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Teaching quantum theory in the introductory course

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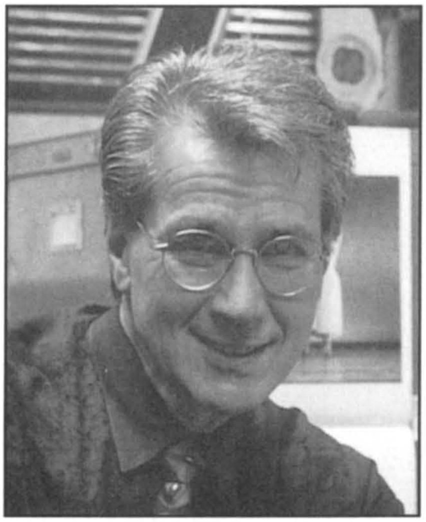
Teaching Quantum Theory in the Introductory Course

By Art Hobson



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Although the quantum and relativity theories have been our basis for understanding the physical universe for almost a century, many introductory physics courses still nearly exclude them. Thus most scientists finish college without discovering that there are a few loopholes in $F = ma$, not to mention misconceptions in the classical views on time, space, mass, radiation, matter, energy, continuity, observation, causality, locality, and physical reality itself.

Furthermore, physics educators shoot themselves in the foot by devoting their introductory course so fully to classical physics. Modern physics is not only the intellectually right thing to teach, if taught properly it is also the more popular thing to teach! For confirmation, merely peruse the better-selling physics-related trade books. How many are primarily devoted to Newtonian topics, and how many to modern topics?

One bright light is the reform efforts of the Introductory University Physics Project,[1] cosponsored by the American Association of Physics Teachers and the American Physical Society. The IUPP takes it as a guiding principle that contemporary physics deserves more prominence in the introductory course.

Fortunately, liberal-arts physics courses can break out of the usual classical mold, because such courses are not training courses for future scientists. Nevertheless, judging at least from the textbooks, it appears that most non-scientists' courses simply follow the technical courses in relegating modern topics to a few superficial lectures at the end, lectures that will be the first to go if the instructor runs overtime on the plethora of classical detail.

Our liberal-arts physics course at the University of Arkansas devotes 50% of the lectures to modern physics, while still including most of the big classical topics: Newtonian mechanics and gravity, thermodynamics, and electromagnetic radiation. This approach has proven popular with students.[2] A textbook is available.[3] Our approach is "conceptual," i.e., nonalgebraic, emphasizing ideas rather than calculations.

The course's main modern topic is quantum theory. This article describes our approach to teaching quantum theory without math, with emphasis on some innovative approaches and topics such as nonlocality and Bell's theorem. The article is written in the form of suggestions to prospective instructors.

Radiation: The Photoelectric Effect

Demystify the quantum right away by saying that some Newtonian ideas are incorrect at the microscopic level, and that *quantum theory* is the set of ideas that appear to be correct. The key non-Newtonian idea is that nature is discontinuous, or *quantized* (broken into discrete chunks or quantities—hence the word *quantum*) at the microscopic level.

The term *quantum mechanics* is an inappropriate holdover from Newtonian mechanics. Although a machine might be a good metaphor for the classical universe, the essence of quantum theory (or quantum physics) is its nonmechanical nature.

Motivate the topic: (1) In predicting such a wide variety of phenomena so accurately, quantum theory is probably history's most successful scientific theory. (2) The theory's practical impact includes most information and communication technologies, most of modern chemistry and thus biology, lasers, nuclear physics, nuclear power, and nuclear weapons. The electron, the quantum particle par excellence, is central to the entire high-tech world. (3) Although its ultimate cultural role is not yet clear, quantum theory deeply affects the Newtonian worldview that is woven so finely into the fabric of the western world.

Although the discovery of quanta (i.e., microscopic discontinuities) occurred in connection with Max Planck's investigation of the radiation from heated bodies, this example makes poor pedagogy and is best omitted or just mentioned in passing. As Hans Bethe[4] has pointed out, the photoelectric effect is far more direct and pertinent. Describe this effect, and the ideas of Planck and Einstein leading up to:

The Particle Theory of Radiation

Electromagnetic radiation is created by vibrating charged particles whose energy is quantized. Thus, radiation appears as particles, called "photons," each having energy hf, where h is Planck's constant (6.6×10^{-34} joule-seconds), and h is the radiation's frequency.

But is radiation really quantized? Review light interference, especially the double-slit experiment. The pattern on the screen is a wave pattern, requiring a wave theory of radiation. Thus some experiments are consistent only with a particle theory of radiation, while others are consistent only with a wave theory of radiation. To begin clarifying (although we never *explain* it—quantum theory simply accepts the duality) this situation, discuss the gradual statistical emergence of the double-slit interference pattern from individual photon impacts.

Matter: The Electron Double-Slit Experiment

As Richard Feynman pointed out, the double-slit experiment "has in it the heart of quantum mechanics. In reality, it contains the only mystery. We cannot make the mystery go away by explaining how it works." The double-slit experiment using electrons instead of light extends wave/particle duality to matter.

