The EPR experiment: what does it tell us?

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“Causarum Investigatio and the Two Bell’s Theorems of John Bell” (H. Wiseman), http://arxiv.org/abs/1503.06413
Loophole–free Bell inequality violation using electron spins separated by 1.3 kilometres

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More than 50 years ago¹, John Bell proved that no theory of nature that obeys locality and realism² can reproduce all the predictions of quantum theory: in any local-realist theory, the correlations between outcomes of measurements on distant particles satisfy an inequality that can be violated if the particles are entangled. Numerous Bell inequality tests have been reported³-¹³; however, all experiments reported so far required additional assumptions to obtain a contradiction with local realism, resulting in ‘loopholes’¹³-¹⁶. Here we report a Bell experiment that is free of any such additional assumption and thus directly tests the principles underlying Bell’s inequality. We use an event-ready scheme¹⁷-¹⁹ that enables the generation of robust entanglement between distant electron spins (estimated state fidelity of 0.92 ± 0.03). Efficient spin read-out avoids the fair-sampling assumption (detection sufficiently separated such that locality prevents communication between the boxes during a trial, then the following inequality holds under local realism:

\[ S = |\langle x \cdot y \rangle_{(0,0)} + \langle x \cdot y \rangle_{(0,1)} + \langle x \cdot y \rangle_{(1,0)} - \langle x \cdot y \rangle_{(1,1)}| \leq 2 \] (1)

where \( \langle x \cdot y \rangle_{(a,b)} \) denotes the expectation value of the product of \( x \) and \( y \) for input bits \( a \) and \( b \). (A mathematical formulation of the concepts underlying Bell’s inequality is found in, for example, ref. 25.)

Quantum theory predicts that the Bell inequality can be significantly violated in the following setting. We add one particle, for example an electron, to each box. The spin degree of freedom of the electron forms a two-level system with eigenstates |\( 1 \rangle \) and |\( 0 \rangle \). For each trial, the two spins are prepared into the entangled state |\( \psi^- \rangle = (|1\rangle \otimes |1\rangle - |0\rangle \otimes |0\rangle) / \sqrt{2} \). The spin in box A is then measured along direction \( y \) for input bit x.
Bell inequality

Make a plan for answering three Yes/No questions.

- Always
- $1/3$ of the time
- Always

Whatever plan is followed, two (different) random questions will get the same answer at least $1/3$ of the time.
Top-level Executive summary

Einstein Podolsky Rosen experiments show that nature is “weird” in some way.

EPR expts are often said to disprove “local realism”. But according to Bell* and others they directly violate Locality itself.

What do we mean by “Locality”? Strong Locality

Where does “realism” come in? It doesn’t, other than Determinism.

<table>
<thead>
<tr>
<th>Principle</th>
<th>EPR verdict</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong Locality</td>
<td>ruled out</td>
</tr>
<tr>
<td>Lorentz Invariance</td>
<td>not ruled out</td>
</tr>
<tr>
<td>Signal Locality</td>
<td>not ruled out</td>
</tr>
<tr>
<td>Determinism</td>
<td>“under stress”</td>
</tr>
</tbody>
</table>

* Bell argued an even stronger case: that EPR violates “local causality”.
Quantum Mechanics has weird features: it violates cherished principles like Determinism and Strong Locality.

EPR is about the weirdness of Nature. Will any future theory that replaces QM have to be equally weird?

- EPR experiments help us to see how weird nature itself is.
- EPR experiments tell us that some cherished principles will have to be violated by any future theory.

But... which ones?
Mid-level Executive summary

EPR-type experiments show that:

- **Strong Locality** is False
- **Determinism** is OK, but...

- **Lorentz Invariance** is OK
- **Signal Locality** is OK, but doesn’t seem like a proper physical principle.
- some amount of **Indeterminism** makes it easier to preserve Signal Locality

where “OK” means “not ruled out by EPR experiment”.
The key principles

**Determinism**: Events are predetermined by earlier events. If you know enough of the history, all probabilities of events are 0 or 1.

