Faster than light: spooky action at a distance in nature

Mark Alford
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Youtube:

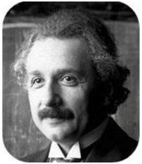
https://www.youtube.com/watch?v=u3FUZ9OvIJ0

Article:

http://arxiv.org/abs/1506.02179

Einstein's Speed Limit

Einstein (1905)



Nothing can go faster than light.

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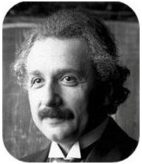

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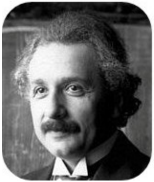

If information can never go faster than light then quantum mechanics is not the whole story.
Einstein-Podolsky-Rosen experiment

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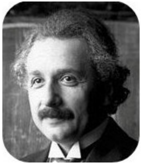

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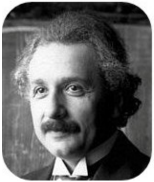

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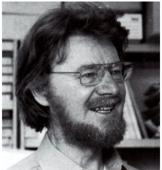
Einstein-Podolsky-Rosen experiment

John Bell (1964)



If nature behaves as quantum mechanics says, information can go faster than light!

EPR expt violates Bell Inequality

Einstein-Podolsky-Rosen(-Bohm) experiments

LETTER

doi:10.1038/nature15759

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 $|\psi^-\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$.

Executive Summary

- Can information *really* go faster than light?
  YES.

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- Is there an experiment that shows this happening?

  YES.

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- Can information *really* go faster than light?
  YES.

- Is there an experiment that shows this happening?
  YES.
  The **Einstein-Podolsky-Rosen** experiment
  violating the **Bell inequality**.

- How does this fit with Einstein's speed limit?

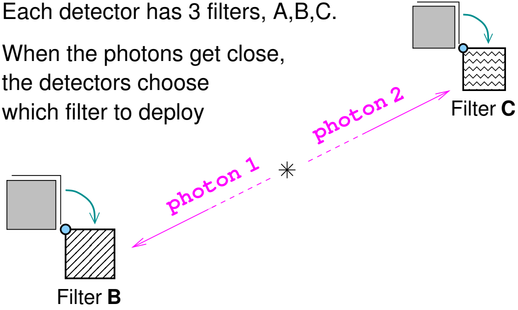
  "No thing can go faster than light"

  As far as we know, no signal can go faster than light.
  The EPR results can be explained by superluminal influences that are of a type that can't be used to send a signal.

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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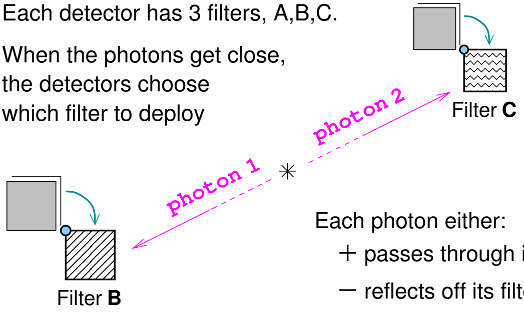
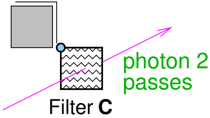
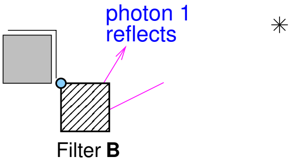


Each photon either:

+ 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.

From Photons to People

To make the explanation more accessible, let's translate the experiment into a story about people.

Pairs of photons	$\rightarrow$	pairs of people, twins
Put filter in path of photon	$\rightarrow$	ask the person a question
3 possible filters	$\rightarrow$	3 possible questions
A		Do you like Avocado?
B		Do you like Beef?
C		Do you like Cheese?
photon goes through / bounces off	$\rightarrow$	person answers "Yes" / "No"

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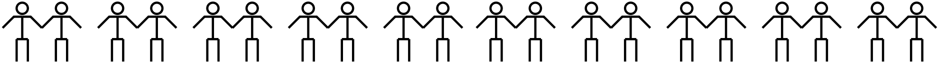
How does this simple experiment reveal superluminal telepathy ?

