Submitted for publication in Proceedings of the Barcelona Meeting on Teacher Education, August 2000

TEACH THE GOOD STUFF: "MODERN" PHYSICS IN INTRODUCTORY COURSES

Art Hobson

Professor Emeritus of Physics, University of Arkansas, Fayetteville, AR 72701
e-mail ahobson@comp.uark.edu, homepage www.uark.edu/depts/physics/about/hobson

ABSTRACT

As we enter the 21st century, most introductory courses still nearly exclude such so-called "modern" topics as quantum physics and relativity--subjects that have been our basis for understanding the universe for most of the 20th century. Thus most students, scientists and non-scientists alike, finish public school and college without discovering the scientific view of time, space, mass, radiation, matter, energy, continuity, observation, causality, locality, cosmology, and physical reality itself. Furthermore, modern physics is not only the intellectually right thing to teach, if taught properly it is the more popular thing to teach! Our one-semester introductory physics course for nonscience college students covers Newtonian mechanics, thermodynamics, electromagnetism, waves, and light during the first half of the course, and devotes the remainder entirely to modern physics: special relativity, the search for extraterrestrial intelligence, quantum theory, nuclear physics, the big bang, and related societal implications such as nuclear power, nuclear weapons, and renewable energy sources. Our textbook [1] also includes general relativity and quantum fields, but we omit these in order to have time for the societal topics. This paper describes how to include modern physics in introductory courses, and presents three examples: $E=mc^2$, Heisenberg's uncertainty principle, and Bell's "interconnectedness" principle.

1. TRIM THE DETAILS, AND TEACH CONCEPTUALLY

In my experience, there are two keys to including modern physics in a broad introductory course. First, in order to leave plenty of time for 20th- and 21st-century physics, teach only the big principles of classical physics and omit many classical details. Our course includes Newton's three laws, Newton's law of gravity, conservation of energy, the second law of thermodynamics, waves, electric forces, magnetic forces, and electromagnetic radiation. But we omit linear momentum, conservation of momentum, impulse, angular momentum, conservation of angular momentum, torque, rigid body rotations, center of mass, stress and strain, heat transfer, the gas laws, specific heat, thermal expansion, liquids, Archimedes principle, Pascal's principle, Bernoulli's principle, sound, electric potential, electric resistance, Ohm's law, electric circuits, Faraday's law, electric motors, electric generators, alternating current, geometric optics, reflection, refraction, diffraction, polarization, mirrors, lenses, and color.

The second key is to keep the modern physics conceptual, i.e. without calculus and with very little or no algebra. The next time you are in a bookstore, browse through the "science" section in order to see what kinds of physics books people pick up voluntarily. I think you will find that most are about modern physics, that they contain little or no mathematics, and that many of these books are very good at explaining physics. For example, Brian Greene's *The Elegant Universe* [2] is a sophisticated presentation of general relativity, quantum field theory, and string theory, without algebra and without oversimplification, in language that non-scientists can grasp.

The remainder of this paper presents three examples.

2. $E = mc^2$

Einstein believed that the most important consequence of his special theory of relativity was the deep connection between mass and energy. It is primarily an idea, not an equation. The equation, $E = mc^2$, expresses merely a numerical relationship, but the idea, namely that mass (inertia) and energy (ability to do work) are really the *same thing*, is expressable only with words and examples. To get this idea across to students, begin with two simple bar magnets (Figure 1).

As you pull the magnets apart, ask your class: Which situation has the most energy? *Answer:* After they are separated. Which has the most *mass* ? *Answer:* The one with the most energy. Where is that extra mass? *Answer:* In the field, located in "empty" space! According to the "field" view of matter, *all rest mass arises in this fashion!* At the microscopic level, there are no "things," only fields.