Leads to “counterfactual definiteness”: it is meaningful to talk about “what would have happened if...” (e.g., what if detector settings had been different from what they actually are).

Wiseman (Nature 526, 649 (2015)) says this is “realism”.

**Strong Locality**: The probability of an event only depends on events in its past light cone.
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Strong Locality: The probability of an event only depends on events in its past light cone.

In EPR experiments, an “event” is something like

- setting what a detector will measure
- a detector giving a measurement result
- the creation of a pair of photons
Determinism

Events are predetermined by earlier events

All uncertainty about the future arises from our ignorance of the current state of the system

Indeterminism

The time evolution of a system has an essentially random component

Some uncertainty about the future arises from fundamental randomness in time evolution of systems
Strong Locality (simple version)

Strong Locality:
The probability of an event only depends on events in its past light cone.

There hasn’t been time for a flash of light created at $C$ to reach $E$.

$E$ cannot be affected by $C$. 
Strong Locality (full version)

Strong locality means *factorization* of probabilities:

The probability of an event is *statistically independent* of everything outside the event’s past light cone.

\[
\text{prob}(E_1, E_2 \mid P_1, P_2, \lambda) = \text{prob}(E_1 \mid P_1, \lambda) \times \text{prob}(E_2 \mid P_2, \lambda)
\]
Meaning of Strong Locality

Strong Locality is

- An operational definition of locality.
- Does not commit to any concept of causation.
- Uses the concept of one correlation “arising from” another.
- Captures our intuition that correlations between spacelike-separated events should arise from each event being correlated with something in their shared history.

\[
\text{prob}(E_1, E_2 \mid P_1, P_2, \lambda) = \text{prob}(E_1 \mid P_1, \lambda) \times \text{prob}(E_2 \mid P_2, \lambda)
\]

- If two events are uncorrelated, their joint prob factorizes,
  \[
  \text{prob}(A, B) = \text{prob}(A) \text{prob}(B).
  \]
- If two events are correlated, their joint prob doesn’t factorize.
- If two events are correlated only because they are both correlated with another event \(\lambda\), not because of any direct connection, then
  \[
  \text{prob}(A, B \mid \lambda) = \text{prob}(A \mid \lambda) \text{prob}(B \mid \lambda)
  \]
“Textbook” QM violates everything

“Textbook” Quantum Mechanics:

- **Indeterminism** — results of measurements are “chosen” randomly when wavefunction collapses
- **Non-locality** — the wavefunction collapses instantaneously over all space
Is nature as weird as QM suggests?

Maybe we could find a non-weird theory that’s equally good:

- **Deterministic**: Systems evolve predictably with no essential randomness.
- **Strongly Local**: Events are only affected by occurrences in their past light cone.

Could QM eventually be replaced with a theory that was Strongly Local and/or Deterministic?

Einstein-Podolsky-Rosen-Bohm experiment says **No**: Nature itself violates Strong Locality
The data refutes Strong Locality in two stages:

- **Same-question agreement** in EPRB results
  ⇒ **Strongly Local** theories **must** be **Deterministic**
- **Violation of Bell inequality** in EPRB results
  ⇒ **Strongly Local** theories **cannot** be **Deterministic**
Einstein-Podolsky-Rosen-Bohm (EPRB) expt

Each detector has 3 filters, A, B, C.

When the photons get close, the detectors choose which filter to deploy.

Filter B

Filter C

Each photon either:
- passes through its filter
- reflects off its filter

B: C:
Result:

Filter B
Filter C

The detectors are so far apart that there is no time for influences that travel slower than light to tell one detector what the other did.
Einstein-Podolsky-Rosen-Bohm (EPRB) expt

Each detector has 3 filters, A,B,C.

When the photons get close, the detectors choose which filter to deploy.

Each photon either:
+ passes through its filter
− reflects off its filter

Filter B

Filter C

Each photon gets close to the detectors,
Which filter to deploy?

Filter C

Filter B

Result:
B: −   C: +

The detectors are so far apart that there is no time for influences that travel slower than light to tell one detector what the other did.
Testing twins for superluminal abilities

Start with a large crowd of twins.

