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The universe really is weird, and a landmark quantum experiment proves it

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Measuring the photons in an entangled state was part of the experiment. Credit: Flickr/Alexandre Normand, CC BY

Only last year the world of physics celebrated the 50th anniversary of Bell's theorem, a mathematical proof that certain predictions of quantum mechanics are incompatible with local causality. Local causality is a very natural scientific assumption and it holds in all modern scientific theories, except quantum mechanics.

Local causality is underpinned by two assumptions. The first is Albert Einstein's principle of relativistic causality, that no causal influences travels faster than the speed of light. This is related to the "local" bit of local causality.

The second is a common-sense principle named after the philosopher Hans Reichenbach which says roughly that if you could know all the causes of a potential event, you would know everything that is relevant for predicting whether it will occur or not.

Although quantum mechanics is an immensely successful theory – it has been applied to describe the behaviour of systems from subatomic particles to neutron stars – it is still only a theory.

Thus, because local causality is such a natural hypothesis about the world, there have been decades of experiments looking for, and finding, the very particular predictions of quantum mechanics that John Bell discovered in 1964.

But none of these experiments definitively ruled out a locally causal explanation of the observations. They all had loopholes because they were not done quite in the way the theorem demanded.

No loopholes

Now, the long wait for a loophole-free Bell test is over. In a paper published today in Nature, a consortium of European physicists has confirmed the predictions required for Bell's theorem, with an experimental set-up without the imperfections that have marred all previous experiments.

A Bell experiment requires at least two different locations or laboratories (often personified as named fictional individuals such as

Alice and Bob) where measurements are made on quantum particles. More specifically, at each location:

1. a setting for the measurement is chosen randomly
2. the measurement is performed with the chosen setting
3. the result is recorded.

The experiment will only work if the particles in the different laboratories are in a so-called entangled state. This is a quantum state of two or more particles which is only defined for the whole system. It is simply not possible, in quantum theory, to disentangle the individual particles by ascribing each of them a state independent of the others.

The two big imperfections, or loopholes, in previous experiments were the separation and efficiency loophole.

To close the first loophole, it is necessary that the laboratories be far enough apart (well separated). The experimental procedures should also be fast enough so that the random choice of measurement in any one laboratory could not affect the outcome recorded in any other laboratory be any influence travelling at the speed of light or slower. This is challenging because light travels very fast.

To close the second, it is necessary that, once a setting is chosen, a result must be reported with high probability in the time allowed. This has been a problem with experiments using photons (quantum particles of light) because often a photon will not be detected at all.

The experiment

Most previous Bell-experiments have used the simplest set up, with two laboratories, each with one photon and the two photons in an entangled state.Ronald Hanson and colleagues have succeeded in making their experiment loophole-free by using three laboratories, in a line of length 1.3km.

In the laboratories at either ends, Alice and Bob create an entangled state between a photon and an electron, keep their electron (in a diamond lattice) and send their photons to the laboratory in the middle (which I will personify as Juanita). Alice and Bob then each choose a setting and measure their electrons while Juanita performs a joint measurement on the two photons.

Alice and Bob's measurements can be done efficiently, but Juanita's, involving photons, is actually very inefficient. But it can be shown that this does not open a loophole, because Juanita does not make any measurement choice but rather always measures the two photons in the same way.

The experiment, performed in the Netherlands, was very technically demanding and only just managed to convincingly rule out local causality. This achievement could, in principle, be applied to enable certain very secure forms of secret key distribution. With continuing improvements in the technology one day this hopefully will become a reality.

For the moment, though, we should savour this result for its scientific significance. It finally proves that either causal influences propagate faster than light, or a common-sense notion about what the word "cause" signifies is wrong.

One thing this experiment has not resolved is which of these options we should choose. Physicists and philosophers remain as divided as ever on that question, and what it means for the nature of reality.

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