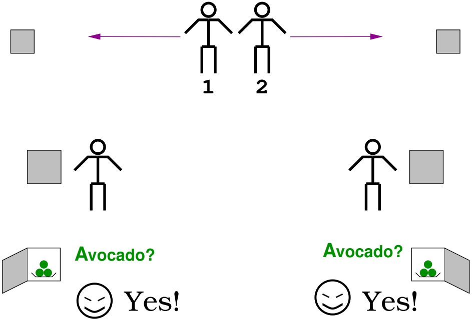
Testing twins for superluminal telepathy



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?



(simulated) EPR experimental data

twin 1	twin 2
Beef: no	Avocado: Yes
Cheese: Yes	Cheese: Yes
Beef: Yes	Avocado: no
Beef: Yes	Cheese: Yes
Avocado: Yes	Avocado: Yes
Beef: Yes	Cheese: no
Beef: no	Beef: no
Avocado: Yes	Cheese: no
Cheese: no	Avocado: no
Avocado: no	Beef: Yes
Beef: Yes	Beef: Yes
Cheese: no	Beef: Yes
⋮	⋮

What does this data tell us about twins?

Do they have faster-than-light telepathy?

EPR data: same-question trials

The questioners choose questions *randomly*. So 1/3 of the time (on average), both twins will happen to get asked the same question.

twin 1	twin 2	
Beef: no	Avocado: Yes	
Cheese: Yes	Cheese: Yes	$\Leftarrow$
Beef: Yes	Avocado: no	
Beef: Yes	Cheese: Yes	
Avocado: Yes	Avocado: Yes	$\Leftarrow$
Beef: Yes	Cheese: no	
Beef: no	Beef: no	$\Leftarrow$
Avocado: Yes	Cheese: no	
Cheese: no	Avocado: no	
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Avocado: Yes	Avocado: Yes	⇐
Beef: Yes	Cheese: no	
Beef: no	Beef: no	⇐
Avocado: Yes	Cheese: no	
Cheese: no	Avocado: no	
Avocado: no	Beef: Yes	
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⋮	⋮	

Whenever both members of a pair of twins get asked the same question, their answers *always agree*.

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Beef: Yes	Cheese: Yes	
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Beef: Yes	Cheese: no	
Beef: no	Beef: no	$\Leftarrow$
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Cheese: no	Avocado: no	
Avocado: no	Beef: Yes	
Beef: Yes	Beef: Yes	$\Leftarrow$
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⋮	⋮	

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How does our cohort of twins manage to do this?

How do the twins stay in sync?

How do our cohort of twins manage to always agree
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Two possibilities:

(a) When questioned, they interact using a faster-than-light influence.

> [It needs to go faster than light because the questioning locations are too far apart for a light-speed signal to pass between them during the question and answer.]

(b) Every pair of twins follows a pre-arranged plan.

> [*Every* pair, because *any* pair may both be asked the same question.
>
> They could make a conscious plan, or use their knowledge of each other, or it could just be that they are built the same.]

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If we can show that they *aren't* following a plan,
that means they are using some faster-than-light influence.

EPR data: different-question trials

Two-thirds of the time (on average),
each twin will be asked a *different* question.

twin 1	twin 2
Beef: no	Avocado: Yes
Cheese: Yes	Cheese: Yes
Beef: Yes	Avocado: no
Beef: Yes	Cheese: Yes
Avocado: Yes	Avocado: Yes
Beef: Yes	Cheese: no
Beef: no	Beef: no
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Avocado: no	Beef: Yes
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Beef: Yes	Cheese: Yes	←
Avocado: Yes	Avocado: Yes	
Beef: Yes	Cheese: no	
Beef: no	Beef: no	
Avocado: Yes	Cheese: no	
Cheese: no	Avocado: no	←
Avocado: no	Beef: Yes	
Beef: Yes	Beef: Yes	
Cheese: no	Beef: Yes	
⋮	⋮	

When both twins get asked different questions, they give the same answer

only 1/4 of the time.