Each pair of twins is tested once:

- Take the twins far apart.
- Each twin is asked one randomly-chosen Yes-or-No question.
- There are three possible questions, e.g.
  - A: Do you like Avocado?
  - B: Do you like Beef?
  - C: Do you like Cheese?
## EPRB Experimental data

\[ + = \circ, \quad - = \frown \]

<table>
<thead>
<tr>
<th></th>
<th>twin 1</th>
<th>twin 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beef: -</td>
<td>Cheese: +</td>
<td></td>
</tr>
<tr>
<td>Cheese: +</td>
<td>Cheese: +</td>
<td>⇐</td>
</tr>
<tr>
<td>Beef: +</td>
<td>Avocado: -</td>
<td></td>
</tr>
<tr>
<td>Avocado: +</td>
<td>Avocado: +</td>
<td>⇐</td>
</tr>
<tr>
<td>Cheese: -</td>
<td>Avocado: -</td>
<td>⇐</td>
</tr>
<tr>
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<td>⇐</td>
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<td></td>
</tr>
<tr>
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<td>Cheese: -</td>
<td></td>
</tr>
<tr>
<td>Avocado: -</td>
<td>Beef: +</td>
<td></td>
</tr>
<tr>
<td>Beef: +</td>
<td>Beef: +</td>
<td>⇐</td>
</tr>
<tr>
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<td>Beef: +</td>
<td>⇐</td>
</tr>
<tr>
<td>Beef: +</td>
<td>Avocado: +</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Whenever both twins get asked the **same** question, their answers **always agree**.

Whenever both twins get asked the **different** questions, their answers **only agree 1/4 of the time**.

What does this tell us?
EPRB data: communication or planning?

How do the twins manage to always agree when asked the same question?
EPRB data: communication or planning?

How do the twins manage to always agree when asked the same question?

(1) They communicate
Violates Strong Locality

(2) They have a plan
Requires Determinism

Same-question agreement says:

<table>
<thead>
<tr>
<th>Strong Locality</th>
<th>requires</th>
<th>Determinism</th>
</tr>
</thead>
<tbody>
<tr>
<td>No communication</td>
<td></td>
<td>The twins follow a plan</td>
</tr>
</tbody>
</table>
Could the twins be following a plan?

I.e., can we have Strong Locality and Determinism?

The fact that \{ \text{when asked different questions} \begin{align*}
&\text{they only agree 1/4 of the time}
\end{align*}\} says No.
Could the twins be following a plan?

I.e., can we have Strong Locality and Determinism?

The fact that \( \{ \text{when asked different questions they only agree 1/4 of the time} \} \) says No.

Bell inequality:

If twins are following a plan then, when each twin in a pair is asked a different randomly chosen question, their answers will be the same, on average, at least 1/3 of the time.

Possible sets of planned answers:

- (a) Yes Yes
- (b) No Yes
- (c) Yes No
- (d) No No

Likelihood of getting the same answer to two different random questions:

- (a) always
- (b) 1/3 of the time
- (c) 1/3 of the time
- (d) always
Summary: Nature violates Strong Locality

In order to agree without communicating, twins must follow a plan.

\[ \text{Strong Locality and same-question agreement} \Rightarrow \text{Determinism} \]

But if twins follow a plan and don’t communicate then they would agree fairly often when asked different questions and we don’t see that.

\[ \text{Strong Locality and Determinism} \Rightarrow \text{Bell Inequality,} \]
\[ \text{(which is violated by the data.} \]

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**Diagram:**

- **Strongly Local**: Red
- **Deterministic**: Green
- **Quantum Mechanics**: Blue
- **Textbook**: Purple

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Strong Locality violation means what?

The probability of an event is not statistically independent of everything outside the event’s past light cone.

\[ \text{prob}(E_1, E_2 \mid P_1, P_2, \lambda) \neq \text{prob}(E_1 \mid P_1, \lambda) \times \text{prob}(E_2 \mid P_2, \lambda) \]

This non-locality is not just a feature of QM, it’s a feature of Nature.
But what about...

