Why do Bell experiments?

by

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Experiments over three decades have been unable to demonstrate weak non-locality in the sense of Bell unambiguously, without loopholes. The last important loophole remaining is the detection loophole\(^1\), which is being tackled by at least three experimental groups\(^4\). This letter counters five common beliefs about Bell experiments, shows the importance of these experiments, and presents alternative scenarios for future developments. Figure here.

The figure shows the bare bones of a system designed to test Bell inequalities\(^7\). It may be considered as a black box at rest in a laboratory frame, with two input ports \(\alpha, \beta\) and two output ports \(a, b\). The input port \(\alpha\) and the output port \(a\) are parts of a subsystem \(A\) on the left of the box, and \(\beta, b\) are parts of a subsystem \(B\) on the right. The minimum distance between \(A\) and \(B\) is \(L\).

One run of an experiment on the black box starts with inputs labelled \(\alpha, \beta\) which end before time \(t = 0\) in the laboratory frame. The outputs are labelled \(a, b\) start after time \(t = T\). The inputs and outputs are entirely classical, but the system has entangled quantum components.

A sufficient number of runs provides transition or conditional probabilities denoted

\[
\Pr(\alpha, \beta \rightarrow a, b)
\]

for the outputs \(a, b\) of the whole system, given the inputs \(\alpha, \beta\). Following Wigner's formulation\(^8\), locality implies that they satisfy the Bell inequality
\[
\Pr(1, 2 \rightarrow +, -) + \Pr(2, 0 \rightarrow +, -) - \Pr(0, 1 \rightarrow +, -) \geq 0,
\]
\(\text{(2)}\)

Together with two more inequalities given by cyclic permutations of 0, 1, 2. The subsystems \(A\) and \(B\) are so far apart that
\[
L > T c,
\]
\(\text{(3)}\)

Where \(c\) is the velocity of light, so it is not possible to send signals from \(\alpha\) to \(b\) or from \(\beta\) to \(a\). Without this condition, the experiment has a loophole, sometimes called the locality loophole\(^9\). All early experiments had this loophole, but Aspect’s group\(^{10}\) and more recently Zeilinger’s and Gisin’s groups\(^{11,12}\) have removed it.

In Bell’s original thought experiment, there are three possible values of \(\alpha\) and corresponding values of \(\beta\), denoted 0, 1, 2. They might be three settings of the angle of a polarizer, or of the angle of measurement of a particle of spin one-half. There are two possible values of each separate output, denoted + and −. They are typically two orthogonal directions of polarization of a photon, or two opposite spins of an atom. In an ideal Bell experiment, the inputs \(\alpha\) and \(\beta\) are determined by completely independent random variables. If they are not random, as for the Aspect and Gisin experiments, there is a further loophole, which was removed by Zeilinger’s group in an experiment in which the locality loophole was also overcome\(^{11}\).

The detection loophole\(^{1,2,3}\) described below has proved to be the most difficult of all, and has never been overcome in any published experiment, though the groups of Fry and Walther\(^4\), of Wineland\(^5\) and of Blatt\(^6\) are trying. Fry and Walther aim to close the locality loophole in the same experiment.

Bell experiments, or experiments of the Bell type, are experiments to test the original Bell inequalities, or one of the many other inequalities that follow from locality. Here are five common beliefs about them.

1 Their only purpose is to exclude local hidden variable theories, which are of little interest anyway.
2 Violation of the inequalities follows inevitably from the laws of quantum mechanics and their interpretation.
3 Experiments have already shown that the Bell inequalities are violated, apart from the detection loophole, which is so unbelievable that it is not worth considering seriously.
4 Einstein’s view that all physical laws are local was his one definite major mistake.
5 Bell experiments are therefore no longer worth doing.

Reasons are presented here for rejecting all of these beliefs, and replacing them by the alternatives:

1 There are more important reasons for doing Bell experiments, including Bell’s weak nonlocality.
2 Neither the violation nor the nonlocality follow inevitably from quantum mechanics.
3 There are at least two good reasons why the detection loophole should be taken seriously.
4 Einstein has been right before, when many in the physics community were wrong, and we need conclusive experimental evidence of nonlocality before judging him on this issue.
5 Bell experiments are among the most important in physics.

**Why do Bell experiments?**

Guinness, Bass and Worthington are brands of beer. It is questionable whether, if Guinness is good for you, Bass is bad and Worthington is worse. These are matters of taste and prejudice. Forward, nonlocal and backward causality are brands of causality. If forward causality is good for you, nonlocal causality is bad and backward causality is worse. These are matters of experience. We are particularly concerned with the question of nonlocal causality, in which cause and effect are spatially separated in spacetime, so that a signal from cause to effect would have to go faster than the velocity of light. According to classical special relativity, an event can affect a future event, in or on its forward light cone, but not a spatially separated event, and certainly not a past event.

