Teaching Quantum Nonlocality[1]

Art Hobson, University of Arkansas, Fayetteville, AR

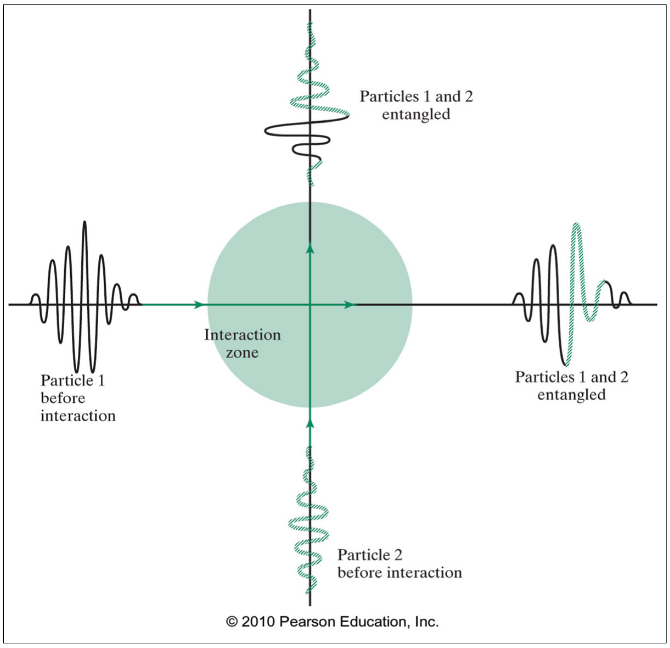
Nonlocality arises from the unified "all or nothing" interactions of a spatially extended field quantum such as a photon or an electron.[2] In the double-slit experiment with light, for example, each photon comes through both slits and arrives at the viewing screen as an extended but unified energy bundle or "field quantum." When the photon interacts (randomly[2]) with the screen, field quantization requires it to alter its state instantaneously rather than gradually. Thus if the photon is absorbed, it must vanish or "collapse" nonlocally and instantaneously across a macroscopic portion of the screen, even across many kilometers in the case of interference patterns of light from a small distant star. The interaction instantly transfers the photon's energy to a single atom of the screen. But a quantized field can contain any whole number of "excitations" (particles such as photons or electrons). If a single field quantum contains, say, two excitations, then generally the unified all-or-nothing character of quanta implies that any interaction of one excitation must also instantaneously affect the other excitation, regardless of the distance between them. The particles are then said to be "entangled" (see the "Background" section for a more precise definition of this term). Particles can become entangled by being created together in a single microscopic process, or by interacting with each other. Quantum entanglement is at least as fundamental as quantum uncertainty but is seldom mentioned in physics courses, although it has received broad attention recently in a wonderful book by Louisa Gilder.[3] A recent paper in this journal presents entanglement in a manner that is useful for high school and college physics teachers.[4] This paper builds on that presentation and looks at a different, more intuitive entanglement experiment that should be accessible to both scientists and nonscientists.

Background

Figure 1 is a way to picture the creation of two-particle entanglement during an interaction. At the left and the bottom of the figure, we see two one-particle wave packets, i.e., two particles (remember that "particles," i.e., field quanta, *are* their wave packets[2]). The particles are initially unentangled and noninteracting, then they move near enough to create a non-negligible probability of interaction, then they separate. Quantum physics predicts that, if an interaction occurs, the packets get mixed up with each other so that, even after they no longer interact, they form a single two-particle wave packet that can't be separated into two one-particle wave packets. Experimentally, this "entanglement" means that the particles exhibit the kind of nonlocal effects described below; theoretically, it means that the particles are in a two-particle quantum state that cannot be factored into the product of two one-particle states. The figure indicates this by coloring one initial packet black and the other green. The post-interaction packets are really two parts of a single black-and-green packet. Even if widely separated in space, they form a single unified field quantum. This is similar to a one-particle wave packet that is separated into two parts (e.g., a photon that has interacted with a half-reflecting mirror and is now a superposition of a wave packet that passed through the mirror and a packet that reflected from the mirror), but now there is a real excitation in each of the two parts. In classes for scientists or engineers, you could follow this qualitative description with an algebraic description.[5]

One popular entanglement method, used in the experiment described below, is called "spontaneous parametric down-conversion." When photons pass through a certain kind of nonlinear crystal, a tiny fraction of them split into two photons of equal energy. It's not understood why this occurs, but Leonard Mandel of the University of Rochester discovered that each pair of daughter photons is entangled.

