The EPR experiment: what does it tell us?

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"Ghostly action at a distance: a non-technical explanation of the Bell inequality"
http://arxiv.org/abs/1506.02179 (American Journal of Physics).

"Causarum Investigatio and the Two Bell's Theorems of John Bell"
(H. Wiseman), http://arxiv.org/abs/1503.06413

LETTER

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Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

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More than 50 years ago[1], John Bell proved that no theory of nature that obeys locality and realism[2] 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 reported[3–13]; 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 scheme[17–19] 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:

$$S = \left| \langle x \cdot y \rangle_{(0,0)} + \langle x \cdot y \rangle_{(0,1)} + \langle x \cdot y \rangle_{(1,0)} - \langle x \cdot y \rangle_{(1,1)} \right| \leq 2 \qquad (1)$$

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.)

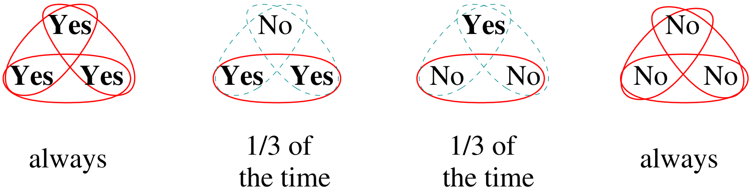
Quantum theory predicts that the Bell inequality can be significantly violated in the following setting. We add one particle, for example an electron, to each box. The spin degree of freedom of the electron forms a two-level system with eigenstates $|\uparrow\rangle$ and $|\downarrow\rangle$. For each trial, the two spins are prepared into the entangled state $|\psi^-\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$.

Do EPR experiments falsify "local realism" ?

Not according to Bell himself.

Bell inequality

Make a plan for answering three Yes/No questions.



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.

Principle	EPR verdict
Strong Locality	**ruled out**
Lorentz Invariance	not ruled out
Signal Locality	not ruled out
Determinism	"under stress"

* Bell argued an even stronger case: that EPR violates "local causality".

Is EPR about Quantum Mechanics?

No.

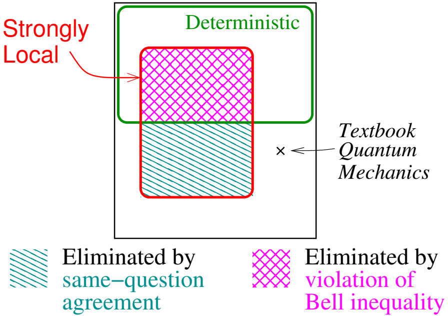
Quantum Mechanics has weird features: it violates cherished principles like Determinism and Strong Locality.

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.

The key principles

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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

Determinism

Events are predetermined by earlier events

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

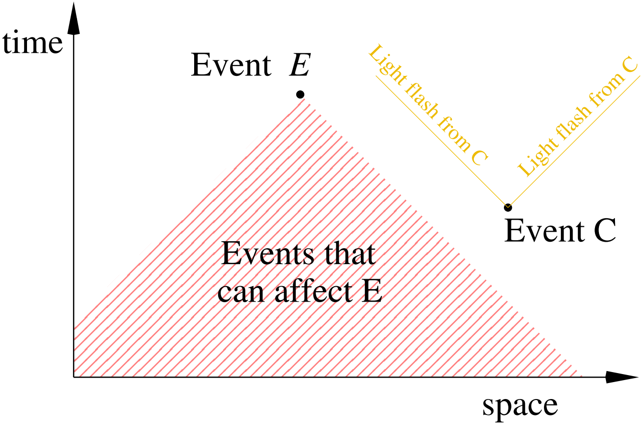
Indeterminism

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.



E cannot be affected by C.

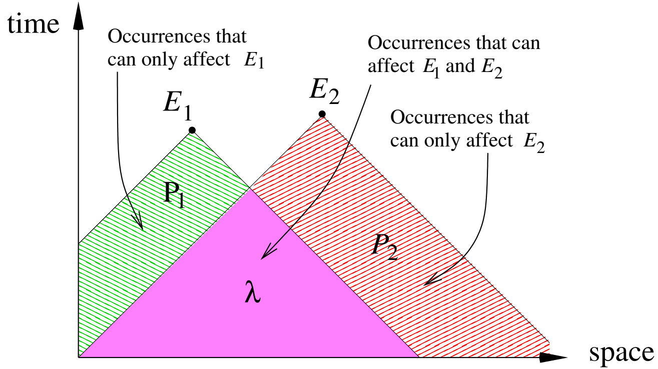
There hasn't been time for a flash of light created at C to reach E.