Review the evidence that electrons are material, and that all matter is particulate. Describe the double-slit experiment using electrons. Compare with a similar but macroscopic experiment using a machine gun and bullets instead of an electron source and electrons.[5] Show the result for electrons with one slit and then both slits open, and show transparencies of the evidence.[6] Take plenty of time to discuss these results, dialoguing and inviting questions and comments. Graph the results, emphasizing especially the positions of total destructive interference. The situation is precisely what it was for radiation. Everything, matter and radiation, has a dual wave/particle nature.

Accompany this discussion with a presentation of de Broglie's inspired prediction of wave effects for matter. His idea nicely balances the preceding particle theory of radiation:

The Wave Theory of Matter

A material particle having mass m and speed v appears in some experiments as a wave whose wavelength is given by $\lambda = h/mv$.

This is a good place to introduce the basics of quantum theory: uncertainties, psi, its probabilistic interpretation, and the idea (but not the mathematics!) of the Schroedinger equation. Wave/particle duality implies that identically prepared particles impact in an extended wave pattern, with different particles impacting at different points, so that there is an inherent *quantum uncertainty* about where any particular particle will impact.

Despite this unpredictability, the overall pattern is reproducible. This led Schroedinger to search for a way to predict the pattern. The result, *Schroedinger's equation*, is the kind of equation that mathematicians use to describe waves. The thing that does the waving in Schroedinger's equation is usually called *psi*. Psi is a fieldlike entity, extended in space, much like an electromagnetic field. In fact, an electromagnetic field actually is a "psi field," for photons, although you might not want to confuse your students with that fact at this point.

Psi has gone by many names: psi wave, matter wave, probability amplitude, Dirac field, ghost field, quantumstuff. The pertinent fact about psi is not that it waves, but rather that it is a *field*. Thus, the term *psi field* seems appropriate.

Make Schroedinger's equation concrete with an example such as Fig. 1. Emphasize that this figure represents the psi field for a *single* electron. There is a sense in which each electron comes through both slits—at any rate, its psi field comes through both slits.

The Quantum Atom

The quantum atom makes all of this concrete. But it is misleading to make the atom the focus of quantum theory, as

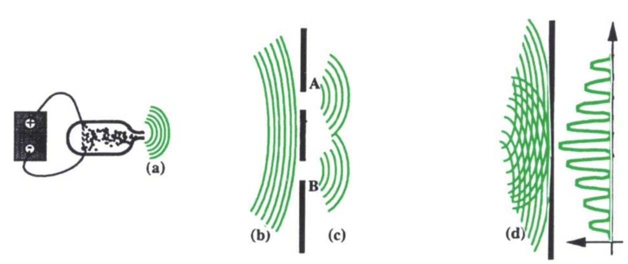

Fig. 1. Probability wave for a single electron at four different instants: (a) as the wave (in other words, the electron) leaves the source, (b) as it approaches the slits, (c) just after passing through the slits, (d) just before the arriving at the screen. The graph, which is a graph of the probability wave at the position of the screen, shows the probabilities that the electron will hit at various positions.

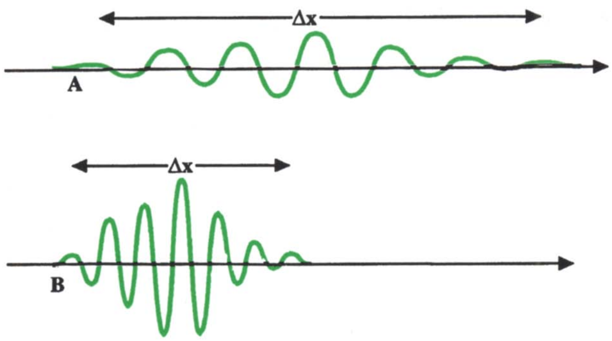

Fig. 2. Two wave packets, having different Δx's.

some presentations do. Quantum theory is about much more than atoms.

Although Niels Bohr's theory of the atom was a beautiful stroke of genius in 1913, and is a useful calculational tool today, its quantum discontinuities combined with deterministic classical orbits are precisely the wrong combination of ideas for enlightening students about quantum theory. The full quantum atom, on the other hand, makes an excellent example.

Begin with the evidence: the line spectra of diffuse gases. How can they be explained in terms of the standard (but nonquantized) planetary model of the atom? Why are only some wavelengths emitted? The deeper problem is that classical electromagnetic theory predicts that an orbiting electron should radiate all the time, which atoms do not actually do, and worse yet it predicts that such an electron must continually lose energy, spiral into the nucleus, and cease orbiting. Classical electromagnetic theory coupled with the planetary model of the atom is not self-consistent, because it predicts that atoms should collapse. A classical universe would be boring, with no chemistry and no life.

Quantum theory says that an "orbiting" electron should be represented by a psi field. Schroedinger's equation predicts that the electron's psi field forms a standing wave around the nucleus. Geometrically, it is easy to see that many different standing-wave patterns can fit around the nucleus. Thus, it is not surprising that Schroedinger's equation predicts that there are many possible psi fields, each representing a different state of excitation of the atom's orbital electron. Make this result more concrete by showing the probability patterns for several of these *quantum states*.[7]

Since each state has a definite frequency, and since frequency is connected with energy, we expect that an atom in one of these states has a definite energy, i.e., the atom's energy is quantized. Thus an atom cannot gain or lose energy continuously. It must instantaneously *quantum jump* from one state to another, releasing or absorbing a specific amount of energy. This is where photons come from!

