The Standard Model

Transcript

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The world is a complicated place. The sheer variety of colors, textures, and shapes that we experience daily is staggering. But physics aims to explain all of the complexity and diversity in the universe with a single, elegant theory. What are the basic building blocks of matter that make up everything that we see? And how do they combine and interact to give rise to the amazing world that we live in? Answers to these questions and others can be found in our current theory of fundamental particles and their interactions: the Standard Model.

The Standard Model was created just within the last century, but people have been pondering this matter for quite a long time. Some of the earliest substantial efforts were made by natural philosophers in antiquity, who believed that everything is composed of four elements: earth, air, fire, and water. Although this theory turned out to be wrong, it was a valiant attempt to reduce the incomprehensible complexity of life into a simple framework.

The next major advancement wasn't made until the 1800s, with the development of atomic theory, the idea that everything is composed of tiny, indivisible particles called atoms. In 1869, Dimitri Mendeleev created the first periodic table of the elements in which he organized the sixty or so atoms known at the time, sorting them into a table based on their chemical and physical properties. When Mendeleev noticed that his table had some holes in it, he predicted that these holes should be filled by yet undiscovered elements, and within short order, these missing pieces to the puzzle were identified, exactly as Mendeleev had predicted. As new elements continued to be discovered, the periodic table grew larger and larger and it now contains over 200 elements.

The next revolution occurred when physicists discovered that atoms are not fundamental, meaning that they can be broken down into even smaller, sub-atomic pieces. They realized that different atoms are really different combinations of just three particles: protons, neutrons, and electrons. With this brilliant insight, the entire periodic table of the elements could be explained with just three simple components — three bulging blocks with which the entire universe could be constructed.

But a wrench was thrown into the works in 1936, when a new particle was discovered. It was exactly like an electron, except it was about 200 times more massive. This strange particle, now called a muon, was such a surprise that physicist I. I. Rabi commented wryly, “Who ordered that?”

And the muon was only the beginning. You see, physicists were smashing particles into each other in particle accelerators trying to probe their inner structure. And before long, these experiments revealed even more exotic particles. By 1960, over 100 distinct particles were known and they just kept rolling in; this period became known as the particle explosion. Things were so simple when everything could be explained by just protons, neutrons, and electrons, but now it was all a mess again.

So physicists set to work trying to find patterns in the data. Just as Mendeleev organized the atomic elements into a table, particle physicists organized the subatomic particles into groups and classes. And just as the entire table of elements could be explained by just protons, neutrons, and electrons, particle physicists realized that the entire zoo of exotic particles could be explained by a simple theory that we now call the Standard Model. Let’s take a look at the Standard Model and then see how it can be used to explain the entire zoo of particles.

In the Standard Model, all fundamental particles can be split into two categories: fermions and bosons. Fermions are the matter particles; they make up the “stuff” in the universe. Bosons are force particles; they are responsible for the interactions between the fermions. We’ll begin by getting to know the fermions, and then we’ll see how the bosons allow them to interact.

Fermions are themselves divided into two categories: quarks and leptons. There are six types of quark, which are called up, down, charm, strange, top, and bottom. There are also six types of lepton: the electron, electron neutrino, muon, muon neutrino, tau, and tau neutrino. Already we can see some of the elegance of the Standard Model. There are the same number of quarks as there are leptons. Particles in the same row of the table have very similar properties. The columns are called generations I, II, and III. Particles in the first generation are the lightest; particles in the second generation are more massive than their first generation analogues, and particles in the third generation are even more massive.

As far as we know, these twelve fermions are the only fundamental matter particles. Everything is made out of just these components. But the Standard Model wouldn’t be complete with just a catalogue of spare parts. We also have to understand the interactions between the fermions, and that’s where the bosons come in.

The bosons act as “exchange particles.” They can be exchanged between the other particles in fundamental interactions. We observe the effects of these interactions as forces between the fermions. Bosons are sometimes called “force carriers” because they carry the fundamental forces between the fermions.

The most familiar boson is the photon. The photon is the carrier of the electromagnetic force. Particles with electric charge can interact with photons and thus they feel the electromagnetic force. Like charges repel and opposites attract. However, if a particle has no electric charge, then it won’t interact with photons and thus won’t experience the electromagnetic force. All of the quarks are electrically charged. The up, charm, and top quarks all have +2/3 electric charge and the down, strange, and bottom quarks all have -1/3 electric charge. The electron, muon, and tau all have electric charge of -1. But the neutrinos are electrically neutral, so they don’t interact with photons.

The next boson is called the gluon. The gluon is the carrier of a force called the strong force, which acts within atomic nuclei. As its name implies, the gluon acts to bind particles together rather like glue. In fact, one major difference between the electromagnetic and strong forces is that, while the electromagnetic force becomes weaker the farther apart two particles are, the strong force actually becomes stronger with increasing distance, rather like a rubber band becoming harder and harder to stretch the more that you pull it. This property of the strong force is very important for building composite particles, as we will soon see.

Unlike the electromagnetic force, which only has positive and negative charges, the strong force actually has three different charges called red, green, and blue. Because of this nomenclature, the strong charges are sometimes called color charges. But it’s important to remember that a particle with blue charge isn’t actually the color blue — that’s just the arbitrary label that physicists have given to a charge of the strong force. It turns out that all of the quarks can take any strong charge, but none of the leptons have strong charges, and for this reason, gluons only interact with quarks.

Next are the $W^{\pm}$ and Z^0 bosons. These are collectively referred to as the weak bosons because they are the carriers of the weak force, which manifests itself in certain types of radioactive decay. The weak bosons mediate the transformation of one type of particle into another. For example, by interacting with a weak boson, a muon can turn into an electron, or a strange quark can turn into a down quark. In fact all of the fermions can undergo weak interactions, but the rule is that quarks can turn into other quarks and leptons can turn into other leptons, but a quark can’t turn into a lepton and vice versa.

There's one final boson that's quite different from the others, called the Higgs boson. The Higgs boson is responsible for determining the masses of the other particles. In other words, if a particle interacts with the Higgs boson, then we observe it as having mass. The Higgs Boson was predicted mathematically in the early 1960s and was finally discovered experimentally in 2012, putting the final touches on the Standard Model.

These are the building blocks out of which everything is made. They are the fundamental components of the universe. It's hard to believe that all of the complexity of life can emerge from such a simple collection of pieces. How can these particles combine to form larger structures?

Well, we can learn a lot about the properties of the particles by recalling which bosons they interact with.

Remember that the neutrinos don't interact with photons or gluons. They do interact with the weak bosons, but as you might expect, this effect is very weak. In fact, every second, billions of neutrinos produced by the sun are flying through your body. Almost all of them will continue through the entire earth without interacting with a single particle along the way. Because they hardly ever interact with other particles, let alone forming stable bonds, neutrinos aren't very good building materials.

Quarks, on the other hand, are perfect for creating composite particles. Because they interact with gluons, quarks are held together by an intensely binding force. In fact, quarks can never be found by themselves; they always come in groups of two or three. Most of the particle zoo that physicists identified during the particle explosion can be explained by different possible combinations of quarks.

But not all quarks are very good for building with. The quarks in generations II and III are unstable and only exist for tiny fractions of a second before they decay into their less massive analogues in generation I. And that leaves us with just the up quark and the down quark. For example, two up quarks and one down quark can combine to form a very stable configuration, acting as a single composite particle called a proton. Since the up quarks each have +2/3 electric charge and the down quark has -1/3 electric charge, the total electric charge of a proton is +1. We can also create a particle out of two down quarks and one up quark. In this case, the charges add to zero. Since this composite particle is electrically neutral, it's called a neutron. Of course, there are other ways that we could combine up and down quarks, but it turns out that the proton and neutron are the only stable ones.

Now that we have created protons and neutrons, we can combine them to build an even larger structure called a nucleus. A nucleus is a cluster of protons and neutrons. For example, a helium-4 nucleus is made of two protons and two neutrons. Now hold on for just a minute. Protons have positive electric charge. Shouldn't the positive electric charges of the protons repel each other, causing them to fly apart? How does the nucleus stay together despite the electromagnetic repulsion between the protons? The answer, it turns out, is that although the protons do repel each other electromagnetically, the strong interaction between their constituent quarks is able to overpower the electromagnetic repulsion at small distances, which is what holds the nucleus together. Because of this opposition between the electromagnetic repulsion and the strong attraction, if a nucleus has the wrong balance of protons and neutrons, it will be unstable and it will decay radioactively. Very roughly speaking, a nucleus is stable if it has about the same number of protons and neutrons.

Since electrons have negative electric charge, they are attracted to the positive electric charges of the protons in a nucleus. When electrons orbit around the nucleus to balance out the positive electric charges of the protons, the resulting structure has zero total electric charge, and we call it an atom. The different types of atoms are catalogued in the Periodic Table of the elements that Dimitri Mendeleev pioneered.

And we can keep going up! When atoms bind together, they form structures called molecules. The study of chemistry is dedicated to understanding the properties and interactions of different types of molecules. There are countless varieties of molecules and they can combine to form even more complex systems. In this way, all of the complexity and diversity of life can be explained by one simple theory of particles. From a handful of fermions and bosons emerges the amazing world that we call home.

In addition to being a triumph of reductionism, the Standard Model is also a beautiful theory in its own right because the underlying mathematics involves many elegant symmetries that draw out the fundamental principles of our universe.

But although the Standard Model is a tremendous accomplishment, it still has some holes in it. For example, the Standard Model doesn't explain gravity. Some physicists suggest that the Standard Model should include another boson, called the graviton, which would act as the carrier of the gravitational force, but so far we still haven't identified the graviton experimentally. The Standard Model also doesn't explain the newly discovered phenomena of dark matter and dark energy that make up the majority of the universe.

And in addition to being incomplete, the Standard Model is also still relatively complicated. With so many particles, each with different properties, we can't help but wonder if maybe someday the Standard Model will be replaced by an even more elegant theory. Some physicists have proposed the existence of supersymmetric particles — extremely massive twins of all of the particles in the Standard Model — in an attempt to endow the Standard Model with another dimension of symmetry, but so far none of these supersymmetric particles have been identified.

Nevertheless, we should still be very happy with how far we have already come. Physicists throughout the centuries have peeled back layer after layer of our perceptions to identify the fundamental laws governing reality. Again and again they have been flummoxed by seas of incongruous data and carefully sifted out the underlying principles. To find patterns in the chaos, to see hidden elegance in our experiences, is the essence of the field of physics.