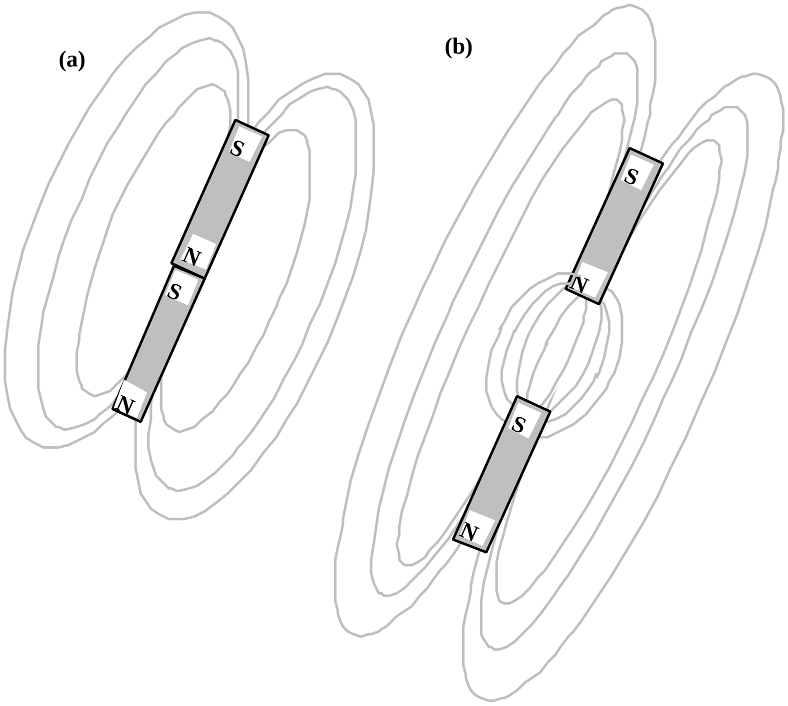

Figure 1. The separated magnets of (b) have more mass than the joined magnets of (a). The excess mass in (b) resides in the invisible and nonmaterial magnetic field.

Physicist Freeman Dyson says "We are fields rather than particles." According to Steven Weinberg, "This point of view ...forms the central dogma of quantum field theory: *the essential reality is a set of fields* …all else is derived as a consequence of ...these fields." As Shakespeare, in *The Tempest,* puts it: "We are such stuff as dreams are made on."

3. HEISENBERG'S UNCERTAINTY PRINCIPLE

Represent quantum uncertainties as rectangles in a position-speed diagram (Figure 2). Nick Herbert [3] calls such a rectangle a "realm of possibilities." When the position of the particle in the quantum state (a) is measured, it instantaneously quantum-jumps to a state such as (b). The measurement has "created" the particle's position. Immediately before measurement, the particle was "all over" its realm of possibilities (a), and should not be thought of as "really" residing at some unknown position within this region. Use speed rather than momentum, because speed is more directly intuitive, and because then the effect of mass can be shown as in (c). As a particle's mass increases, it becomes more Newtonian because its realm of possibilities (whose area is at least $h/2\pi m$) gets smaller.

4. ENTANGLEMENT AND BELL'S INTERCONNECTEDNESS PRINCIPLE

Heisenberg's uncertainty principle is one of the great general laws arising from quantum physics. Of comparable significance, but more recent and seldom presented in courses at any level, is Bell's interconnectedness principle (or "Bell's theorem"). It applies to systems of two or more *entangled* particles. Mathematically, entanglement means that the two-body psi field (or wave function) cannot be factored into a product of two one-body psi fields. But students don't need this mathematical description. Physically, entanglement means that the particles' psi fields are mixed with each other. This can occur by means of an interaction in the past (Figure 3).

John Clauser and Alain Aspect were the experimental pioneers of entanglement. In their work, photon spins, rather than positions as in Figure 3, were entangled. For pedagogical purposes, it is better to present the 1990 experiment of Rarity and Tapster [4] (similar work has been done by D. M. Greenberger, M. A. Horne, A. Zeilinger, and L. Mandel). They investigate photon position-entanglement rather than photon spin-entanglement (Figure 4).

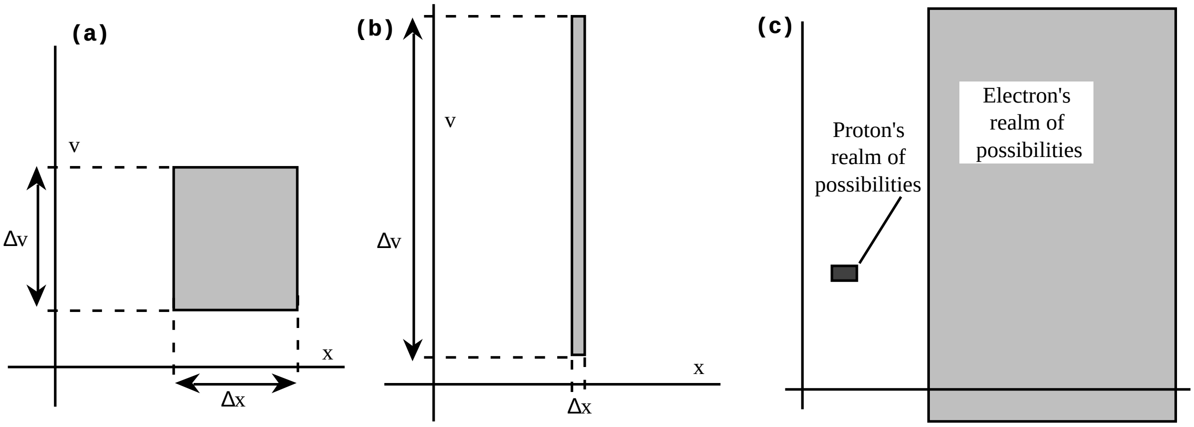

Figure 2. (a) A "realm of possibilities" for a single particle. (b) When the position of the particle in (a) is measured, its quantum state instantaneously jumps to a new state. (c) Because of its larger mass, a proton's realm of possibilities is smaller than an electron's. Thus, protons are more"Newtonian" than electrons. What is the area of the realm of possibilities of the center of a golf ball? *Answer:* Zero, for all practical purposes. That is why golf balls are Newtonian!