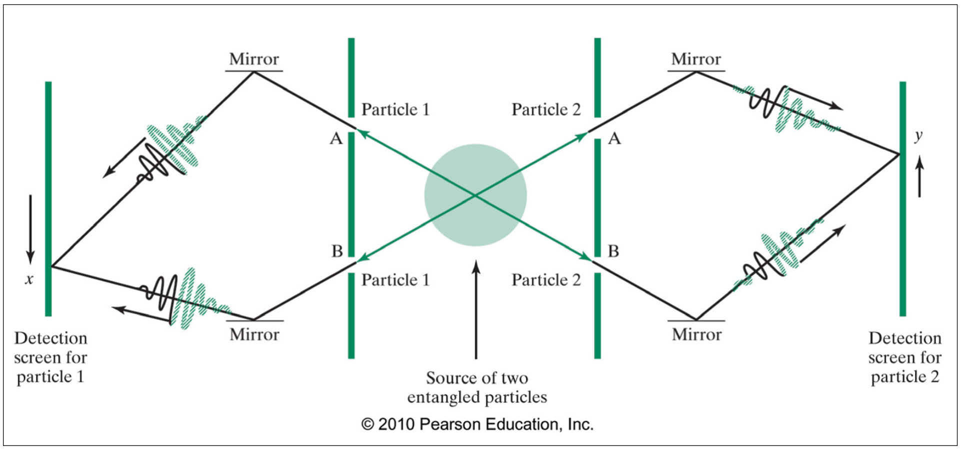
If one of the two entangled particles experiences a macroscopic interaction, for example by striking a viewing screen, that portion of the two-particle wave packet instantly collapses everywhere. According to quantum physics, this instantly affects the other particle, even if the two are light-years apart. Anton Zeilinger's group has confirmed this effect at distances up to 144 kilometers.[6] Alain Aspect's group has confirmed that the second particle alters its state in response to an interaction of the first particle in a time shorter than is required for light to connect the two particles.[7] It's an irony of physics



© 2010 Pearson Education, Inc.

Fig. 1. When two particles interact and then separate, their quantum fields usually become entangled. See the text for explanation. (Reprinted by permission of Pearson Education Inc., Upper Saddle River, NJ.)

DOI: 10.1119/1.3703540



© 2010 Pearson Education, Inc.

Fig. 2. The RTM entanglement experiment. Photons 1 and 2 coordinate their impact points *x* and *y* instantaneously despite their separation. Photon 1 goes through the double slits on the left, and photon 2 goes through the double slits on the right. The entanglement is created at the source. The mirrors only reflect the packets so that they can interfere. (Reprinted by permission of Pearson Education Inc., Upper Saddle River, NJ.)

history that, in 1934, Albert Einstein and coworkers were the first to use quantum theory to present a detailed prediction of entanglement.[8] Einstein, believing that "physics should represent a reality in time and space, free from spooky interactions at a distance (*spukhafte Fernwirkung*),"[9] used this prediction as an argument against the "completeness" of quantum theory. Later events have, however, confirmed the physical reality of spooky interactions at a distance, and thus the incorrectness of Einstein's argument. It was one of the most brilliant and fruitful incorrect arguments ever posed!

An entanglement experiment

Because "how do we know?" is science's most basic question, it's always good pedagogy to ground basic concepts in experiments, especially if the topic is as elusive and unbelievable as quantum physics. Entanglement has been demonstrated in photon pairs at 144-km separations,[6] in a variety of atomic and photonic systems,[10] in atom pairs at meter separations,[11] and between two gas clouds, each made of a trillion cesium ions, at millimeter separations.[12] Most experiments entangle photon polarizations[4]—a rather abstract hook on which to fasten students' understanding of this difficult concept. But some entangle the positions of photon pairs passing through separate double-slit setups—an experiment that can be appreciated by any student familiar with Young's double-slit experiment for single photons or electrons.[2] In 1990, the first experiments of this type were performed by J. G. Rarity and P. R. Tapster, and independently by Leonard Mandel's team at the University of Rochester.[13] This "RTM experiment"(as I will call it) serves admirably for presenting entanglement in introductory courses.

Figure 2 shows the experiment. Two entangled photons were emitted from a central source and then moved through different double-slit setups. The entanglement was created by spontaneous parametric down-conversion. Instead of double slits, RTM used Mach-Zehnder interferometers involving phase shifters, beam splitters, and photon detectors, but the setup of Fig. 2 is physically equivalent to the RTM experiment and easier for students to understand.[14] As Fig. 2 shows, mirrors brought the two packets on each side together for interference.

