Symmetry in Particle Physics

From Circles to the Standard Model

The Standard Model of particle physics is one of humanity's greatest achievements. It describes three of the four fundamental forces and, as a result, it is our most complete understanding of nature. It gives us a framework within which all fundamental interactions can be understood. Formulated in the 1960s and 1970s, it has proven itself time and again, with one exception: the Higgs boson, a crucial component of the theory, was nowhere to be found.

Then, in July 2012, the European particle physics lab CERN announced the discovery of the Higgs boson almost 50 years after its prediction, adding the final missing piece of the universal puzzle. But what is the Higgs boson? To understand that, and the importance of its discovery, we need to understand the Standard Model itself.

Fields and Forces

To begin, there are four fundamental forces: the electromagnetic force, the strong force, the weak force and gravity. The Standard Model describes the first three of these forces. The electromagnetic force is responsible for the familiar effects of electricity and magnetism, the strong force is responsible for the composition of subatomic particles (which are made of quarks), such as the proton and neutron inside the nucleus of atoms, and the weak force affects radioactive decay.

The Standard Model uses quantum field theory, a mathematical framework developed in the 20$^{\text{th}}$ century, to describe these forces in terms of fields. This idea is familiar to anyone who has played with iron filings and a magnet, where the filings fall into the shape of the field lines. In physics, a field is something that takes a value at every point in space and time. For example, consider the height of the surface of the sea. This takes a value (measured in metres, for instance) at every point on the sea, at any time. This is slightly different to the magnetic field, whose value doesn't just include the strength of the field (analogous to the height of the sea) but also what direction it is pointing in. Physicists call the former a scalar field and the latter a vector field, because vectors are mathematical objects with magnitude and direction while scalars have only magnitude (like numbers). The strong, weak and electromagnetic forces of the Standard Model are all vector fields.

But how do the iron filings know how strong the field is where they are, or which direction to point in? The field must transmit this information to them somehow, i.e. it must be mediated by something. This is analogous to waves in the sea changing a buoy's height. The ripples in the sea are, in quantum field theory, considered as excitations of the field. These excitations which mediate the force are called bosons — quantum particles which move around and interact with other particles, informing them of the field strength. This identification of waves with particles is one of the profound results of quantum mechanics, called wave-particle duality. For electromagnetism, the boson is called the photon — the particle of light.

The reverse must also be true: since excitations of fields can be thought of as particles, particles themselves must also be thought of as excitations of fields. Thus we have e.g. the electron field permeating all of space, whose excitations are the particles we call electrons.

One striking feature of these fields is that fundamentally they cannot be measured. Instead, their various properties, such as charge, energy, etc., can be. For example, the fundamental field associated with electromagnetism is called the vector potential A. The value of this field is not a measurable quantity; instead we measure the values of the electric and magnetic fields and infer from these measurements the value of A.

Symmetry

Physicists have a formal notion of what a symmetry is. A square is symmetric because you can rotate it by 90 degrees and it will return to the same shape. Mathematically, we would describe this symmetry by listing all the operations we can do to it such that it remains the same. The list we end up with contains four rotations (by 90, 180, 270 and 360 degrees), and four reflections (about the horizontal and vertical axes and about the diagonal lines from top-left to bottom-right and bottom-left to top-right). This list of operations is called a symmetry group. Mathematicians would say that this group is the symmetries of the square, named the dihedral group D_4.

But what of a circle? Rotating this shape by any angle at all is a symmetry, as is reflecting it about any axis. So, the list of all the elements of this symmetry group is infinite. Mathematicians call this group U(1).

One of the hallmarks of modern physics is the use of symmetry. A central idea is that an experiment performed in some location should have the same result as an identical experiment performed elsewhere. That is, the result should be invariant under translation across space. The same is true across time. Thus, we say that theories should be translation-invariant. The same holds for rotations and, crucially, boosts in any direction. This means that an experiment in a car moving at a constant velocity (no acceleration) will yield the same results as a stationary one. This is called a Galilean transformation and the collection of all of these operations together is called the Galilean group. Since physics is unchanged under the operations of the Galilean group, we say that this group is a symmetry.

However, Galileo didn't know about special relativity. This group of symmetries is actually only approximate, and doesn't hold for high velocities and energies. The actual symmetry group is a generalisation of this one, called the Poincaré group. At low energies, where the speeds involved are much less than the speed of light, it reduces to the more familiar Galilean symmetries.

Because of this, we say that the Poincaré group is a symmetry of physics. If we come up with a theory of nature, it has to be invariant under the operations of this group. Since these symmetries deal with space and time, we call them spacetime symmetries. But there are other symmetries — internal symmetries — disconnected from these external spacetime symmetries.