Does this tell us anything?

Can we use this data to show that they **aren't** following pre-determined plans?

Could the twins be following plans?

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

But in the data: when they are asked different questions they only agree 1/4 of the time.

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Conclusion:

- So they *aren't* following a plan
- So how do they always agree when asked the same question?
- They must be using a superluminal influence

Bell inequality: a simple proof

1) Make a plan for answering three possible Yes/No questions.

(e.g.: Avocado? Yes. Beef? No. Cheese? Yes.)

There are only four types of pre-determined plan:

Yes	No	**Yes**	No
Yes **Yes**	**Yes** **Yes**	No No	No No

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2) Suppose you and your twin are asked two different random questions.

If you both follow your plan when giving your answers, how likely is it that you will both end up giving the same answer to both questions?

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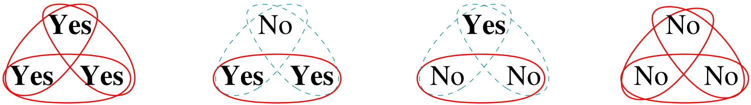

always | 1/3 of the time | 1/3 of the time | always

Answer: at least 1/3 of the time

EPR data and Bell inequality

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Beef: no	Avocado: Yes	
Cheese: Yes	Cheese: Yes	
Beef: Yes	Avocado: no	
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Avocado: Yes	Avocado: Yes	
Beef: Yes	Cheese: no	
Beef: no	Beef: no	
Avocado: Yes	Cheese: no	
Cheese: no	Avocado: no	←
Avocado: no	Beef: Yes	
Beef: Yes	Beef: Yes	
Cheese: no	Beef: Yes	
⋮	⋮	

When both twins get asked different questions, they give the same answer *only 1/4 of the time.*

But **Bell inequality** says:
If each pair of twins follows a pre-determined plan then this is **impossible**.

So their answers aren't pre-determined.

Summary: there is a superluminal influence

In order to always agree when asked the same question, each pair of twins would have to

Either: Both follow a pre-determined plan

Or: Use superluminal communication

But the pattern of their answers when asked different questions violates the **Bell inequality**.

So they *can't* be following a plan

The twins are using superluminal communication

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But the pattern of their answers when asked different questions violates the **Bell inequality**.

So they *can't* be following a plan

The twins are using superluminal communication

Either

- to co-ordinate their answers when asked the same question

or

- to discoordinate their answers when asked different questions.

(i.e. to know when *not* to follow the plan, e.g. when they are asked different questions)

EPR vs. Relativity?

Relativity + Free Will says:

Superluminal signalling cannot be allowed
You could send a message to the past $\Rightarrow$ causal paradoxes

Superluminal signalling requires two things:

Superluminal transfer of information,

and *Control* over the information that is transferred.

So the superluminal transfer of information that we see in EPR experiments is OK if the information is *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.

Avoiding superluminal signalling

The laws of nature must:
(a) allow for EPR-type superluminal information transfer, but
(b) ensure that the information transferred is uncontrollable.

Current best theory is **quantum mechanics**.
How does quantum mechanics accomplish this?

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How does quantum mechanics accomplish this?

Quantum mechanics (textbook standard version):

- Wave-function collapse is superluminal
- Information arising from wave-function collapse is indeterministic (random) so there is no way to control it.

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. e.g. `http://arxiv.org/abs/1611.06985`
- If we believe in **Macro-realism**, can we find and empirically validate a blatantly relativity-compatible ("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 alternative theory to QM? (E.g. a Lorentz-invariant Bohmian Mechanics?)

More

Youtube video: