Spooky action at a distance: how quantum mechanics reflects the weirdness of nature

Mark Alford
Washington University in St. Louis

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

Is Nature Fundamentally Weird? (Video)
https://www.youtube.com/watch?v=Rk-Fr1lIV1Y

How weird is Quantum Mechanics?

- Everything is "both a particle and a wave".
- "Uncertainty principle" says we can't know some things about a system.
- Indeterminism: QM makes predictions that are probabilities, not *definite* predictions.
- "Entanglement": measurements on one thing seem to affect other things instantaneously.

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> *“I think it is safe to say that no one understands quantum mechanics.” (Richard Feynman)*

> *“Anyone who is not shocked by quantum theory has not understood a single word.” (Niels Bohr)*

Why does QM have to be so weird?

Is it because

- Physicists tend to be strange people with weird ideas.
  QM could be replaced by a non-weird theory that works equally well.
- Nature itself is weird.
  Any theory that accurately describes nature will have to be weird.

Is there an experiment that could shed light on this?

Einstein-Podolsky-Rosen(-Bohm) experiments

LETTER

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

B. Hensen[1,2], H. Bernien[1,2]†, A. E. Dréau[1,2], A. Reiserer[1,2], N. Kalb[1,2], M. S. Blok[1,2], J. Ruitenberg[1,2], R. F. L. Vermeulen[1,2], R. N. Schouten[1,2], C. Abellán[3], W. Amaya[3], V. Pruneri[3,4], M. W. Mitchell[3,4], M. Markham[5], D. J. Twitchen[5], D. Elkouss[1], S. Wehner[1], T. H. Taminiau[1,2] & R. Hanson[1,2]

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 $|\psi^-\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$. The spin in box A is then measured along direction Z (for input bit

Top-level Executive summary

- What do the experiments show?

EPRB experiments show that nature is "weird" in some way.

- Weird in what way?

The results can only be explained by
influences that travel faster than light.

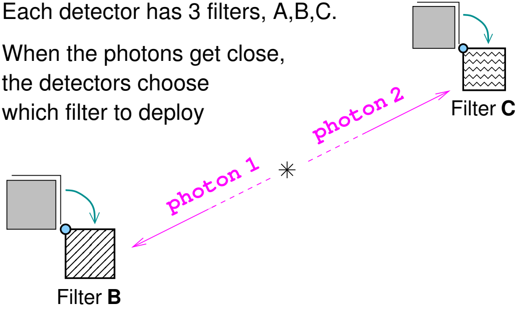
- But I thought nothing could go faster than light!

As far as we know, no *signal* can go faster than light.
But the EPRB 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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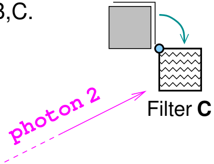
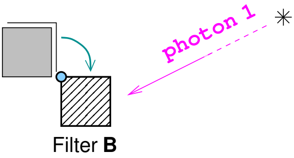
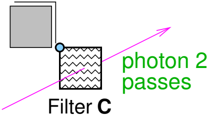


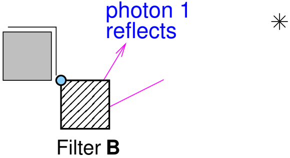


Each photon either:

+ passes through its filter

− reflects off its filter



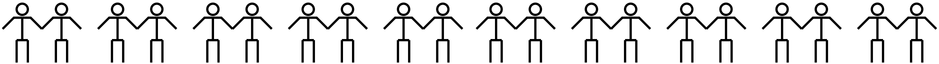


Result:

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.

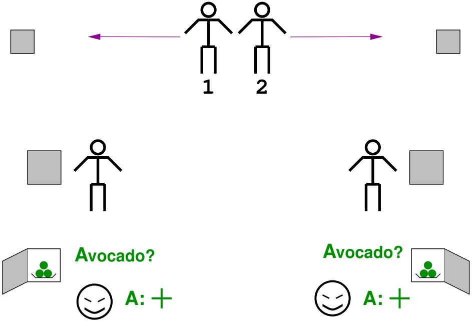
Testing twins for superluminal abilities



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?



(fake) EPRB experimental data

$+ = ☺, \quad - = ☹$

twin 1	twin 2	
Beef: $-$	Cheese: $+$	
Cheese: $+$	Cheese: $+$	$\Leftarrow$
Beef: $+$	Avocado: $-$	
Avocado: $+$	Avocado: $+$	$\Leftarrow$
Cheese: $-$	Avocado: $-$	$\leftarrow$
Beef: $-$	Beef: $-$	$\Leftarrow$
Beef: $-$	Avocado: $+$	
Avocado: $+$	Cheese: $-$	
Beef: $+$	Avocado: $+$	$\leftarrow$
Avocado: $-$	Beef: $+$	
Beef: $+$	Beef: $+$	$\Leftarrow$
Cheese: $+$	Beef: $-$	
$\vdots$	$\vdots$	

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

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

What does this tell us about twins?

EPRB data: what are the twins doing?

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

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

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

(2) They follow a pre-arranged plan

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

Could the twins be following a plan?

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

How does that follow?

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How does that follow?

Bell's theorem:
If twins are following a plan then, when each twin in a pair 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.

This can't happen if you are following a plan!

So there must be a faster-than-light influence that connects them!

Bell inequality

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

e.g.: A? Yes. B? No. C? Yes.

2) Suppose you are asked two (different) random questions.

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

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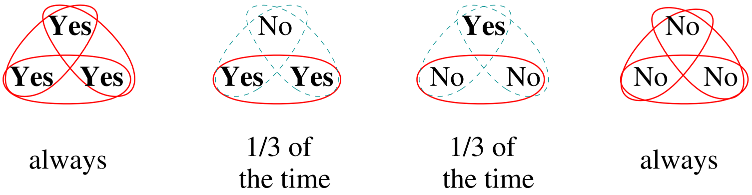

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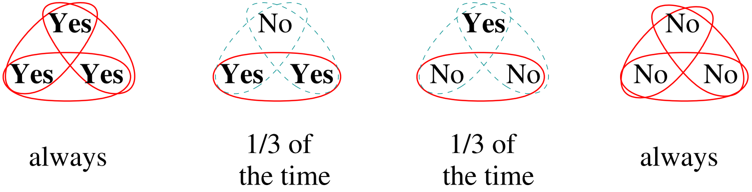

If your answers don't obey the Bell inequality, then you cannot be following a plan. You must be "making up some answers on the spot". Indeterminism!

Summary: Nature contains superluminal influences

- EPR-type experiments show phenomena that can only be explained if

  there are superluminal influences in nature.

- *Einstein's theory of relativity* is not (noticeably) violated:

  The superluminal influences can be of a kind
  that can't be used to send signals.

How can there be a superluminal influence
that can't be used to send superluminal signals?

In Quantum Mechanics, the superluminal influence operates between uncontrollably random events.
Sending a signal requires a *controllable* influence.

What next?

- Do EPRB experiments say anything about determinism?
  - QM uses indeterminism to avoid superluminal signalling.
  - Is there a deterministic theory that can do the same thing?
  - Or do EPRB experiments also tell us that there is indeterminism in Nature?
- Perform better experiments that close some remaining loopholes, e.g. the "random choices" loophole: ensure that each experimenter uses an independent random choice generator. e.g. `http://arxiv.org/abs/1611.06985`