A Children's Picture-book Introduction to Quantum Field Theory

August 20, 2015 By Brian Skinner

First of all, don't panic.

I'm going to try in this post to introduce you to quantum field theory, which is probably the deepest and most intimidating set of ideas in graduate-level theoretical physics. But I'll try to make this introduction in the gentlest and most palatable way I can think of: with simple-minded pictures and essentially no math.

To set the stage for this first lesson in quantum field theory, let's imagine, for a moment, that you are a five-year-old child. You, the child, are talking to an adult, who is giving you one of your first lessons in science. Science, says the adult, is mostly a process of figuring out what things are made of. Everything in the world is made from smaller pieces, and it can be exciting to find out what those pieces are and how they work. A car, for example, is made from metal pieces that fit together in specially-designed ways. A mountain is made from layers of rocks that were pushed up from inside the earth. The earth itself is made from layers of rock and liquid metal surrounded by water and air.

This is an intoxicating idea: everything is made from something.

So you, the five-year-old, start asking audacious and annoying questions. For example:

What are people made of?
People are made of muscles, bones, and organs.
Then what are the organs made of?
Organs are made of cells.
What are cells made of?
Cells are made of organelles.
What are organelles made of?
Organelles are made of proteins.
What are proteins made of?
Proteins are made of amino acids.
What are amino acids made of?
Amino acids are made of atoms.
What are atoms made of?
Atoms are made of protons, neutron, and electrons.
What are electrons made of?
Electrons are made from the electron field.
What is the electron field made of?

…And, sadly, here the game must come to an end, eight levels down. This is the hard limit of our scientific understanding. To the best of our present ability to perceive and to reason, the universe is made from fields and nothing else, and these fields are not made from any smaller components.

But it's not quite right to say that fields are the *most fundamental* thing that we know of in nature. Because we know something that is in some sense even more basic: we know the rules that these fields have to obey. Our understanding of how to codify these rules came from a series of truly great triumphs in modern physics. And the greatest of these triumphs, as I see it, was quantum mechanics.

In this post I want to try and paint a picture of what it means to have a field that respects the laws of quantum mechanics. In a previous post, I introduced the idea of fields (and, in particular, the all-important electric field) by making an analogy with ripples on a pond or water spraying out from a hose. These images go surprisingly far in allowing one to understand how fields work, but they are ultimately limited in their correctness because the implied rules that govern them are completely classical. In order to *really* understand how nature works at its most basic level, one has to think about a field with quantum rules.