Quantum theory has a simple answer to the problem of the collapsing atom: An atom in its ground state cannot radiate because it has no lower-energy state to jump to. The reason is that no more compact standing wave patterns will fit. Thus, quantum uncertainties prevent the atom's collapse.

The Uncertainty Principle

Treat Heisenberg's uncertainty principle in some depth. It is easy to qualitatively derive its main features, starting from the plausible notion that the psi field for a moving localized particle should be a moving wave of limited spatial extension. Draw a few *wave packets* (Fig. 2), qualitatively describing their uncertainties Δx.

De Broglie's waves are similar to wave packets, but being infinitely long they correspond to an entirely nonlocalized particle—one for which Δx is infinite. Draw a few de Broglie waves, discussing the electron's speed for each (Fig. 3). Now explain that it is possible to obtain a wave packet by judiciously combining different de Broglie waves so that they cancel each other everywhere except in a limited region Δx. Furthermore, any such "superposition" fulfills the Schroedinger equation.

But now look at what has happened: In order to get a localized wave packet, we had to combine de Broglie waves having a range of wavelengths, i.e., a range of particle velocities. Thus a wave packet represents a particle whose velocity is uncertain by some amount Δv.

Now compare two wave packets A and B with different Δx's and Δv's (Fig. 2), where B is obtained by squeezing A down to half its original length. Since B's wavelengths are shorter, its velocities are higher. In fact the velocities represented by B are twice those represented by A, because all the wavelengths are half as long and $\lambda = h/mv$. This means that the *uncertainty* in velocity is also twice as large. So in halving Δx, we doubled Δv, and the product $\Delta x \cdot \Delta v$ remained unchanged.

Extending this reasoning, Heisenberg discovered:

> **Heisenberg's Uncertainty Principle**
>
> Every material particle has inherent uncertainties in position and velocity. Although either one of these uncertainties can take on any value, the two are related by $\Delta x \cdot \Delta v \approx h/m$.

This form seems preferable to $\Delta x \cdot \Delta p \approx h$ because v is a simpler concept than p, because Δv is more directly related to the future predictability of x, and because this form shows why larger masses have smaller uncertainties.

Classically, every particle has a definite x and v, from which the future x and v are predictable provided we know the external forces. But quantum mechanically, a particle's x and v have an "uncertainty range" or, in Nick Herbert's nice

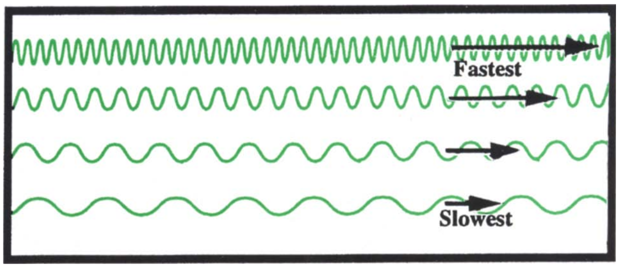

Fig. 3. Four different psi fields, each representing a single freely moving particle.

phrase,[8] a "realm of possibilities." Show this range graphically, to illustrate the relation between Δx and Δv as well as the relation between a particle's mass and its realm of possibilities (Fig. 4).

Give some applications: (1) A proton is about 2000 times more predictable than an electron [Fig. 4(e)]. A grain of sand is so massive (some 10^{18} atoms) that quantum uncertainties are negligible. (2) A particle whose Δx is squeezed into a small region must have a large Δv. But you can't have a large Δv without also having a large average speed. So more highly confined particles must move faster. Thus nuclear particles have much higher energies than do orbital electrons. The uncertainty principle will not allow the microscopic world to slow down! (3) Since most students will have heard of radioactive decay, it is worth pointing out here that quantum uncertainties within the nucleus cause radioactive decay to be unpredictable. (4) When a child is conceived, the DNA molecules of each parent are randomly combined in a process in which the quantum features of the DNA's chemical bonds play a role. So quantum uncertainties operating at the microscopic level play a role in our genetic inheritance.

In these and other ways, we are in the hands of the "god who plays dice."

Quantum Jumps

Many of quantum theory's "spooky" (Einstein's word) predictions and nonlocal effects arise from the instantaneous *quantum jumps* that can occur throughout an extended psi field.

Discuss atomic transitions as well as other examples of quantum jumps. Suppose, for instance, that a freely moving electron has a position uncertainty Δx, and that we then measure the electron's position to within a smaller $\Delta x'$. The measurement causes the electron's psi field to quantum jump to a tighter wave packet. In the double-slit experiment, for instance, an electron's wave packet is spread out over a large portion of the screen just before impact, but upon impact it "collapses" into a much smaller region. Quantum jumps are unpredictable: We cannot predict, before impact, what the new psi field will be after impact.