If the pairs were not entangled, each detection screen would show the familiar double-slit interference pattern.[2] But it turns out[15] that the position uncertainty of the source must be large if the two particles are to remain entangled, and this large source size "smears out" and thus destroys the two single-particle interference patterns so that the photons hit randomly all over the expected interference region, with no trace of interference. Nevertheless, an interference pattern is present but it is buried more deeply, in the *correlations* of the positions of the two members of each pair. It shows up when we compare each pair's impact points. These near-simultaneous "coincidences" show that the two impact points of each pair are "statistically correlated" as follows: Each particle's interference pattern is centered at a different point, and that center point is determined by the impact point of the other particle. Thus the two photons interfere *with each other* even though they impacted on widely separated screens! Let me explain.

Suppose the particles obeyed Newtonian physics. Assume for simplicity that each pair's photons were emitted in precisely opposite directions, and that the left side of the apparatus in Fig. 2 was precisely symmetric with the right side. Then the two "classical photons" would impact at exactly equal distances x below the first screen's center, and y above the second screen's center (see Fig. 2). But quantum physics tells us that there are uncertainties in the initial directions and positions of the two photons so that x and y are uncertain, and y cannot be precisely predicted from knowledge of x. However *quantum physics predicts*[15] *and the experiment confirms that, for a given* $x = x_0$, *the possible* y*-values form a well-defined interference pattern centered at* $y = x_0$. Thus, the *difference* y-x, when graphed for all pairs of particles, forms an interference pattern as shown in Fig. 3. This works in reverse too: For a given $y = y_0$, the possible values of x form an interference pattern centered at $x = y_0$.

This correlation between the two separated impact points x and y is astonishing. Here's why. Suppose photon 1 hits first. As stated above, quantum physics predicts its impact point x to be entirely random; in other words, prior to impact the first photon's position is spread out evenly all over the screen so that even nature has no idea where the photon will hit.[2] The experiment confirms this. Despite this randomness of the first impact point, photon 2 (which could be light-years

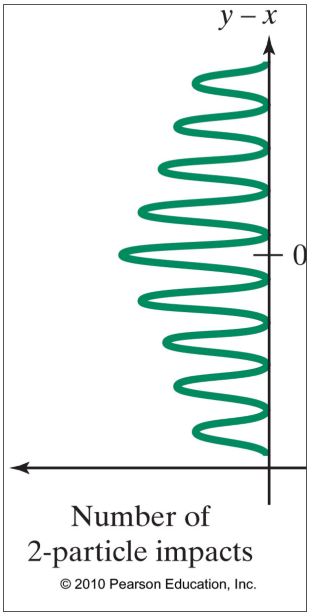


Fig. 3. Although photon 1's impact points x are entirely random (no pattern), and so are photon 2's impact points y, each pair x and y are correlated in such a way that y-x forms an interference pattern. How does photon 2, impacting at y, "know" at which point x the first photon impacted? Photon 2 instantly coordinates its impact point with photon 1's impact point, despite the uncertainty principle's implication that both impact points are uncertain in advance. (Reprinted by permission of Pearson Education Inc., Upper Saddle River, NJ.)

away) *instantly* adjusts its wave packet to just "fit" photon 1's impact point, as shown in Fig. 3. *How does photon 2 instantly "know" photon 1's impact point in order to physically adjust its wave packet?*

Spell this out in more detail for your students. Suppose the points of constructive interference in Fig. 3 are 1 mm apart. Then, if photon 1 impacts at some particular point x, photon 2 must impact near a point y that differs from x by 0, 1, 2, 3, … mm, and avoid the points that differ from x by 0.5, 1.5, 2.5, … mm. *How can photon 2 "know" which points to hit or avoid?*

Einstein considered such behavior spooky, and so do I.

We see now why the screens cannot show the usual two-slit interference pattern. Once photon 1 (say) impacts, the entangled photon 2 must instantly readjust to form an interference pattern whose center is determined by photon 1's impact point. But photon 1's impact point is indeterminate, so each photon 2 impact conforms to an interference pattern with a different center, smearing out any possible observable pattern on screen 2. In fact, the probability distribution of impacts on both screens is predicted, and observed, to be just a constant, i.e., impacts occur randomly on both screens.[15] So, in agreement with special relativity's prohibition on instantaneous signaling, it's impossible for, say, observer 2 to receive information from observer 1 by merely looking at observer 2's screen. The entanglement is entirely hidden until one compares impacts on *both* screens. More generally, Ballentine and Jarrett showed in 1987 that one cannot use entanglement to send information or energy at speeds exceeding the speed of light.[16] It's remarkable how nature delicately manages to exhibit quantum nonlocality without impairing the principles of relativity.