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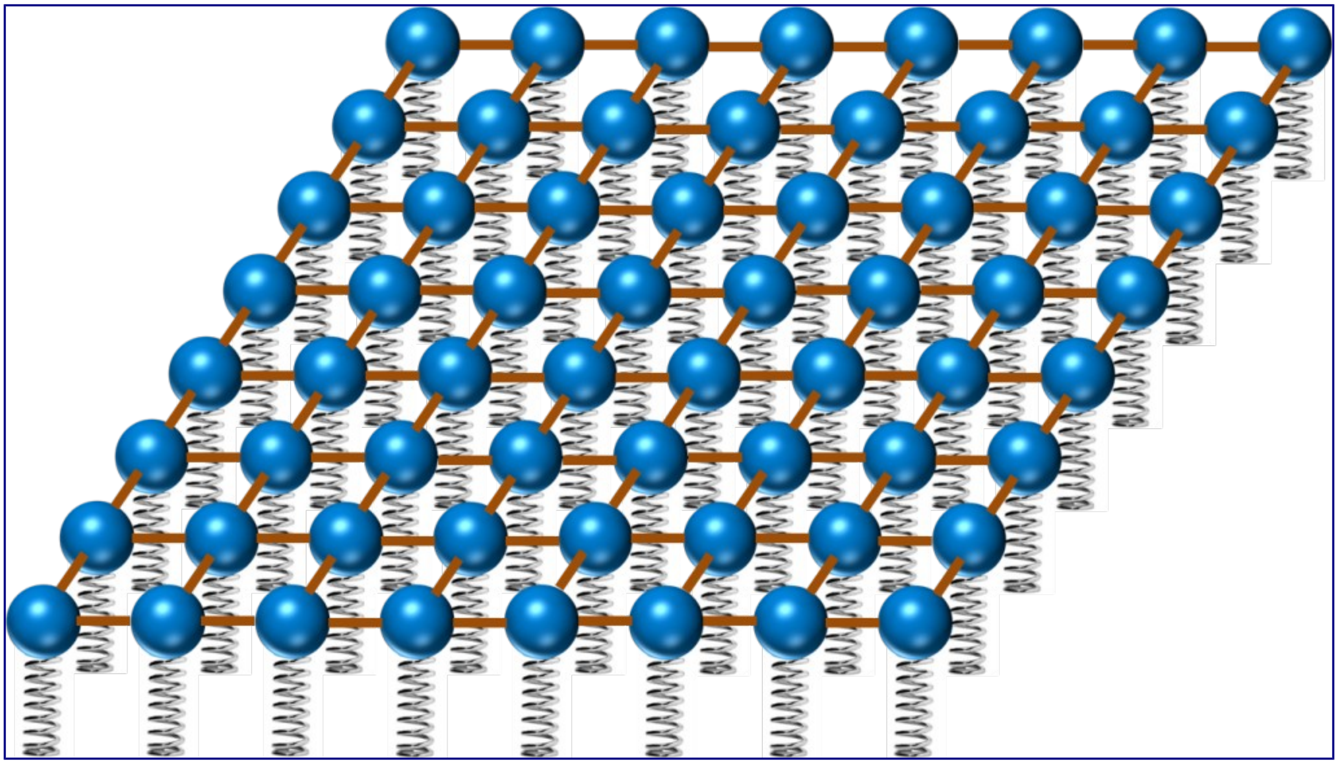
The first step in creating a picture of a field is deciding how to imagine what the field is made of. Keep in mind, of course, that the following picture is mostly just an artistic device. The real fundamental fields of nature aren't really made of physical things (as far as we can tell); physical things are made of *them*. But, as is common in science, the analogy is surprisingly instructive.

So let's imagine, to start with, a ball at the end of a spring. Like so:

This is the object from which our quantum field will be constructed. Specifically, the field will be composed of an infinite, space-filling array of these ball-and-springs.

To keep things simple, let's suppose that, for some reason, all the springs are constrained to bob only up and down, without twisting or bending side-to-side. In this case the array of springs can be called, using the jargon of physics, a *scalar field*. The word "scalar" just means a single number, as opposed to a set or an array of multiple numbers. So a *scalar field* is a field whose value at a particular point in space and time is characterized only by a single number. In this case, that number is the height of the ball at the point in question. (You may notice that what I described in the previous post was a *vector field*, since the field at any given point was characterized by a velocity, which has both a magnitude and a direction.)

In the picture above, the array of balls-and-springs is pretty uninteresting: each ball is either stationary or bobs up and down independently of all others. In order to make this array into a *bona fide* field, one needs to introduce some kind of coupling between the balls. So, let's imagine adding little elastic bands between them:



Now we have something that we can legitimately call a field. (My quantum field theory book calls it a "mattress".) If you disturb this field – say, by tapping on it at a particular location – then it will set off a wave of ball-and-spring oscillations that propagates across the field. These waves are, in fact, the *particles* of field theory. In other words, when we say that there is a particle in the field, we mean that there is a wave of oscillations propagating across it.

These particles (the oscillations of the field) have a number of properties that are probably familiar from the days when you just thought of particles as little points whizzing through empty space. For example, they have a well-defined propagation velocity, which is related to the weight of each of the balls and the tightness of the springs and elastic bands. This characteristic velocity is our analog of the "speed of light". (More generally, the properties of the springs and masses define the relationship between the particle's kinetic energy and its propagation velocity, like the \(KE = \frac{1}{2}mv^2 \) of your high school physics class.) The properties of the springs also define the way in which particles interact with each other. If two particle-waves run into each other, they can scatter off each other in the same way that normal particles do.