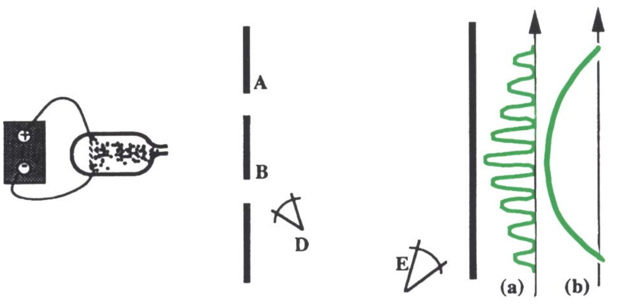

Fig. 5. Merely switching on a particle detector, at a point such as D, causes the psi field to jump from the interference pattern (a) to the noninterference pattern (b). Even with the detector at position E, and even if the detector is then switched on after the particle passes through the slits, the same effect occurs.

Quantum jumps can affect very large regions. For example, the psi field for each photon from any very distant star is spread out over many kilometers by the time it reaches Earth. Robert Hanbury Brown confirmed this prediction in 1965 by measuring, for the light from an individual star, interference patterns over 100 meters wide. Despite its large size, a photon's entire psi field contracts to a point at the instant the photon hits a detector.

Quantum jumps are generally associated with detection events, where some microscopic event is recorded by a macroscopic recording device such as a fluorescent screen. As an example of the effect of detectors, return to the double-slit experiment with electrons. We have seen that one of the mysteries of this experiment is that the interference pattern implies that the electron cannot be said to come through either slit A or through slit B. This suggests that we place, just behind one or both slits (at position D in Fig. 5), a detector that can tell us whether the electron came through slit A, or slit B, or both. When experiments of this sort are done, the electron is observed to come through only one slit, not both. But this does not imply that the electron really does come through only one slit in the double-slit experiment, because in every instance *the presence of the detector destroys the interference pattern*, producing pattern (b) of Fig. 5, rather than pattern (a). The detector changes the experiment, from a two-slit experiment to two one-slit experi-

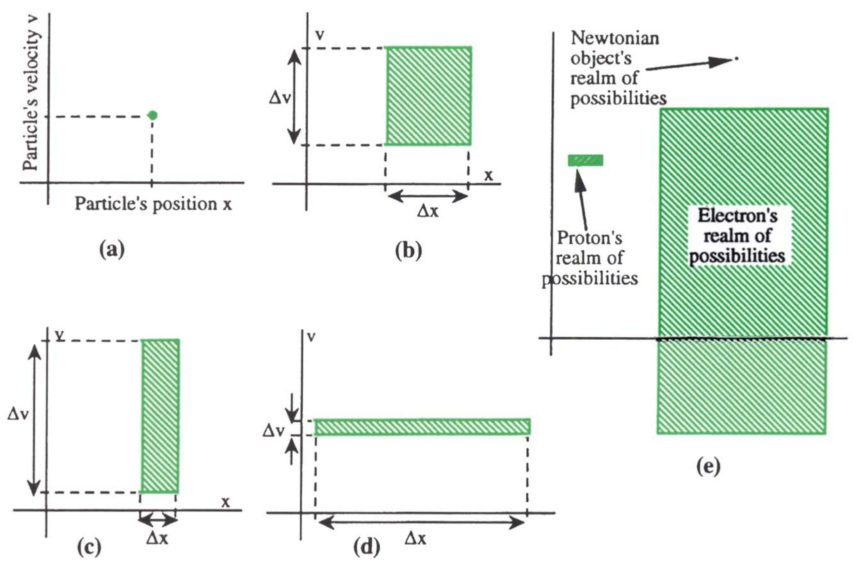

Fig. 4. (a) A single point on an *x*-vs-*v* diagram, such as the point shown here, represents a precise value of both *x* and *v*. Quantum theory does not allow such precise values. (b) A realm of possibilities for a single particle, according to quantum theory. The total area of the shaded region, $(\Delta x)\cdot(\Delta v)$, must be roughly equal to h/m. (c) If for any reason Δx is reduced, then Δv must expand to fill up the same overall realm of possibilities. (d) If Δv is reduced, Δx must expand. (e) Because of its larger mass, a proton's uncertainties are much smaller than an electron's.

ments, so that we have failed in our effort to learn through which slit an electron goes in the two-slit experiment. The electron "knows" whether a detector is present. More accurately, the experiment has a "holistic" quality: A two-slit experiment with a detector present is fundamentally different from a two-slit experiment with no detector present.

Physicists have performed some interesting variations of this experiment, using a detector that can be suddenly switched on or off during the experiment. The electron's psi field quantum jumps from one pattern to the other when the detector switches: pattern (b) suddenly replaces pattern (a) when the detector switches on, and pattern (a) reappears when the detector switches off. As a Newtonian explanation of this effect, perhaps the detector interacts with each particle as it comes through a slit, forcing the electron to impact in accordance with pattern (b) instead of pattern (a). To check this, the detector can be placed far from the slits, near the screen, at position E. Again, when the detector is on, we get pattern (b).

The detector can even be switched on *after* the electron is well past the slits (but still before its impact on the screen). Surely then the detector cannot exert a force on the electron as it comes through the slits, because the detector isn't even turned on then. Yet even in this case, quantum theory predicts and experiment confirms that the interference pattern quantum jumps to pattern (b) at the instant the switch is thrown! It is as though the detector switch caused the electron (or its psi field at any rate) to go, *in the past and at some distance away*, through only one slit instead of both.

The lesson is that microscopic experiments are critically dependent on the entire experimental arrangement, especially the placement of detectors. The behavior of entities such as electrons is intimately bound up with such macroscopic entities as slits and fluorescent screens.

The Nonlocal Effect of Detectors

In 1991 Leonard Mandel and coworkers conducted a striking test of quantum theory's predictions about the effect that detectors can have on distant events.[9] Figure 6 shows Mandel's experimental arrangement, modified for pedagogical reasons as described in the next paragraph. A source emits a single particle whose psi field travels along two paths A and B (just as an electron's psi field can travel through two slits). This single particle is then converted into *two* particles, 1 and 2, each moving along two possible paths, labeled 1A, 2A, 1B, 2B. Particle 1 (i.e., its psi field) moves along paths 1A and 1B through a double-slit apparatus having slits A and B and impacts a screen, while particle 2 moves along paths 2A and 2B toward a detector. Paths 2A and 2B are right in line with each other, so that a particle moving along either path would strike the detector at the same point. As we know from the ordinary double-slit experiment, if there is no way of knowing which slit (A or B) particle 1 comes through, then particle 1's psi field comes through both slits and forms the interference pattern (a).

For pedagogical purposes, Fig. 6 modifies Mandel's original arrangement, but in ways that do not affect the fundamentals. The actual experiment is done with photons. I just call them "particles" in class, because in principle they could be material particles. The source is an argon laser, and the two paths A and B are created by a beam splitter (a half-silvered mirror). The key to performing the experiment is the two devices, called "down-converters," that create photons 1 and 2 from the original single photon. Down-conversion is a process in which one ultraviolet photon converts into two photons inside a nonlinear crystal. Finally, paths 1A and 1B are actually recombined not at a screen but instead by a beam-splitter placed at the intersection of the two paths with a stationary detector that records the interference of the recombined beams. Phase shifts associated with various path differences are observed by altering the length of one of the two fixed paths 1A and 1B, rather than by observing various points on a screen.

The unique feature of Mandel's arrangement is that the pairs of paths are related in the following way: if particle 2 is observed to be on path 2A, then particle 1 must be on path 1A; and if particle 2 is observed to be on path 2B, then particle 1 must be on path 1B.

Now suppose that a barrier is placed in the way of path 2A, as shown, and that the source emits a single particle. Then if we see a flash on the screen and also detect a particle hitting the detector, we can conclude that particle 2 came along path 2B, so the flash on the screen was caused by a particle moving along path 1B. And if we see a flash on the screen but we do *not* detect a particle hitting the

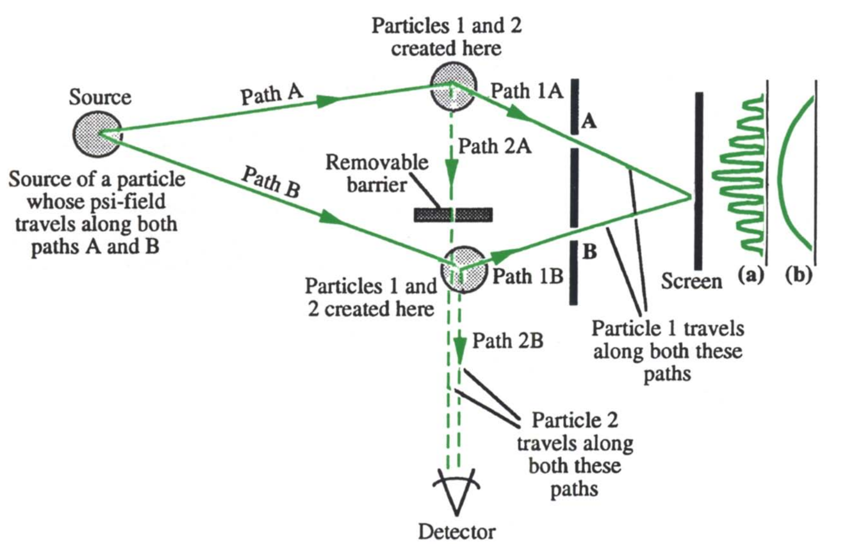

Fig. 6. Mandel's experiment. A barrier placed in path 2A causes the pattern on the screen to quantum-jump from pattern (a) to pattern (b), even though the barrier does not directly disturb the particle that impacts the screen, and even though the barrier and detector can be quite distant from the screen.

detector, we can conclude that particle 2 came along the blocked path 2A, so particle 1 must have moved along path 1A.

In other words, with the barrier in place, the detector placed along path 2B can determine which slit particle 1 comes through. But if the barrier is removed, then the detector along path 2 no longer gives any information about particle 1, because paths 2A and 2B are aligned with each other. The barrier and detector interact only with particle 2, and could be quite distant from the path of particle 1—they could be many kilometers away, or even on the moon or in a distant galaxy. Thus, the detector and barrier constitute an extremely remote and noninterfering detection scheme for particle 1. It is hard to believe that the placement or removal of a barrier along path 2A could affect what happens to particle 1 at the screen.

Yet quantum theory predicts, and the experiment confirms, that when the barrier is placed in path 2A, the interference pattern quantum-jumps from pattern (a) to pattern (b). Furthermore, the effect persists even when the detector is removed—the mere blocking of path 2A destroys the interference between paths 1A and 1B! Apparently, the mere possibility that an observer *could* insert a detector and thus determine whether path 1A or 1B was taken causes the interference pattern to switch to non-interference. We conclude that detectors that can provide information about distant events can change those events even without directly physically interfering with those events. Microscopic events respond to the entire macroscopic experimental arrangement.

