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Quantum Physics and the Boundaries of Space and Time

"An object is influenced directly only by its immediate surroundings."
"An object has pre-existing values for any possible measurement before these measurements are made."

Do you find these statements about reality plausible? Historically, most physical theories have adhered to such principles which, in combination, are referred to as 'local realism'. Local realism corresponds so well with our everyday experience of the world that most people intuitively assume it to be an essential part of any natural scientific theory. The quantum theory developed in the early 19th century was therefore controversial at the time, since it did not comply with local realism. This was addressed by Einstein, Podolsky and Rosen (EPR) in their seminal paper "*Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?*" [A. Einstein *et al.*, 1935]. EPR constructed a thought experiment that reveals a peculiar feature of the quantum theory: In special situations, measurements performed on two particles with arbitrary separation can have an instantaneous influence on one another. This effect is known today as the 'EPR paradox' and is in violation of local realism. Despite this apparent inconsistency, quantum theory could not be disregarded since it accurately described new experiments probing the properties of light and atoms. Early discussions of the EPR paradox were of a metaphysical nature as the questions raised could not be experimentally investigated. A very important discovery was made in 1964 by John S. Bell, who formulated a mathematical inequality governing the possible outcomes of EPR experiments [J. S. Bell, 1964]. This analysis provided a test to see whether local realism could be falsified. The stage was set for experimentalists to answer the questions posed by EPR.

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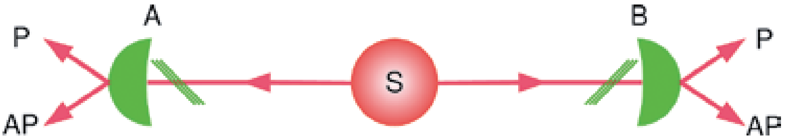

Figure 1: Schematic of the EPR experiment. The source S produces pairs of entangled photons (light particles) that are sent in opposite directions to measurement apparatus A and B. The polarization of an incoming particle is measured in a direction (triple lines) determined independently at A and B, and a measurement gives either outcome parallel (P) or antiparallel (AP) to this direction.

The Einstein-Podolsky-Rosen thought experiment

Let us now describe the EPR thought experiment in more detail. Imagine that two particles have been emitted from the same source and travel in opposite directions, eventually reaching the widely separated measurement apparatus denoted A and B, see Fig. 1. Precisely which particle property to measure at A and B (in Fig. 1, this property is the direction of polarization for light particles) is decided upon after the particles have traveled far away from each other. Now if we choose a separation of A and B that is large enough, no information about the measurements at A can reach B in time before the measurement has been made there. In this case, the measurements at A and B should be independent. According to the special theory of relativity, no information can travel faster than the speed of light. So to obtain independent measurements, the separation of A and B should be large enough that no light can travel from A to B during the time it takes to make the measurements, see Fig. 2.

Surprisingly, quantum theory tells us that the above mentioned criteria do not guarantee independence between measurements at A and B. If the pair of particles are in a so-called "quantum entangled state", they can no longer be assigned individual properties. Rather, the pair of particles must be considered a single non-separable object. This introduces the possibility for dependence between measurements at A and B, regardless of their separation. Moreover, in quantum theory the actual outcome of a measurement is not always given in advance, but determined statistically when actually taking the measurement. Generally speaking, we might say that when a measurement is made on one of the particles, we also modify the possible outcomes of measurements on the other. So there appears to be some communication between the two particles: the measurement on the particle at A influences the particle at B instantaneously, independently of the distance between them. This feature of the quantum theoretical description is described as 'nonlocality' and is in contradiction with local realism, which states that only events in the vicinity of B can affect measurements there. The skeptical Einstein referred to nonlocality as "spooky action at a distance", regarding the possibility for nonlocal influences - a fatal blow to quantum theory.

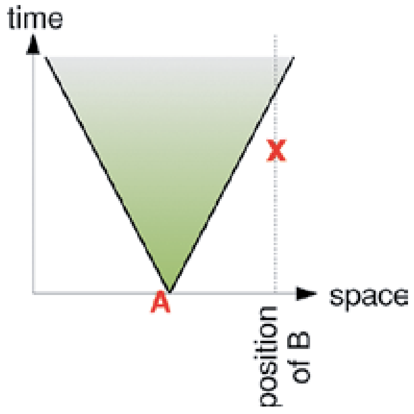

Figure 2: Spacetime diagram illustrating the conditions for measurements at A and B to be independent according to special relativity. The measurement at A takes place at point A. Information about this event spreads out into the green area at the speed of light, eventually reaching the position of B. If the measurement at B is done before the green area intersects with B's position (e.g. at position x), the measurements at A and B should be independent.