(A technical note: the degree to which the particles in our field scatter upon colliding depends on how "ideal" the springs are. If the springs are perfectly described by Hooke's law, which says that the restoring force acting on a given ball is linearly proportional to the spring's displacement from equilibrium, then there will be no interaction whatsoever. For a field made of such perfectly Hookean springs, two particle-waves that run into each other will just go right through each other. But if there is any deviation from Hooke's law, such that the springs get stiffer as they are stretched or compressed, then the particles will scatter off each other when they encounter one another.)

Finally, the particles of our field clearly exhibit "wave-particle duality" in a way that is easy to see without any philosophical hand-wringing. That is, our particles by definition *are* waves, and they can do things like interfere destructively with each other or diffract through a double slit.

All of this is very encouraging, but at this point our fictitious field lacks one very important feature of the real universe: the discreteness of matter. In the real world, all matter comes in discrete units: single electrons, single photons, single quarks, etc. But you may notice that for the spring field drawn above, one can make an excitation with completely arbitrary magnitude, by tapping on the field as gently or as violently as one wants. As a consequence, our (classical) field has no concept of a minimal piece of matter, or a smallest particle, and as such it cannot be a very good analogy to the actual fields of nature.

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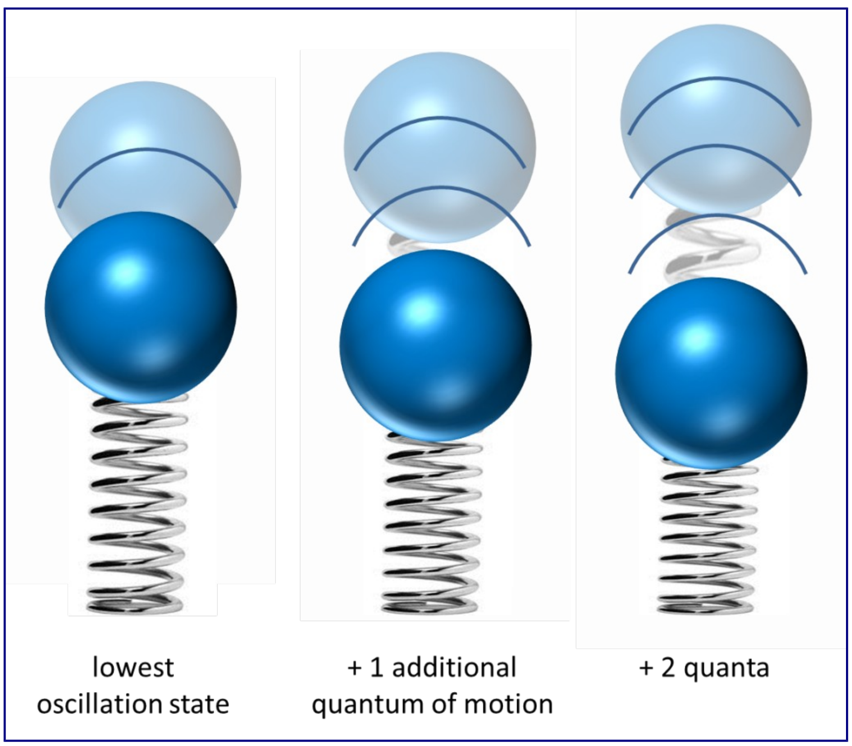
To fix this problem, we need to consider that the individual constituents of the field – the balls mounted on springs – are themselves subject to the laws of quantum mechanics.

A full accounting of the laws of quantum mechanics can take some time, but for the present pictorial discussion, all you really need to know is that a quantum ball on a spring has two rules that it must follow. 1) It can never stop moving, but instead must be in a constant state of bobbing up and down. 2) The amplitude of the bobbing motion can only take certain discrete values.