John Bell's analysis

It's often suggested that this instantaneous cooperation between two distant objects only seems spooky, but is actually just a case of correlations arising from past history. As an example of this common, classical, and non-spooky correlation from past history, suppose Bob is in Paris, Alice is in Beijing, and you are in New York City. You tell Bob and Alice, "I'm mailing one of you a gold coin and the other a silver coin" without saying who gets which coin. Because of this prior correlation, Bob, upon opening his envelope and discovering a silver coin, knows instantly that Alice received a gold coin. There's nothing nonlocal about this; Bob's receipt of the silver coin didn't alter Alice's coin; her coin was gold from the time you mailed it in New York.

According to quantum physics, the RTM experiment differs fundamentally from the gold and silver coins. An observer with complete knowledge of the initial conditions (silver is mailed to Bob and gold is mailed to Alice) knows the outcome of the coin experiment in advance, while quantum physics tells us that, in the RTM experiment, a specific x and y don't exist in advance. The coins had an identity (gold or silver) in advance, but the photons have no position until impact.

Nevertheless, it's reasonable to ask if there could be some subtle pre-arranged cooperation between the two RTM particles, similar to the gold-and-silver coin pre-arranged cooperation. Such cooperation would amount to advance instructions, based on the other particle's initial trajectory, as to where each particle should impact. In 1964, John Bell analyzed this question directly from standard probability arguments, and proved that the answer is "no." Kuttner and Rosenblum derive the relevant principle, known as "Bell's inequality," using a simple photon-polarization-like analogy for illustration.[4] Bell's inequality is a numerical relationship between experimental outcomes at two separated locations, assuming only that observations at one location cannot instantly alter the real physical state of the objects observed at the other location.

In the RTM experiment, the correlations (Fig. 3) between the photons turn out to violate Bell's inequality by 10 standard deviations. The correlations are too detailed, too tight, to be the result of any locally real cooperation, i.e., any pre-arranged scheme. This result supports the conclusion that, regardless of whether quantum physics is true or false, nonlocality is a fact of nature.

Furthermore, by correctly predicting the RTM experiment and other experiments that violate Bell's inequality, quantum physics predicts nonlocality. It predicts that objects can instantly influence each other's real physical state directly across an arbitrarily large distance.

Recall that, in the simple double-slit experiment, the impact point of an electron or photon is undetermined before the instant of impact.[2] In the same way, quantum physics says that the impact points in the RTM experiment are not predetermined by initial conditions at the source. To return to the gold-and-silver coin example, it's as though both coins were made of a gold-silver alloy until Bob opened his envelope, and at that instant they changed into a silver coin and a gold coin.

Conclusion

The concept of field quanta helps in understanding entanglement. Two entangled particles form a single unified quantum, but with two excitations. The entire quantum behaves as a single entity, undergoing instant collapses, just as a singly excited field quantum collapses everywhere when a tiny flash appears on the viewing screen in the simple double-slit experiment. Entangled particles do not coordinate their actions by means of information transfer between them; rather, their actions *must* be coordinated because the two particles form a single unified object, just as a single-particle wave packet that comes through two slits is a single unified object even though it is in two different places—think, for example, of a single photon that is both reflected and transmitted by a half-reflecting mirror. Figure 1 tries to picture this unified nature of entangled particles. Whether it contains one or many particles (excitations), a field quantum is a single object; you can't alter any part without affecting all parts. Bell's inequality tells us that, regardless of whether quantum physics is true or false, the entanglement experiments (assuming that no holes are found in the experiments themselves) imply the nonlocality, at arbitrarily large distances, of nature.

As Alain Aspect, leader of the first experimental demonstration[7] that nonlocal interactions occur within a time shorter than the time needed for a light beam to connect the two objects, put it: "The experimental violation of Bell's inequalities confirms that a pair of entangled photons separated by hundreds of meters must be considered a single nonseparable object—it is impossible to assign local physical reality to each photon."[17]