The Interconnectedness Principle

Quantum theory has evolved considerably since its founding in the 1920s. Einstein, in the 1930s, found the theory too counterintuitive to believe. He along with Boris Podolsky and Nathan Rosen showed in 1935[10] that, because of quantum uncertainties, quantum theory predicts some phenomena that are as he put it so "spooky" that "no reasonable definition of reality could be expected to permit this." Einstein took these predictions as evidence that a complete and correct theory would not contain quantum uncertainties, but he did not suggest a way to put the spooky predictions to an experimental test.

Because quantum theory proved so gloriously successful in practice, few physicists worried about such untested objections. Among those who did worry were David Bohm and John Bell. Bohm began publishing his analysis of quantum theory during the 1950s.[11] Bell showed in 1964 that some of quantum theory's spooky predictions are *experimentally testable.*[12] John Clauser and four collaborators[13] carried out the first such test in 1972 and found that, contrary to the expectations of Einstein and others, the spooky phenomena actually occur! In 1982, Alain Aspect and two collaborators[14] refined Clauser's test so as to leave little doubt that the real world is stranger than Einstein and others had thought.

Although these wonderful "nonlocal" phenomena are now well established both theoretically and experimentally, they are not generally known, even by physicists, because they are

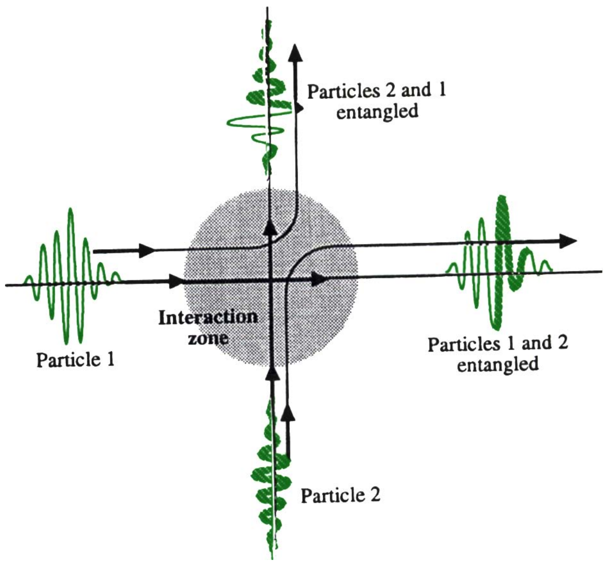

Fig. 7. When two particles interact and then separate, their psi fields generally become entangled.

seldom taught at an introductory level. Like uncertainty, nonlocality is one of quantum theory's far-reaching non-Newtonian predictions that deserves discussion in every introductory presentation.

The spooky predictions stem from quantum jumps in the many-body psi field of two or more *entangled* particles. If two or more particles are created together or if they interact with each other, their psi fields can become intimately interconnected. Mathematically, a two-body state vector of the form

$$\Psi_{1,2} = (1/\sqrt{2})\,(\alpha_1\beta_2 \pm \beta_1\alpha_2)$$

where α_1 and β_1 represent two orthogonal one-body state vectors of particle 1 while α_2 and β_2 have analogous meanings for particle 2, represents two entangled particles. Such a two-body state cannot be written as a product of single-particle states.

Of course, introductory classes should be given a conceptual, rather than mathematical, description of entanglement. Figure 7 is one way of pictorially representing the interaction and subsequent entanglement of two particles. The point is that the two spatially separated psi fields are connected to each other in such a way that any quantum jump in one field implies a simultaneous quantum jump in the other.

Bell's work and Clauser's and Aspect's experiments studied entangled polarization states of photons, rather than entangled positions of material particles. More recently, John Rarity and Paul Tapster performed an entanglement experiment that shows the corresponding effects for position entanglement.[15] This experiment is pedagogically advantageous in introductory classes, because of its close relation to the double-slit experiment. The following description of the Rarity-Tapster experiment is pedagogically modified in the same

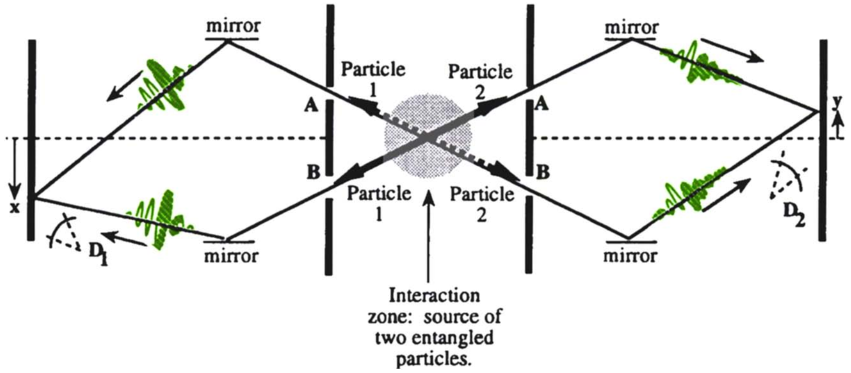

Fig. 8. Position-entanglement experiment. Because of their entanglement, particles 1 and 2 coordinate their impact points *x* and *y* instantaneously, regardless of the distance between them.

manner as was the Mandel experiment: The original experiment used photon beams, phase shifters, and beam splitters.