Bell inequalities

The EPR thought experiment did not immediately suggest an experimental quantity that could be used in a measurement to demonstrate any nonlocal influences. Three decades after EPR's paper, J. S. Bell derived a mathematical inequality that defines the conditions under which the measurements cannot be explained by any theory where the particles are treated as unconnected and independent [J. S. Bell 1967]. Bell's analysis opened a new direction for research on the EPR paradox, and "Bell inequalities" were derived for realistic implementations of the EPR experiment [J. F. Clauser *et al.* 1969]. In principle, Bell's reasoning was the following [N. D. Mermin 1985]: Assume that an EPR experiment has been implemented so that the measurements at A and B cannot influence each other according to special relativity. Then, calculate the statistical probability that measurements at A and B would give the same result given that only local interactions exist. When the experiment is repeated millions of times, the fraction of agreeing measurement pairs should be maximum at this probability - this constitutes the Bell inequality. If the fraction of agreeing data collected from A and B exceeds the probability, there must be something wrong with the assumptions made to calculate the probability. Careful scrutiny of the calculation will show that the only possible explanation for a violation of the Bell inequality is the assumption of locality. In case of a violation, the conclusion would thus be that some nonlocal influence must be taken into account. Bell even calculated what the agreement, or more generally the correlation, between data from A and B should be according to quantum theory. This prediction violates the inequality. A theorem accredited to Bell states that "no physical theory of local hidden variables can ever reproduce all of the predictions of quantum mechanics", thus establishing that if the nonlocal effects predicted by quantum theory in the EPR experiment were measured, a local realist theory would be falsified.

Experiments to test Bell inequalities

Various experimental setups were devised to test Bell's inequality. The measurement apparati used are usually polarization filters that measure the polarization direction of pairs of photons (light particles) emitted from laser stimulated atoms, see Fig. 1. The measurement outcomes are stored on a local computer, and data from A and B are compared after the end of a run. Under the assumption that the polarization measurement at e.g. A cannot influence the measurement on the photon at B, a Bell inequality gives the statistical limit for how often pairs of measurements can give the same outcome. Technological progress has enabled experimenters to test the Bell inequalities with impressive precision. A first series of tests in the 1970s gave results that violated the Bell inequalities and agreed with quantum theory, but the experimental inaccuracy was large. More elaborate experiments were performed in Orsay, France, in the early 1980s. They convincingly showed violation of the Bell inequality [A. Aspect *et al.*, 1982]. However, skeptics have pointed out a number of weaknesses in the experiment, often called 'loopholes'. One of these concerns is nonlocality, i.e. the particles were not sufficiently separated that communication between them could be ruled out as a mechanism for correlating measurements. This was improved upon in an experiment in which the measurement apparati were separated by a distance of 400 m across the Innsbruck University science campus [G. Weihs *et al.*, 1998]. This precludes communication between A and B during the measurement process at a velocity less than or equal to that of light.

Nature is nonlocal

Today, the accumulated knowledge from EPR experiments overwhelmingly show that Bell's inequalities are violated [A. Aspect 1999 and W. Tittel *et al.* 2001]. The experimental data provide a fatal blow to the local realist theory, and are also taken in favor of quantum theory.[1] Some of the current focus of research into Bell inequalities is directed at detecting quantum entanglement rather than ruling out local realist theories. This task is different since one accepts quantum theory at the outset. One research direction that assumes this position is aimed at implementing EPR experiments in nano-electronic devices. The experimental system could in this case be put on a micrometer-size piece of semiconductor; a violation of Bell's inequalities is understood as a signature of nonlocal pairs of quantum entangled electrons.

The success of quantum theory has also motivated research in philosophical directions. For example, some philosophers question the notion of a reality that exists independently of human observers, and others advocate a "many-worlds interpretation" where every possible outcome to every event defines or exists in its own 'history' or 'world' [A. Goswami 2001].

To conclude, we have followed a scientific endeavor where impressive progress has been made. What started as a metaphysical debate over the validity of quantum theory was brought into the realm of experimental physics by the Bell inequalities. In the end, technological achievements made a decisive conclusion possible after 60 years: Local realism is dead. How to reconcile this fact with human perception of reality is still an open question.

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1: Although the experiments exhibit nonlocality, this does not open for superluminal communication between observers at A and B. The observer studying the measurement outcomes at A will see a random sequence of data. Only by comparing her data to those measured by observer B will she be able to discover the nonlocal influence. To do this, the data from B must be transmitted to A by conventional means, like a radio signal.