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 λ, not because of any direct connection, then
  $$\text{prob}(A, B|\lambda) = \text{prob}(A|\lambda)\,\text{prob}(B|\lambda)$$

"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:

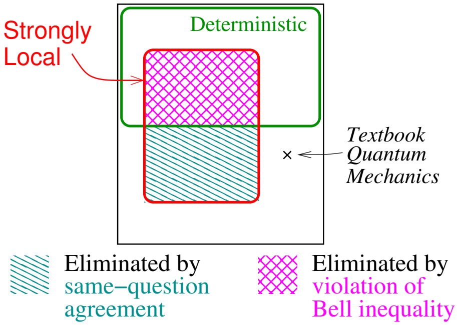
- Deterministic: Systems evolve predictably with no essential randomness.
- Strongly Local: Events are only affected by occurrences in their past light cone.

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

Strong Locality vs. the EPR expt



The data refutes Strong Locality in two stages:

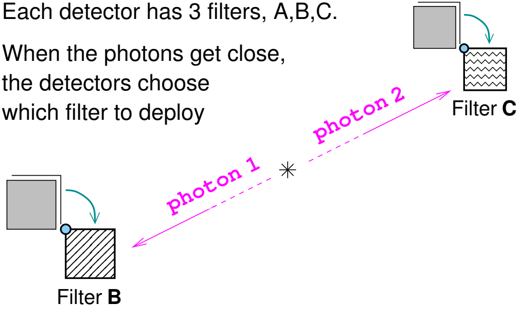
• Same-question agreement in EPRB results
⇒ Strongly Local theories <u>must</u> be Deterministic

• Violation of Bell inequality in EPRB results
⇒ Strongly Local theories <u>cannot</u> 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



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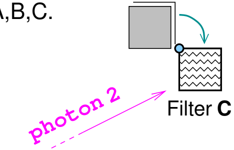
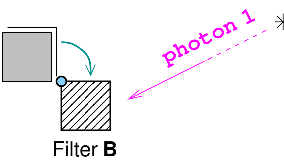
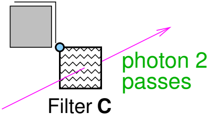


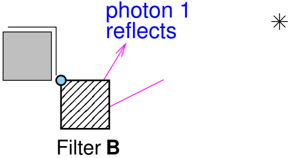


Each photon either:

+ passes through its filter

− reflects off its filter



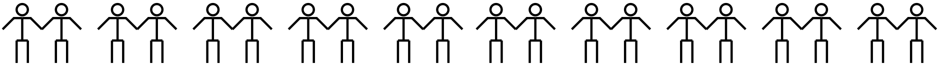


Result:

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.

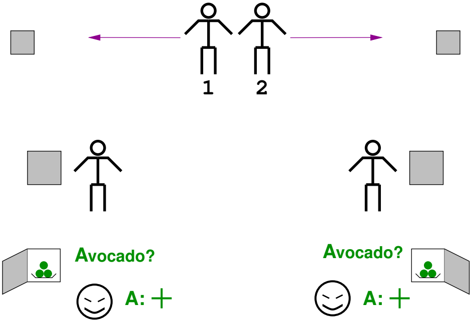
Testing twins for superluminal abilities



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

$+ = ☺, \quad - = ☹$

twin 1	twin 2	
Beef: −	Cheese: +	
Cheese: +	Cheese: +	⇐
Beef: +	Avocado: −	
Avocado: +	Avocado: +	⇐
Cheese: −	Avocado: −	←
Beef: −	Beef: −	⇐
Beef: −	Avocado: +	
Avocado: +	Cheese: −	
Avocado: −	Beef: +	
Beef: +	Beef: +	⇐
Cheese: +	Beef: +	←
Beef: +	Avocado: +	
...		

