

Teaching Elementary Particle Physics: Part I¹

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I'll outline suggestions for teaching elementary particle physics, often called *high energy physics*, in high school or introductory college courses for non-scientists or scientists. Some presentations of this topic simply list the various particles along with their properties, with little overarching structure. Such a laundry list approach is a great way to make a fascinating topic meaningless. Students need a conceptual framework from which to view the elementary particles. That conceptual framework is quantum field theory (QFT). Teachers and students alike tend to quake at this topic, but bear with me. We're talking here about concepts, not technicalities. My approach will be conceptual and suitable for non-scientists and scientists; if mathematical details are added in courses for future scientists, they should be simple and sparse. Introductory students should not be expected to *do* QFT, but only to *understand its concepts*. Those concepts take some getting used to, but they are simple and can be understood by any literate person, be she plumber, attorney, musician, or physicist.

Relativity (including general relativity) and quantum physics (including quantum fields) have been science's foundation for understanding the universe for about a century. So it's surprising that some introductory physics courses still nearly exclude so-called "modern," i.e. post-1900, physics. Such courses neglect the contemporary view of time, space, matter, radiation, particles, atoms, fields, energy, causality, locality, or the origin, structure, and evolution of the universe. In other words, such courses fail to teach much about the real physical universe as science understands it today. But isn't that what we're supposed to be teaching?

Introductory students need to get their bearings by beginning with such enduring classical concepts as Newton's first law, velocity, acceleration, and energy, but why focus on all things classical to the near exclusion of modern and contemporary physics, especially in broad introductory courses? Avoiding contemporary physics is ironic in view of its popularity as shown by such books as Brian Greene's *The Elegant Universe*, which was on *The New York Times* bestseller list for months, reaching number four. *The Elegant Universe* deals with general relativity, quantum field theory, and string theory, without equations but with sophisticated conceptual explanations that are missing from many traditional highly math-based introductory courses.

Modern physics is especially appropriate for non-science students, because these courses are not under the gun of specific professional expectations and can take advantage of the present golden age of discovery of the universe, from the quarks to the cosmos. Since the dawn of history, and surely for hundreds of thousands of earlier years, we have wondered where the universe comes from and what it's made of. Such

questions define what it means to be human. Now science is beginning to learn the answers. We should let our students in on the excitement.

The reason there are particles

As Stephen Weinberg has said, "The basic ingredients of nature are fields; particles are derivative phenomena."² Students should have learned about ordinary (or classical) fields earlier in the course. Remind them that fields are spread out over a region of space, and that this region needn't contain any matter or any "thing" at all. A field is a condition of space, a kind of stress in space. For example, there is an electric field at any point where an electric charge *would* feel a force, regardless of whether there is any charge there to actually feel a force. And remind them that fields are physically real, as real as energy and momentum. We know this because we know that they carry energy and momentum. For example, if I send a radio signal to Mars, its journey might take 20 minutes. But radio signals transmit energy from source to receiver. If energy is conserved, that energy must have been somewhere during those 20 minutes. Where was it? The answer: In the electromagnetic field that carried the signal. This argument persuaded Maxwell³ and Einstein⁴ that fields are real. A similar argument applies to any force that is transmitted non-instantaneously.

The central notion of quantum field theory is that the universe is made only of fields. It's an odd idea. Viewed microscopically, the desk in front of you is a configuration of quivering fields similar to the invisible force field surrounding a magnet. When you slap the desk, however, your hand does not pass through the desk because, at short distances, the fields that are the desk repel the fields that are your hand.

But the fields of quantum physics (and of QFT) are not classical fields. They are quantized fields, as I'll explain in a moment.

Your students will probably know something of quantum physics by this point in the course. Ideally, their introduction to quantum physics incorporated the full QFT view from the start, because QFT is the only way to resolve such obvious apparent paradoxes as wave-particle duality. Briefly, here's the idea.⁵

A good way to begin teaching quantum physics is with the quantization of electromagnetic (EM) radiation. The interference pattern obtained in Young's double-slit experiment shows that light is a wave phenomenon, and classical electromagnetism explains this as a wave in an EM field. Quantum physics does not alter this statement. But when Young's experiment is done with dim light using time lapse photography, we find that the interference pattern is formed

by numerous tiny point-like impacts on the viewing screen, in the same way that a pointillist painting is formed by numerous small dots.⁵ The explanation of this phenomenon requires a new physical principle: All EM fields are “quantized.” For a monochromatic EM field, “quantization” means that the field’s energy is restricted to the quantities 0, hf , $2hf$, $3hf$, etc. (plus the “vacuum energy” $hf/2$). This means that, upon interaction with the viewing screen, the field must lose exactly hf (or $2hf$, etc.) joules, instantaneously. It cannot, for example, lose $0.9hf$ or $1.1hf$ joules. This hf joule interaction energy is called a “quantum” of field energy, and is also called a “photon.” It comes from the entire field, which is spread out continuously all over the screen just before interaction. Upon interaction with the screen, the quantum suddenly “collapses” by depositing its energy into just a single atom of the screen, because it would violate the quantization principle if a single quantum split into parts.

Each photon is associated with (i.e., comes through) both slits, resolving the wave-particle apparent paradox. The process is highly non-local: hf joules of field energy collapse instantaneously throughout the macroscopic region in front of the screen.

And the interaction process is probabilistic, as appears obvious in the random distribution of impacts, with the probability of interaction between the photon and a particular atom in the screen being proportional to the intensity of the EM field at the position of the atom. These three new features, namely non-locality, field collapse, and randomness within a predictable statistical pattern, are the fundamental features of quantum physics. They all follow from the quantization principle.

Now we turn to the quantization of matter. In 1974, Young’s interference experiment was performed with a matter beam—an electron beam—instead of a light beam.⁶ The experiment was the exact analogue of Young’s experiment with light, as was its result, namely the double-slit interference pattern. In 1989, the weak-beam version of this experiment was done, and it was seen that (as was obviously expected by 1989) the interference pattern was again formed from individual point-like interactions.⁷ This experiment’s explanation requires another new concept: There’s a new kind of field in nature, known variously as a wave function, ψ , a matter field, or an electron-positron field. Like all fundamental fields, it is physically real, and (as the experiment shows) it’s quantized. But this time the quanta are called “electrons.” Each field quantum, i.e. each electron, passes through both slits, forms an interference pattern at the screen, and then collapses non-locally and randomly into a tiny portion of the screen.⁵

Students should understand that, strictly speaking, neither photons nor electrons are particles, but are in fact always chunks (or bundles) of field, spread out over a region of space Δx that obeys the uncertainty principle. Electrons, for example, are “point particles” only in the sense that Δx can be made arbitrarily small, but always at the cost of a larger and larger Δp (and thus larger energy). These field quanta are

radically different from the tiny, indestructible, unchangeable particles of which Newton, along with most people today, imagined the world to be made. Portraying this more accurate picture of the world’s microscopic architecture is one of the more important tasks of physics education. Like quantized EM fields, quantized matter fields again embody the fundamental quantum properties: non-locality, field collapse, and randomness (uncertainty).

Quantum electrodynamics

The preceding section presented non-relativistic quantum physics in its proper context as an aspect of QFT. Presenting quantum physics in this manner changes none of the standard quantum mathematical formalism, but it does change the physical meaning of several items that appear in this formalism. For instance, the Schrodinger equation is the field equation for the matter field for non-relativistic material particles. And the wave function ψ is a real physical field, not simply a mathematical probability amplitude for finding a particle.

What effects does relativity have on this setup?

Quantum electrodynamics (QED) is historically the first of the relativistic QFTs; it’s arguably the most quantitatively accurate scientific theory of all time. It’s concerned with two fields, the EM field and the electron matter field, and their interactions. Classically, the path of a moving electron is determined by the forces exerted on it by the EM fields through which it passes. We’ve seen that, according to QFT, the EM field consists of field quanta called photons. So it’s perhaps not surprising to learn that the basic principle of QED is that all EM forces on an electron arise from the creation or destruction of photons. In this theory, “electric charge” means “the ability to create and destroy photons,” and photons become force-carrying particles for the electric force. More precisely, photons carry energy and momentum, and thus photon creation or destruction by an electron must (because of conservation of energy and momentum) cause sudden changes in the electron’s path. In the case of two electrons moving under the influence of their mutual EM force, the creation and destruction of photons by both electrons results in path changes that, on the average, amount to a repulsive force. The process is often described as an “exchange” of photons between the two electrons, and the created and destroyed photons are called “exchange particles.” Thus, QED replaces classical continuous and predictable EM forces by an instantaneous, quantized, and unpredictable transfer of momentum and energy, at random times. In the limit of low energies and weak fields, this unpredictable path becomes the predictable, smooth path of classical theory.

QED is surprisingly simple in principle. There are no forces; there is only creation and destruction of photons.

And something more surprising emerges. Special relativity implies that a new type of material particle must exist in nature. The argument for this is based on symmetry and is typical of modern physics. In order to obey special relativity, QFT must be symmetric under time reversal. That is, QFT must

also be valid in a universe just like ours but with time flowing the other way. Richard Feynman showed that an electron that is imagined to move backward in time would have precisely the same observable effects as would another particle just like the electron, only carrying a positive charge and moving *forward* in time. In order for the laws of physics to be symmetric under time reversal, this positive electron, or “positron,” must exist. As was the case for two electrons, QED explains the repulsive force between two positrons, as well as the attractive force between a positron and an electron, as arising from the creation and destruction of photons.

This makes QFT qualitatively different from all previous physics theories. Earlier theories, including relativistic or quantum theories, described only how things change in time. QFT describes not only how things move but also what kinds of things can exist.

The requirement that QFT be symmetric under time reversal implies that for every existing type of particle there must be an antiparticle analogous to the positron. There must be an antiproton, an antineutron, and so forth.

When an EM field and an electron field interact, one thing that can happen is that the EM field can give up energy (photons) to the electron field. At low energies, this simply increases the energy of any electrons that might be present. But if the EM field gives up sufficiently high-energy photons to the electron field, something new can happen: Additional material quanta (electrons or positrons) can be created. However, experiments show that total electric charge is conserved in microscopic interactions, so it’s always electron-positron pairs that are created. QED gives the probabilities for this to occur.

Conversely, the electron field can give up energy to the EM field, as it does when an electron creates a photon. Another way this can occur is for an electron and positron to vanish and be replaced by one or more photons. Thus both pair creation and pair annihilation are possible, with probabilities predicted by QED. An extremely high-energy photon can appear as an electron-positron pair, two pairs, etc., or simply as a photon. It oscillates randomly between these different manifestations of energy—a far cry from Newton’s “solid, massy, hard, impenetrable, movable particles” that “God, in the beginning, formed” and that are “even so very hard as to never wear or break in pieces.”⁸

Antiparticles imply the possibility of antimatter, just like normal matter but made of antiprotons, etc. Indeed, scientists today study thousands of antihydrogen atoms at a time, measuring their spectrum and other properties.

QFT paints an odd new view of “empty” space. For example, the possible energies of a monochromatic EM field are $hf/2, 3 hf/2, 5 hf/2, \dots$. When the field has its lowest energy $hf/2$, it has only half the energy of a single photon, so no field quanta are present; it cannot interact with a charged object by giving up a photon, and it cannot for example cause a flash of light on a viewing screen. So this is the “vacuum state” of the field. No actual field quanta (photons) are present, but the field nevertheless exists, has energy, and can cause observable

effects such as the Lamb shift of the hydrogen atom. This is also true of other quantum fields. The universe won’t permit a true vacuum, absent of all fields. Thus every region of space must contain at least these “zero-point fields,” and there is really no such thing as “nothingness.”

Furthermore, quantum uncertainties require that the energies of all these fields fluctuate, over short time-spans, around their long-time average value. The shorter the time interval, the larger these fluctuations can be. So there’s a possibility that, at any point in empty space, a photon or a particle-antiparticle pair will spontaneously pop into and out of existence during short times. Empty space is seething with activity.

QED describes not only electrons and positrons but also the electron-like muons that are 207 times more massive, and the electron-like tau particles that are 3500 times more massive—nearly twice as massive as a proton—along with their antiparticles. Nobody knows why there must be these two additional “generations” of electron-like material particles nor why they have the masses they do have. QED does not predict them, nor does it predict electrons or photons. It only describes their behavior. As you’ll see in Part II (to be published), the three-generational pattern of material particles persists through the electroweak force theory and the strong force theory. There is astronomical evidence for exactly three generations: As predicted by nuclear physics and confirmed by observation of the oldest stars, during its first four minutes the big bang created about 75% hydrogen and 25% helium plus a trace of lithium, after which no further elements formed until the first stars appeared. The predicted helium fraction grows larger if the number of generations grows larger. Three generations leads to the observed helium fraction, while less than three leads to too little helium and more than three leads to too much helium.

The muon and tau are unstable—they decay spontaneously into lower-energy quanta. Thus they aren’t prevalent today, showing up only briefly in accelerator experiments and other high-energy events that create them. But the two additional generations were probably crucial during the big bang. Besides helping create the observed helium fraction, they might have played a crucial role in creating a slight excess of matter over antimatter. Without that excess, all the matter would have quickly annihilated with all the antimatter and neither you nor I would be here to think about such things.

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References

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3. Howard Stein, in *Historical and Philosophical Perspectives of Science*, edited by Roger H. Stuewer (Gordon and Breach, New York, 1989), p. 299.
4. Albert Einstein and Leopold Infeld, *The Evolution of Physics* (Simon and Schuster, New York, 1938), p. 151: “The electromagnetic field is, in Maxwell’s theory, something real. The electric field is produced by a changing magnetic field, quite independently, whether or not there is a wire to test its existence; a magnetic field is produced by a changing electric field, whether or not there is a magnetic pole to test its existence.” It’s worth noting that this important book is entirely conceptual; there are no equations.
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