The experiment (Fig. 8) begins with the creation of two entangled particles that move directly away from each other. Each particle then passes through a double-slit apparatus. Because of their opposite directions, if #1 goes through slit A then #2 must go through slit B (dashed arrow), and vice-versa (solid arrow). The experiment could be described as a "duplicate double-slit experiment" with two entangled particles. Because of the particles' opposite directions and entanglement, there are *statistical correlations* between the impact-point of particle #1 on its screen, and the impact-point of particle #2 on its screen.

Statistical correlations are common in situations involving uncertainties. For a typical example, having nothing to do with quantum theory, suppose your friend tells you that he has sealed a gold coin and a silver coin in separate envelopes, and mailed one to you in Tokyo and one to Betty in Paris. You don't know, before receiving your envelope, which coin you will receive. However, you do know of a relation between your envelope and Betty's envelope: *If* your envelope contains gold then Betty's contains silver, while *if* your envelope contains silver then Betty's contains gold. Such a relation between the probabilities of different events is called a "statistical correlation." Two events are statistically correlated if the outcome of one affects the probabilities associated with the other. Note that in this example, the correlation is not the result of any actual physical interaction between the two coins in the two cities; that is, neither coin causes the other coin to actually change from gold to silver. The correlation is only due to the prior fact that your friend put a gold coin in one envelope and a silver coin in the other.

In the experiment, detectors D_1 and D_2 are placed at each screen. Each detector monitors one fixed point on the screen, registering a "hit" whenever a particle impacts at (or very near) that point. The experimenters measure the degree of statistical correlation between simultaneous hits and misses on the two detectors: Given a hit on, say, D_1, how likely is a simultaneous hit on D_2?

Because the two particles separate in opposite directions, we expect some correlation. For instance, if the distances x (of D_1 *below* the midpoint of its screen) and y (of D_2 *above* the midpoint of its screen) are equal to each other, then hits on D_1 should usually (but not always, because of quantum uncertainties) occur simultaneously with hits on D_2, because the two particles have opposite directions. Such a correlation is similar to the gold and silver coin correlations, and is simply due to the prior opposite directions of the two particles.

The interesting correlations occur when x and y differ from each other. Quantum theory predicts an interference pattern for these correlations: If D_1 is held fixed at any point x, while D_2 is moved from one position y to another, quantum theory predicts positions where hits on D_2 are particularly likely to occur simultaneously with hits on D_1, and other positions where misses on D_2 always occur simultaneously with hits on D_1. The second case is the most striking: Misses on D_2 always occur when x and y differ by certain fixed amounts, such as (for example) 0.5 mm, 1.5 mm, 2.5 mm, etc. That is, the two particles somehow "know" that they are not supposed to impact at points x and y that differ by these particular amounts. *How can they "know" that?* Each particle's interference pattern, for a fixed impact position of the other particle, is dependent on where the other particle impacts its screen.

As another way of putting this: The two particles instantaneously adjust their psi fields to each other's impact point, even though that impact point was unpredictable before impact! The two particles are truly entangled or *interconnected*, and are sometimes spoken of as a single entity, "a two-particle."[16]

The two screens can be as widely-separated as you like, they could be in different galaxies, yet quantum theory predicts the same results. Interconnected particles "know" instantaneously about the outcome of each others' quantum jumps. They coordinate their impact points so as not to impact when the difference x-y is, say, 0.5 mm, 1.5 mm, 2.5 mm, etc. If particle 1 happens to impact at $x = 0.3$ mm, particle 2 instantaneously "knows" it must not impact at $y = 0.8$ mm, 1.8 mm, 2.8 mm, etc., whereas if particle 1 happens to impact at $x = 0.4$ mm, particle 2 "knows" it must not impact at $y =$ 0.9 mm, 1.9 mm, 2.9 mm, etc. How can they cooperate this way, when they are far apart?

Maybe this cooperation is not spooky. Maybe it is merely of the gold-and-silver-coin variety, due entirely to prior information. John Bell analyzed this question in 1964 and proved that the correlations are *not* of this common variety. In other words, Bell proved that this cooperation is due to a real, instantaneous, physical interconnection between the particles—each particle really does cooperate with what the other particle is doing from one instant to the next. We summarize Bell's idea as follows:

Bell's Interconnectedness Principle

Quantum theory predicts that entangled particles exhibit correlations that can only be explained by the existence of real *nonlocal* (that is, instantaneous and distant) *connections* between the particles.[17]

The experiments of Clauser, Aspect, Rarity and Tapster, and others fully confirm this "spooky" quantum prediction.

The Copenhagen Interpretation

It isn't easy to say what quantum theory means. During the 1920s and 1930s, Niels Bohr along with Heisenberg, Born, and others, developed a viewpoint that has withstood the test of time, that has been strengthened by new experiments such as those showing nonlocality, and that is generally, but not universally, accepted among physicists today.