References

1. One of a series on teaching modern physics: A. Hobson "Teaching $E=mc^2$: Mass without mass," *Phys. Teach.* **43**, 80–82 (Feb. 2005); "Teaching quantum physics without paradoxes," *Phys. Teach*. **45**, 96–99 (Feb. 2007); "Teaching elementary particles: Part I," *Phys. Teach.* **49**, 12–15 (Jan. 2011); "Teaching elementary particles: Part II," *Phys. Teach.* **49**, 137–138 (March 2011); "Teaching quantum uncertainty," *Phys. Teach.* **49**, 434–437 (Oct. 2011). All are based loosely on the author's liberal arts physics textbook *Physics: Concepts & Connections,* 5th ed.(Pearson Education Inc., Upper Saddle River, NJ, 2010).
2. A. Hobson, "Teaching quantum uncertainty," *Phys. Teach.* **49**, 434–437 (Oct. 2011).
3. L. Gilder, *The Age of Entanglement: When Quantum Physics Was Reborn* (Alford A. Knopf, New York, 2008).
4. F. Kuttner and B. Rosenblum, "Bell's theorem and Einstein's 'spooky actions' from a simple thought experiment," *Phys. Teach.* **48**, 124–130 (Feb. 2010).
5. A pre-interaction factored two-body wave function $\psi(x)\phi(y)$ evolves into a post-interaction wave function $\psi(x,y)$ that cannot generally be factored. If x is then measured and found to be x_m, the second particle instantly collapses to become the one-particle wave packet $\psi(x_m,y)$, which depends, however, on the measured value of the measured particle—a nonlocal effect that involves both particles. Such an effect is called "entanglement."
6. A. Zeilinger et al.,"Free space distribution of entanglement and single photons over 144 km," *Nature Phys.* **3**, 481–486 (2007); also see "Quantum leap reported for entangled photons," *APS News* **16**, 3 (May 2007).
7. A. Aspect, P. Grangier, and G. Roger, "Experimental test of Bell's inequalities using time-varying analyzers," *Phys. Rev. Lett.* **49**, 1804–1807 (1982).
8. A. Einstein, B. Podolsky, and N. Rosen,"Can quantum-mechanical description of physical reality be considered complete?" *Phys. Rev*. **47**, 777–780 (1935).
9. A. Einstein, *The Born-Einstein Letters: Correspondence between Albert Einstein and Max and Hedwig Born from 1916 to 1955* (Walker, New York, 1971); cited in H. Buhrman et al., "Quantum entanglement and communication complexity," *SIAM J. Comput.* **30**, 1829–1841 (2001).
10. M. M. Raimond, M. Brune, and S. Haroche, "Manipulating quantum entanglement with atoms and photons in a cavity," *Rev. Mod. Phys.* **73**, 565–582 (2001).
11. C. Monroe,"Experiment demonstrates quantum entanglement between atoms a meter apart," *Phys. Today* **60** (11), 16–18 (Nov. 2007).
12. "Entanglement of macroscopic objects," in *Physics News* in 2001 (a supplement to *APS News*), p. 3; see also the reference therein.
13. J. G. Rarity and P. R. Tapster, "Experimental violation of Bell's inequality based on phase and momentum," *Phys. Rev. Lett.* **64**, 2495–2498 (1990); Z. Y. Ou, X. Y. Zou, L. J. Wang, and L. Mandel,"Observation of nonlocal interference in separated photon channels," *Phys. Rev. Lett.* **65**, 321–324 (1990). For the theoretical background, see J. D. Franson, "Bell inequality for position and time," *Phys. Rev. Lett*. **62**, 2205–228 (1989), particularly Eq. (16) for the coincidence rate between the two photon detectors as a function of the settings of the two phase shifters.
14. For those who are familiar with Mach-Zehnder interferometry, the RTM experiment can be related to the more common photon polarization experiments by noting that resetting, say, particle 1's phase shifter at the last moment before impact instantly changes the correlations between the two particles from, say, constructive to destructive interference. How did particle 2 "know" about the change in particle 1's phase shifter? Such a fast change in two-particle correlations hasn't yet been achieved in an RTM-like experiment (correlated positions), but it has been checked in the polarization experiments. See Ref. 17 and the references therein.
15. This is explained in two analyses of this experiment: D. M. Greenberger, M. A. Horne, and Zeilinger, "Multiparticle interferometry and the superposition principle," *Phys. Today* **46** (8), 22–29 (Aug. 1993); and K. Gottfried, "Two-particle interference," *Am. J. Phys.* **68** (2), 143–147 (Feb. 2000).
16. L. E. Ballentine and Jon P. Jarrett, "Bell's theorem: Does quantum mechanics contradict relativity?"*Am. J. Phys.* **55** (8), 696–701 (Aug. 1987).
17. A. Aspect, "Bell's inequality test: More ideal than ever," *Nature* **398**, 189–190 (18 March 1999).

Art Hobson *is emeritus professor of physics at the University of Arkansas, Fayetteville. He is author of* Physics: Concepts & Connections, *a conceptual liberal arts physics textbook for college students (Ref. 1).*
Department of Physics, University of Arkansas, Fayetteville, AR 72701; ahobson@uark.edu