The results of Rarity and Tapster's position-entanglement experiment confirm the nonlocal effects predicted by Bell's principle: The simultaneous impact points of the two photons (better: the 2-photon) on the two screens are perfectly correlated, in a non-classical manner. That is, the correlation cannot have been caused by any prior statistical correlation of the ordinary classical type in which both photons are in definite but (to the observer) unknown states prior to measurement, and in which no instantaneous physical connection between the separated photons is required in order to explain the correlated outcomes. In quantum entanglement experiments, a real physical change (and not merely a change in the observer's knowledge) occurs, simultaneously and in a coordinated way, at both observation points.

Reference [5] contains further information about teaching quantum theory.

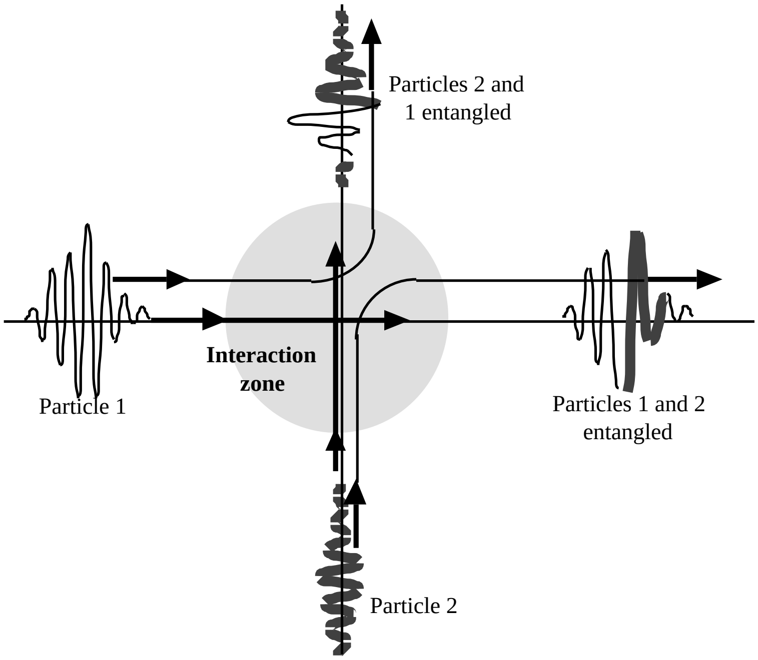

Figure 3. When two particles interact and then separate, their psi fields usually become entangled.

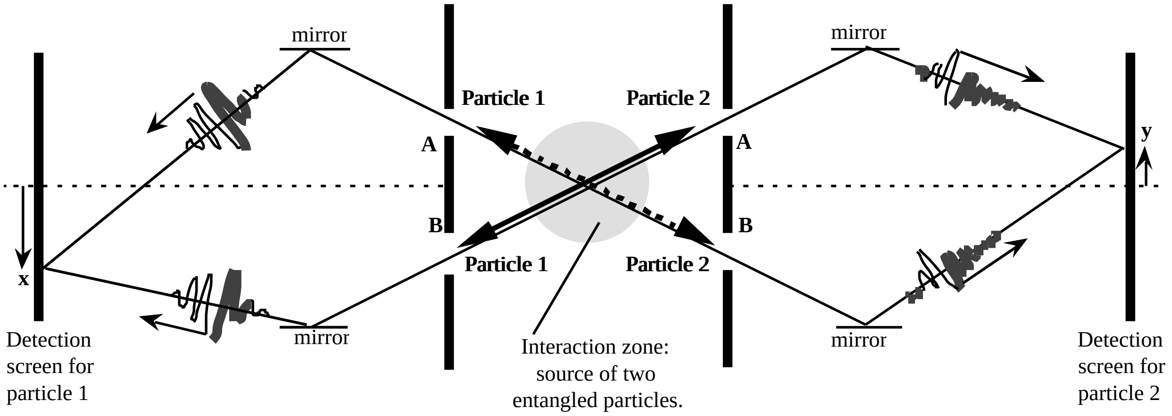

Figure 4. The position-entanglement experiment. Particles 1 and 2 coordinate their impact points x and y instantaneously, regardless of the distance between them.

5. REFERENCES

1. A. Hobson, *Physics: Concepts and Connections* Prentice Hall, Upper Saddle, NJ, 2nd ed l999.
2. B. Greene, *The Elegant Universe,* W. W. Norton, New York, 1999.
3. Nick Herbert, *Quantum Reality,* Anchor Press, New York, 1985.
4. J. G. Rarity and P. R. Taptster, Experimental Violation of Bell's Inequality Based on Phase and Momentum, *Physical Review Letters,* vol. 64, pp. 2495-2498, 1990.
5. Art Hobson, Teaching quantum theory in the introductory course, *The Physics Teacher,* vol. 34, pp. 202-210, 1996.