According to this *Copenhagen interpretation*, quantum uncertainties are inherent in nature, and do not merely reflect our own lack of knowledge. When we say that the microscopic particle's position is uncertain, we mean that the particle *has* no definite position. The particle is in some sense all over its realm of possibilities $\Delta x \cdot \Delta v$ As Heisenberg put it, a particle's psi field "introduces something standing in the middle between the idea of an event and the actual event, a strange kind of physical reality just in the middle between possibility and reality."

Consider a particle described by a wave packet, and suppose a measurement then detects the particle at some specific position x. It would be a mistake to conclude that the particle was at or even near x just before the measurement. Instead, we must visualize that the particle "potentially resides" all over the range Δx before measurement, and that the measurement actually *creates* the particle's position rather than simply discovering it. Measurements to some extent create the properties they detect (Fig. 9).

Reality is "contextual." The properties of a particle have meaning only in the context of the entire experimental environment that helps determine the particle's psi field. An electron's position, for example, means the position as defined by some particular position-measuring device. It is improper to think of the electron as *having* a position, in the absence of such a measurement. As Bohr often said, attributes of microscopic particles do not belong to the particle itself but reside in "the entire measurement situation."

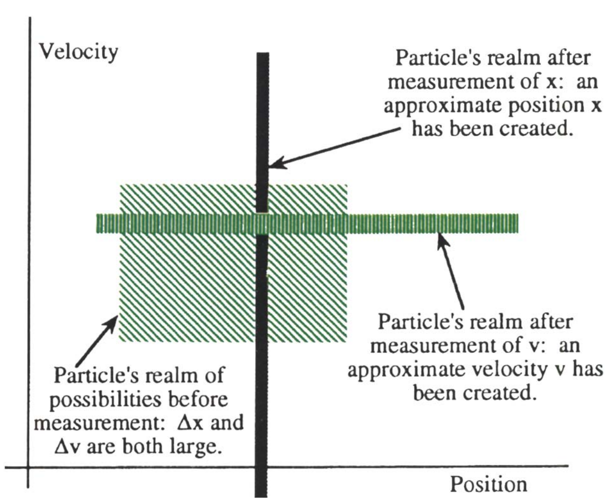

Fig. 9. The effect of a position measurement, or of a velocity measurement, is to create a position or velocity for the measured particle.

In the absence of an experimental arrangement to detect x and v, a particle's x and v cannot be said to exist. But the experimental arrangements for detection of x and for the detection of v preclude each other—we cannot set up both arrangements at the same time. This is why a particle cannot simultaneously have both a precise x and precise v. It is as though a baseball could be either white or spherical, but not both at once. Because the existence of either property precludes the existence of the other, x and v are said to be "complementary" to each other. When Bohr was knighted as an acknowledgment of his achievements in science and his contributions to Danish culture, he chose as a suitable motif for his coat-of-arms the Chinese symbol representing a similar complementary relationship of the archetypal opposites yin and yang.

Observations instantaneously and radically change the observed system. As a particle "approaches" an observing screen, all its possibilities are live possibilities. Just before impact, the particle is at many locations at once. With the flash on the screen, the particle quantum-jumps to a new state, giving it a location. We could not predict the particle's position before impact, because there was nothing there to predict. The particle *had* no position.

But "observation" must be understood broadly. It really means any "detection," and can occur without human observers. An "observation" or "detection" is any permanent, thermodynamically irreversible, macroscopic imprint, such as a flash on a screen or a click of a Geiger counter, or a chemical reaction in a human retina. In Mandel's experiment, we have seen that even the threat of possible detection can cause a quantum jump.

Microscopic particles do not have the reality status of, say, a penny. To the extent that an object must be described by quantum theory, the object has as Heisenberg put it "a strange kind of physical reality just in the middle between possibility and reality." On the other hand, microscopic particles are by no means subjective or only in the mind. For example, the flash of an electron on a screen is real, and it occurs even when no observer is looking (it could for example be recorded by an automatic camera). The microscopic world is real, but its reality status is not what we are used to.

Entanglement represents an extreme form of contextual reality. When two particles are entangled, each particle becomes the context for the other. The two form a single experimental situation, a single object, even though they might be in different galaxies. Just as we must not think of a particle in a wave-packet as really being at one point x, and we must not think of a particle in the double-slit experiment as really coming through one slit, we must not think of entangled particles as really separate. Any attempt to do so will run into contradictions with experiment.

Quantum theory inverts the conventional relationship between microscopic and macroscopic. In the usual view, macroscopic objects such as tables are less fundamental than atoms because they are made of atoms. But quantum theory provides a sense in which tables are more fundamental than atoms, because macroscopic objects define the conditions of existence for atoms. Quoting Heisenberg again: "Some physicists would prefer to come back to the idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether we observe them. This however is impossible.... Materialism rested upon the illusion that the direct 'actuality' of the world around us can be extrapolated into the atomic range. This extrapolation, however, is impossible—atoms are not things."

***Note:** The figures used in this article are reproduced from* Physics: Concepts and Connections, *by Art Hobson (Prentice-Hall Publishing Co., Englewood Cliffs, NJ, 1995). They are reproduced here by permission from Prentice-Hall.*

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This handsome artistic creation of a spectrum graced the front of an advertising brochure sent to us by John Childs, Grenville Christian College, Brockville, ONT K6V 5V8 Canada. It appears that once again art has improved on nature.