But apparently, according to quantum theory, classical events that are linked by quantum systems are different. For them, there is a sense in which causality might act nonlocally, but without any signalling faster than light. This
is Bell’s weak nonlocality, which can be formulated in terms of the classical inputs and outputs of a black box.  

An electrical engineer’s black box consists of a circuit with input and output terminals. He may not know what circuit is inside, but it is assumed here to be classical. If there is no noise in the circuit, then the black box is deterministic. The outputs then depend on the inputs through a unique transfer function $F$, and by experimenting with different inputs and looking at the outputs, engineers can find $F$. In practice the resistors in the circuit produce noise, which we assume to be classical noise. The system is then stochastic. The noisy circuit can be represented by a probability distribution $Pr(F)$ over the transfer functions $F$, in which the unknown values of supposedly classical background variables, like the coordinates of thermal electrons, determine the particular $F$ that operates.  

A physicist’s black box contains an evolving physical system, such as a classical electrical circuit, or an entangled quantum state with classical inputs and outputs. She may not know what physical system is inside, but by experimenting with different inputs and looking at the outputs, she can find out something about it.  

For deterministic systems, special relativity distinguishes between local transfer functions $F$ in which the influence of an input on an output goes at no more than the velocity of light, and nonlocal transfer functions $F$, for which the influences can act over spacelike intervals. It is possible to determine whether the transfer function of a system is local or not by experimenting with different values of the inputs, and observing the outputs. There is no need to look inside the black box. All real classical systems have local transfer functions, as required by special relativity.  

When classical or quantum systems are stochastic, special relativity distinguishes between three types of black box system, defined in terms of probabilities $Pr(F)$ of transfer functions. The first are local systems, for which the transition probabilities of the outputs given the inputs can be obtained from a probability distribution $Pr(F)$ in which only local $F$ contribute. It is therefore not possible to send signals faster than the velocity of light. For the second type, the transition probabilities can only be obtained from $Pr(F)$ in which at least one nonlocal transfer function has nonzero probability, so there is an element of nonlocality. But nevertheless it is not possible to send
signals faster than the velocity of light. The system is then said to be weakly nonlocal, or nonlocal in the sense of Bell. For the third type, which has never been seen, it is possible to send signals faster than the velocity of light.

The stochasticity of classical systems comes from background variables that are not included in the system, but for quantum systems it does not come from any background variables that we can see, so either they are assumed not to exist, as in the Copenhagen interpretation, or they are called hidden variables.

A Bell experiment is a black box with classical terminals and an entangled quantum system inside, where the source of entanglement is inside the box. For photon polarization the setting of the orientations of the polarizers is an input, and the detection of the directions of polarization is an output. All the inputs and outputs are classical events.

Real laboratory Bell experiments are treated in the next section. In this one we treat only ideal Bell thought experiments in which the entangled quantum system is sufficiently close to a pure state, and the measurements sufficiently good, that the black box is weakly nonlocal.

The classic Bell was proposed to test whether local hidden variable theories are possible. But quantum black boxes also tell us something about the world: there are correlations between classical events that can only be produced by quantum links. These correlations are important in their own right. They demonstrate weak nonlocality. They also show that the properties of our world cannot be explained using local hidden variables, but that is not their main significance, which persists independently of any theory, local or nonlocal. An experimenter who has never seen the apparatus before can tell by experimenting with the inputs and outputs, and without looking inside, that the black box contains a quantum system. This property of quantum black boxes comes from weak nonlocality.

So Bell experiments and weak nonlocality are important for all quantum physicists, whether they support hidden variable theories or not. The weak nonlocality of quantum measurement is unique in modern physics: classical dynamics, quantum dynamics and general relativity are all local. Today only ideal experiments are weakly nonlocal, though tomorrow they could be real.

In modern quantum computation it is proposed to put quantum correlations
to good use. Violation of Bell inequalities is a benchmark experiment for quantum computers, and for this reason alone would be worth doing even if there were no interest in weak nonlocality.

**Nonlocality and quantum mechanics**

Real experiments, with or without loopholes, are approximations to ideal experiments without them. There are possible limits on the approach to the ideal that are explored by attempts to carry out an experiment without loopholes. Theoretically it appears that it is possible to approach arbitrarily close to the ideal, by improving the efficiency of detectors, collimation, etc., but there appears to have been a 'conspiracy' of nature that prevented this. Such conspiracies in physics have a long history.