Let's return again to electromagnetism and the vector potential. Since this potential is responsible for the values of the electric and magnetic field, it can be inferred from these values. However, it turns out that there are many possible potentials that would give rise to the same electric and magnetic fields. In fact, from a given potential there are a set of operations we can do to it to give us new potentials which generate identical electric and magnetic fields. This is a symmetry of electromagnetism, distinct from the spacetime symmetries of the Poincaré group. Any field theory with this symmetry will be identical to electromagnetism, which means the symmetry in some sense defines electromagnetism. As it happens, this symmetry is exactly the same as the circle! This means we can say that electromagnetism is invariant under U(1) symmetry.

Gauge Theory

The most remarkable feature of this symmetry is that it in some sense depends on the location in space and time. In order to take this dependency into account, but still write down a theory that is U(1)-invariant, we must allow the vector potential to interact with matter, such as electrons. This is called gauge theory. It is responsible for electric charge, which determines the strength of the force on a charged particle in an electromagnetic field. Bosons which mediate the force of these gauge fields are called gauge bosons.

All fundamental forces have gauge symmetry (including gravity). It is believed to be a universal symmetry of nature, just like the symmetries of the Poincaré group.

The gauge bosons of the strong force are called gluons, which bind the quarks together to form protons and neutrons. The symmetry involved is called SU(3), a more complicated group than U(1). One feature of U(1) is that the operations in the group commute. This is intuitively obvious, since if you rotate a shape by some angle, then again by any other angle, the result would be the same as rotating in the opposite order. The strong force does not have this property, which makes the interactions between gluons and quarks (and between gluons and themselves) much more complex.

The weak force has three gauge bosons, W^+, W^- and Z^0. The $W^\pm$ bosons have electric charge and the Z^0 boson does not. This means that the weak force and electromagnetism must be related somehow. In fact, they are really manifestations of some larger force, the electroweak force. This has symmetry group SU(2) × U(1). The U(1) of electromagnetism is a subgroup of this.

This is why the Standard Model of particle physics is sometimes called

$$\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1).$$

The product of these symmetry groups completely describes the fundamental forces of nature.

Unfortunately, the nature they describe seems to be quite different to the world we live in. One problem concerns the mass of the $W^\pm$ and Z^0 bosons. According to the above theory, these particles should be massless (like the photon, or all gauge bosons). Instead they have mass. Another problem is the dissimilarity between the weak force and electromagnetism in practice, despite them being in actuality part of the same thing.

The phenomenon which solves these problems is called electroweak symmetry breaking. At low energies, the weak force and electromagnetism are actually separate. Only when the energy is high enough do these two forces unify. The mechanism which breaks this symmetry is the Higgs mechanism, which also produces the famous Higgs boson.

The Higgs Field

Compared to the strong, weak and electromagnetic forces, which all have vector bosons, the Higgs field is scalar. It is the only scalar field so far discovered in nature. It is also unique in its role in the Standard Model. As a scalar field, it has an associated boson — but not a gauge boson like the forces.

The Higgs field undergoes something called spontaneous symmetry breaking. This means that on the face of it, the field should be symmetric under some group, but in fact due to the values of the potential this symmetry is broken. In the process it spits out three massless bosons, called Goldstone bosons.

These bosons get "eaten" by the weak force — each one gets absorbed by the $W^\pm$ and Z^0 bosons, giving them mass. The fourth and final boson is the Higgs, a massive neutrally charged particle.

It had long been known that this was the simplest consistent way to give mass to the $W^\pm$ and Z^0 bosons, so even before the Higgs boson was discovered physicists would say "$\frac{3}{4}$ of the Higgs has been discovered".

Finally, this Higgs boson interacts with matter through a mechanism called Yukawa interaction, the last part of the Standard Model. This allows the Higgs field to give mass to matter particles such as electrons.

This compartmentalises the standard model into four parts: the strong force, which includes gluons and their interactions with quarks; the electroweak force, which governs the four electroweak gauge bosons and their coupling to charged particles; the Higgs sector; the Yukawa interaction, which couples the Higgs field to massive fundamental particles.

As the Higgs boson is so massive, enormous energies are required to produce and detect it. This is why it went undiscovered for so long. It was eventually detected using a particle accellerator 27 km long under the Swiss–France border. Its discovery is of immense importance: it validates the standard model, explains the origin of mass for the weak bosons and other fundamental particles, demonstrates that real scalar fields can exist in nature and paves the way for new physics which will hopefully explain cosmic inflation and the fate of the universe. Professor Rolf-Dieter Heuer, director of CERN, said in 2011:

> *All the matter particles are spin-$\frac{1}{2}$ fermions. All the force carriers are spin-1 bosons [vectors]. Higgs particles are spin-0 bosons [scalars]. The Higgs is neither matter nor force. The Higgs is just different. This would be the first fundamental scalar ever discovered. The Higgs field is thought to fill the entire universe. Could it give some handle on dark energy? Many modern theories predict other scalar particles like the Higgs. Why, after all, should the Higgs be the only one of its kind?*

Since its discovery, these and other important questions have been put to the forefront of theoretical physics and will guide research for decades to come.