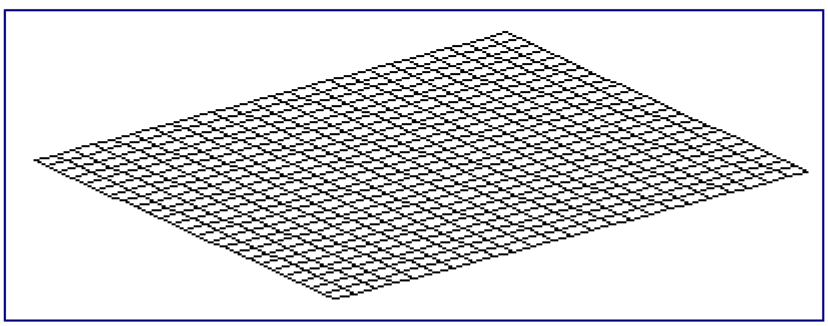


This quantization of the ball's oscillation has two important consequences. The first consequence is that, if you want to put energy into the field, you must put in at least one quantum. That is, you must give the field enough energy to kick at least one ball-and-spring into a higher oscillation state. Arbitrarily light disturbances of the field are no longer allowed. Unlike in the classical case, an extremely light tap on the field will produce literally zero propagating waves. The field will simply not accept energies below a certain threshold. Once you tap the field hard enough, however, a particle is created, and this particle can propagate stably through the field.

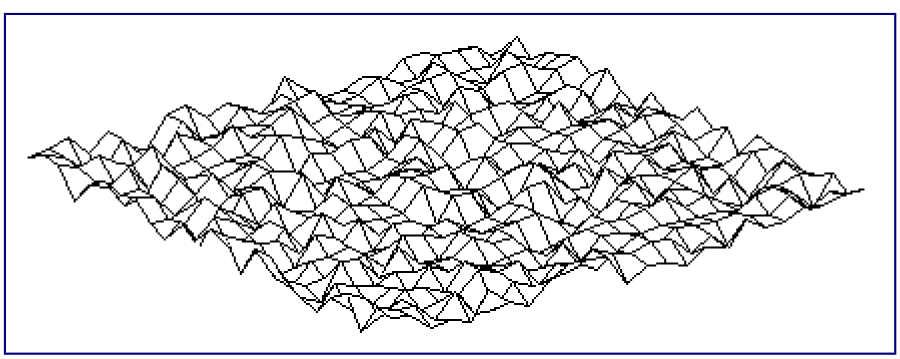
This discrete unit of energy that the field can accept is what we call the *rest mass energy* of particles in a field. It is the fundamental amount of energy that must be added to the field in order to create a particle. This is, in fact, how to think about Einstein's famous equation $E = mc^2$ in a field theory context. When we say that a fundamental particle is heavy (large mass m), it means that a lot of energy has to be put into the field in order to create it. A light particle, on the other hand, requires only a little bit of energy.

(By the way, this why physicists build huge particle accelerators whenever they want to study exotic heavy particles. If you want to create something heavy like the Higgs boson, you have to hit the *Higgs field* with a sufficiently large (and sufficiently concentrated) burst of energy to give the field the necessary one quantum of energy.)

The other big implication of imposing quantum rules on the ball-and-spring motion is that it changes pretty dramatically the meaning of empty space. Normally, empty space, or *vacuum*, is defined as the state where no particles are around. For a classical field, that would be the state where all the ball-and-springs are stationary and the field is flat. Something like this:



But in a quantum field, the ball-and-springs can *never* be stationary: they are always moving, even when no one has added enough energy to the field to create a particle. This means that what we call *vacuum* is really a noisy and densely energetic surface:



This random motion (called *vacuum fluctuations*) has a number of fascinating and eminently noticeable influences on the particles that propagate through the vacuum. To name a few, it gives rise to the Casimir effect (an attraction between parallel surfaces, caused by vacuum fluctuations pushing them together) and the Lamb shift (a shift in the energy of atomic orbits, caused by the electron getting buffeted by the vacuum).

In the jargon of field theory, physicists often say that “virtual particles” can briefly and spontaneously appear from the vacuum and then disappear again, even when no one has put enough energy into the field to create a real particle. But what they really mean is that the vacuum itself has random and indelible fluctuations, and sometimes their influence can be felt by the way they kick around real particles.

That, in essence, is a quantum field: the stuff out of which everything is made. It’s a boiling sea of random fluctuations, on top of which you can create quantized propagating waves that we call particles.

I only wish, as a primarily visual thinker, that the usual introduction to quantum field theory didn’t look quite so much like this. Because behind the equations of QFT there really is a tremendous amount of imagination, and a great deal of wonder.