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

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

What does this tell us?

EPRB data: communication or planning?

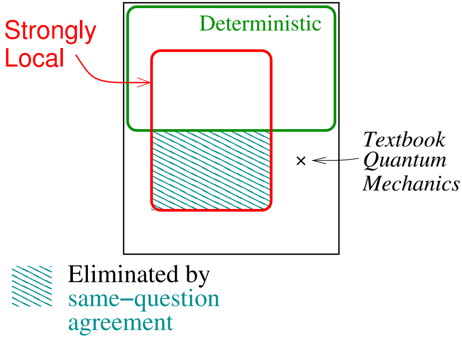
How do the twins manage to always agree when asked the same question?

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:

Strong Locality No communication	*requires*	Determinism The twins follow a plan

Could the twins be following a plan?

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

The fact that $\left\{ \begin{array}{l} \text{when asked different questions} \\ \text{they only agree 1/4 of the time} \end{array} \right\}$ says **No**.

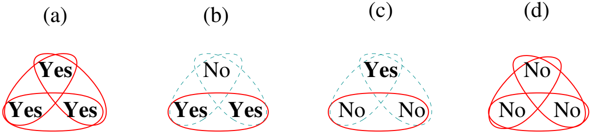
Could the twins be following a plan?

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

The fact that { 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.



	(a)	(b)	(c)	(d)
Possible sets of planned answers:	Yes, Yes, Yes	No, Yes, Yes	Yes, No, No	No, No, No
Likelihood of getting the same answer to two different random questions	always	1/3 of the time	1/3 of the time	always

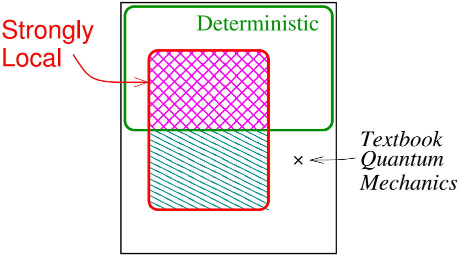
Summary: Nature violates Strong Locality

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

(Strong Locality and same-question ageement ⇒ 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.

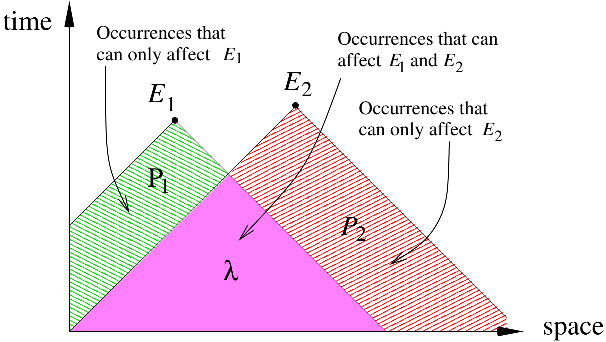
(Strong Locality and Determinism ⇒ Bell Inequality, which is violated by the data.)



Strong Locality violation means what?

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

$$\mathrm{prob}(E_1, E_2 \,|\, P_1, P_2, \lambda) \neq \mathrm{prob}(E_1 \,|\, P_1, \lambda) \times \mathrm{prob}(E_2 \,|\, P_2, \lambda)$$



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

Principle of Relativity		Lorentz Invariance
Laws of physics are the same in all inertial frames	=	Laws of physics are invariant under rotations and boosts

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 ⇒ 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 ⇒ no superluminal information transfer

But EPR tells is 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 ?

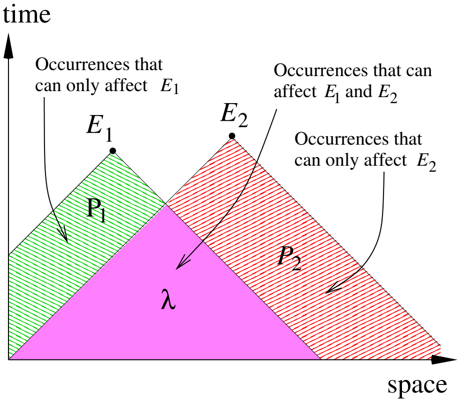
Summary

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 Superdeteterminist 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?)