2 \rangle_b \). Evolves via the Schrodinger equation.

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

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 \( |\psi\rangle_{\text{singlet}} = c_{++}|+\rangle_a |+\rangle_b + c_{+-}|+\rangle_a |-\rangle_b + c_{-+}|+\rangle_a |+\rangle_b + c_{--}|+\rangle_a |+\rangle_b \).

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

\( \psi \)-epistemic

Bell correlations reproduced.
A relativistic Bell scenario

\[ \Delta \tau_r < \Delta \tau_e \]

Indrajit Sen  (Clemson University)  Exploring alternatives to quantum nonlocality  December 9, 2020
The total Hamiltonian of the systems in non-relativistic quantum mechanics

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

valid approximation iff \( p_e, p_r \ll mc \)

Impossible in any single frame of reference.
The total Hamiltonian of the systems in non-relativistic quantum mechanics

\[ \hat{H} = \left( \frac{\hat{p}_r^2}{2m} \otimes \hat{1} \otimes \hat{1} \otimes \hat{1} + g\hat{p}_r \otimes \hat{\sigma}_r \otimes \hat{1} \otimes \hat{1} \right) + \left( \hat{1} \otimes \hat{1} \otimes \frac{\hat{p}_e^2}{2m} \otimes \hat{1} + g\hat{1} \otimes \hat{1} \otimes \hat{p}_e \otimes \hat{\sigma}_e \right) \]

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

\[
\chi_r(\vec{x}_r, t) \rightarrow \chi_r(\vec{x}_r, \tau_r) \\
\chi_e(\vec{x}_e, t) \rightarrow \chi_e(\vec{x}_e, \tau_e)
\]

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

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

\[
\hat{H}_r \chi_r(\vec{x}_r, \tau_r) |i_1\rangle_r = i \frac{\partial \chi_r(\vec{x}_r, \tau_r)}{\partial \tau_r} |i_1\rangle_r
\]
Description in the retrocausal model

Ontology
\[
\hat{H}_r\chi_r(x_r, t)|i_1\rangle_r \otimes \chi_e(x_e, t)|i_2\rangle_e = i\frac{d\chi_r(x_r, t)|i_1\rangle_r \otimes \chi_e(x_e, t)|i_2\rangle_e}{dt}
\]
\[
\hat{H}_e\chi_e(x_e, \tau_e)|i_1\rangle_e = i\frac{\partial \chi_e(x_e, \tau_e)|i_1\rangle_e}{\partial \tau_e}
\]
\[
\hat{H}_r\chi_r(x_r, \tau_r)|i_1\rangle_r = i\frac{\partial \chi_r(x_r, \tau_r)|i_1\rangle_r}{\partial \tau_r}
\]

\[
\frac{\nabla S(x, t)}{m} \rightarrow \frac{\nabla S(x, \tau)}{m}
\]

Distribution
\[
|\psi(t)\rangle \rightarrow |\psi(\tau_e, \tau_r)\rangle
\]
\[
\hat{H}|\psi(t)\rangle = i\frac{d|\psi(t)\rangle}{dt}
\]
\[
\hat{H}_e|\psi(\tau_e, \tau_r)\rangle = i\frac{\partial |\psi(\tau_e, \tau_r)\rangle}{\partial \tau_e}
\]
\[
\hat{H}_r|\psi(\tau_e, \tau_r)\rangle = i\frac{\partial |\psi(\tau_e, \tau_r)\rangle}{\partial \tau_r}
\]
Retrocausality in relativistic settings

a) Earth lab

\[ 2g \Delta \tau_e \]

b) Rocket lab

\[ 2g \Delta \tau_r \]
Problems in defining the notion of a particle\textsuperscript{6}.
Problems in defining the notion of a particle\(^6\).

No time-dependent description of the measurement process.
Problems in defining the notion of a particle\textsuperscript{6}.

No time-dependent description of the measurement process.

Particle number not conserved.
Description in Pilot-wave theory

Proper treatment involves qft version.
Suppose $|\psi(\tau_e(t), \tau_r(t))\rangle$ is a nonlocal guiding wave for particle positions.
Nonlocal velocity field depends on the preferred foliation.
Proper treatment involves qft version.

Suppose $|\psi(\tau_e(t), \tau_r(t))\rangle$ is a nonlocal guiding wave for particle positions.