For example, the first law of thermodynamics says that heat is a form of energy. In the early 19th century there appeared to be a conspiracy that prevented anyone from extracting all this energy from a system and using it. We now call this conspiracy the second law of thermodynamics. Bell’s opinion, ‘It is hard for me to believe that quantum mechanics works so nicely for inefficient practical setups and is yet going to fail badly when sufficient refinements have made.’ may be right, but irrelevant. Quantum theory does not have to fail. The necessary refinements may not be possible. Current quantum theory would then be incomplete, just as the first law of thermodynamics is incomplete. Einstein thought that quantum mechanics is incomplete\(^{14}\), but this was not the kind of incompleteness he described.

Santos has suggested earlier that the laws of quantum measurement might be compatible with locality\(^ {15} \). This idea can be illuminated by an analogy, comparing the second law of thermodynamics and the possible breakdown of the nonlocality argument. Classical systems obey the laws of Hamiltonian dynamics, despite the second law, which limits energy transfer from real systems with many particles. Similarly quantum systems might obey all the laws of quantum dynamics and quantum measurement, despite a supplementary law which excludes weakly nonlocal systems, thus ensuring that physics remains local. No one yet knows any such supplementary law.

In thermodynamics, the second law was discovered as a result of many trials showing practical limitations on getting useful energy from heat. Locality holds for all Bell experiments to date, but it is on much weaker ground, as
Bell experiments are relatively few, so experiments designed to test it are among the most important in physics.

**Experiments and the detection loophole**

A Bell experiment without loopholes would be an experiment from which we could deduce weak nonlocality without further assumptions. It is nearly four decades since the inequalities were obtained and experiments tentatively suggested, and three decades since the first experiments. There is still no published clear experimental demonstration of weak nonlocality, because of the detection loophole, which follows.

Real experiments have outcomes that are excluded in ideal experiments. For example, a photon or an atom may be detected at \( A \), but not at \( B \), as a result of imperfect detectors, or losses due to absorption or bad collimation. These outcomes affect the inequalities, and the tests of nonlocality. There are further assumptions that have to be made in order to obtain the probabilities that appear in the inequalities. One such assumption is that the detector efficiency is independent of the local ‘hidden’ variables, as discussed by Clauser and Horne\textsuperscript{16} and by Gisin and Gisin\textsuperscript{17}. If the possibility of such a dependence is accepted, nonlocality cannot be demonstrated until the detection efficiency reaches a threshold. This is the loophole.

At first sight such a dependence seems unlikely, but there are two good reasons why the detection loophole should not be ignored.

The first reason lies in the definition of efficiency, for which the analogy with thermodynamics is useful. If only the first law of thermodynamics applied, then it would be reasonable to measure the efficiency of a heat engine as the proportion of the total energy that is extracted. But once the second law is recognized, this definition is inappropriate, and we revise the definition to take temperature differences into account. Similarly, if there are values of local hidden variables that play a role in determining whether or not there is a response from a particle detector, it is no longer appropriate to measure the efficiency of the detector in the conventional way. The measure of efficiency should take into account the values of the hidden variables. With such a new definition, the dependence seems natural\textsuperscript{17}.

The second reason lies in the alternative. The dependence appears unlikely to some people, but the alternative is nonlocality, which is a break with
the whole of the rest of physics. We must not base conclusions about such an overwhelmingly important universal issue on some prejudice about the properties of mere detectors.

We cannot dismiss the detection loophole. We have to try to close it by improving the experiments.

**Einstein’s mistake?**

Einstein introduced light quanta in 1905, but leading physicists still did not accept them as late as 1913, so we should be careful before rejecting his other ideas, whatever the majority thinks. He believed that nature obeys local laws, and Bell showed that this assumption might be tested experimentally. It appeared that weak nonlocality followed from the laws of quantum dynamics and quantum measurement, but this is not so.

**What now?**

Quantum technology has advanced so much during the last decade that the detection loophole might soon be closed, using spin states of atoms or otherwise. For the future, there are several possible scenarios, of which two are the most likely:

**EITHER**

1. The inequalities cannot be violated. The apparent conspiracy is due to a new law of nature, consistent with current quantum theory, but limiting the accessible states of matter to those for which locality reigns. The common view is wrong and Einstein was right.

**OR**

2. The inequalities can be violated. The apparent conspiracy that has prevented the unambiguous experimental confirmation of Bell nonlocality is due to practical difficulties that can be overcome. Experiments will close the detection loophole. This would be a significant advance, a benchmark on the way to quantum computation. Simultaneous closure of both the detection and locality loopholes would confirm the common view that the laws of nature are weakly nonlocal and that Einstein was wrong.
This issue can only be resolved by experiment. That is why Bell experiments are so important.

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Percival Fig 1