Relativity

► Don’t we know that nothing can go faster than light?
► Does EPR contradict the Principle of Relativity?
► Does EPR contradict Lorentz Invariance?

*One of my missions in life is to get people to see that if they want to talk about the problems of quantum mechanics—the real problems of quantum mechanics—they must be talking about Lorentz invariance.* (John Bell)

Determinism

► Doesn’t EPR say something about Nature not being Deterministic?
► Could QM eventually be replaced by a theory that is Deterministic (but not Strongly Local)?
EPR and Relativity

<table>
<thead>
<tr>
<th>Principle of Relativity</th>
<th>Lorentz Invariance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laws of physics are the same in all inertial frames</td>
<td>=</td>
</tr>
<tr>
<td>Laws of physics are invariant under rotations and boosts</td>
<td></td>
</tr>
</tbody>
</table>

EPR is consistent with Relativity

Why?

- Because of Quantum Field Theory?
  No. QFT is a form of QM; it includes the measurement postulate, which violates Relativity (wavefunction collapses instantaneously).

- There is a Lorentz-invariant modification of QM (spontaneous collapse theory) that is consistent with EPR. (Tumulka, arXiv:quant-ph/0406094)
  Whether this theory is valid or not, it shows that EPR does not contradict Relativity.
EPR and superluminal signalling

Superluminal signalling cannot be allowed!
You could send a message to the past $\Rightarrow$ causal paradoxes (assuming Relativity and Free Will)

Superluminal signalling requires both:
1. Superluminal transfer of information,
2. Control over the information that is transferred.

The natural way to forbid superluminal signalling is:

Impose strong locality $\Rightarrow$ no superluminal information transfer

But EPR tells us that strong locality is violated!
There are superluminal correlations that transfer information.

How is signal locality preserved?
Signal Locality and Uncontrollability

To preserve signal locality, the EPR information transfer must be *uncontrollable*.

Already this is weird. “Controllability” is not a fundamental physics concept. It is based on high-level concepts such as agency and free will.

How can the laws of nature guarantee that the EPR information transfer will always be uncontrollable?

(1) In an *indeterministic* theory (like QM), if the superluminally transferred information arose from the indeterministic evolution, then there would be no way to control it.

(2) In a *deterministic* theory (like Bohmian Mechanics), we need some special mechanism to ensure that no one can control the information that is transferred superluminally.
EPR-type experiments show that

- **Strong Locality is Violated**
  There are superluminal correlations in nature.

- **Determinism is OK, but**
  **Indeterminism** makes it easier to preserve Signal Locality.

- **Lorentz Invariance** is OK

(where “OK” means “not ruled out by EPR experiment”)

If Lorentz Invariance is valid, can we find a Lorentz-invariant alternative to wavefunction collapse?
Background assumptions

1. **Macro-realism**: Each measurement has a unique outcome.
2. **Random choices**: each experimenter’s choice of what to measure is random; uncorrelated with the particle states and the other experimenter’s choices.
3. **Perfect detectors**: This “inefficiency loophole” was closed by Hensen et al.

Who would disagree?

- Many-worlds believers would deny **Macro-realism**.
  Need to explain how decoherence leads to probabilistic predictions.
- A Superdeterminist would deny **Random choices**
  But experimenter choices can be made effectively random.
- Retrocausality believers think the experimenters’ choices can affect the preparation of the particles. Causal paradoxes!
What next?

- Close the **random choices** loophole: each experimenter uses a noise source that is outside the other experiment’s past light cone.

- If we believe in **Macro-realism**, can we find and empirically validate a **Lorentz-invariant** version of wavefunction collapse in textbook QM?

- If we don’t believe in **Macro-realism**, can we show that **Lorentz-invariant** many-worlds-type QM (no wavefunction collapse) leads to the same predictions as textbook QM (non-local collapse)? (Kent, arXiv:0905.0624; Hsu, arXiv:1511.08881; “Many worlds? Everett, quantum theory, and reality”, OUP, 2010.)

- Is there a **Lorentz-invariant Deterministic** theory that could replace QM? (E.g. a **Lorentz-invariant Bohmian Mechanics**?)