Nonlocal velocity field depends on the preferred foliation.

Hypersurfaces tangent to the simultaneity surfaces?
Proper treatment involves qft version.
Suppose $|\psi(t, \tau(t))\rangle$ is a nonlocal guiding wave for particle positions.
Nonlocal velocity field depends on the preferred foliation.

Hypersurfaces tangent to the simultaneity surfaces?
Possible for all trajectories?
Description in Pilot-wave theory

Proper treatment involves qft version.
Suppose $|\psi(\tau_e(t), \tau_r(t))\rangle$ is a nonlocal guiding wave for particle positions.
Nonlocal velocity field depends on the preferred foliation.

Hypersurfaces tangent to the simultaneity surfaces?
Possible for all trajectories?
Suppose a foliation $\mathcal{F}$.
Born distribution on leaves of the foliation.
Description in Pilot-wave theory

Proper treatment involves qft version.
Suppose $|\psi(\tau_e(t), \tau_r(t))\rangle$ is a nonlocal guiding wave for particle positions.
Nonlocal velocity field depends on the preferred foliation.

Hypersurfaces tangent to the simultaneity surfaces?
Possible for all trajectories?
Suppose a foliation $\mathcal{F}$.
Born distribution on leaves of the foliation.
Non-Born rule distribution if $\sigma \notin \mathcal{F}$. 
Proper treatment involves qft version.
Suppose $|\psi(\tau_e(t), \tau_r(t))\rangle$ is a nonlocal guiding wave for particle positions.
Nonlocal velocity field depends on the preferred foliation.

Hypersurfaces tangent to the simultaneity surfaces?
Possible for all trajectories?
Suppose a foliation $\mathcal{F}$.
Born distribution on leaves of the foliation.
Non-Born rule distribution if $\sigma \not\in \mathcal{F}$.

No direct experimental contradiction.
$|\psi(\tau_e, \tau_r)\rangle$ is ontological.
Measurement results due to instantaneous collapse.
$\psi$-onticity and collapse $\rightarrow$ nonlocality (preferred frame).
\[ |\psi(\tau_e, \tau_f)\rangle \] is ontological.

Measurement results due to instantaneous collapse.

\( \psi \)-onticity and collapse \( \rightarrow \) nonlocality (preferred frame).
$|\psi(\tau_e, \tau_r)\rangle$ is ontological.
Measurement results due to instantaneous collapse.
$\psi$-onticity and collapse $\rightarrow$ nonlocality (preferred frame).

‘Flash’ ontology models.
$|\psi(\tau_e, \tau_r)\rangle$ never collapses.
\[ |\psi(\tau_e, \tau_r)\rangle \] is ontological.

Measurement results due to instantaneous collapse.

\(\psi\)-onticity and collapse \(\rightarrow\) nonlocality (preferred frame).

‘Flash’ ontology models.

\[ |\psi(\tau_e, \tau_r)\rangle \] never collapses.

Probabilities not objective descriptions of the flash process.
Description in Collapse models

\(|\psi(\tau_e, \tau_r)\rangle\) is ontological.
Measurement results due to instantaneous collapse.
\(\psi\)-onticity and collapse \(\rightarrow\) nonlocality (preferred frame).

‘Flash’ ontology models.
\(|\psi(\tau_e, \tau_r)\rangle\) never collapses.
Probabilities not objective descriptions of the flash process.

**Bottom-line:** \(\psi\)-epistemicity, locality, separability are useful properties.
Summary

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

Superdeterminism – requires overhead finetuning, requires arbitrary large correlations.
Can violating M.I. provide a credible alternative to quantum nonlocality?

- **Superdeterminism** – requires overhead finetuning, requires arbitrary large correlations.
- **Retrocausality** – Appears to have advantages in describing relativistic effects on entangled quantum systems.
Summary

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

- **Superdeterminism** – requires overhead finetuning, requires arbitrary large correlations.
- **Retrocausality** – Appears to have advantages in describing relativistic effects on entangled quantum systems.

Which idea does Nature use?

Indrajit Sen  (Clemson University)  
Exploring alternatives to quantum nonlocality  
December 9, 2020
Future work

Near future

- Palmer’s superdeterministic proposal\(^7\) \(\rightarrow\) 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.

---

Thank you!

Questions?

Indrajit Sen  (Clemson University)  Exploring alternatives to quantum nonlocality  December 9, 2020