Chapter 2

Fundamental forces and particles

There are all sorts of interactions that take place in the universe every day. Atoms fuse together inside stars, electricity provides light to your home, particles turn into other particles, the moon circles Earth. All of the physical interactions in the universe can be explained by one or more of the four fundamental forces: the strong force, electromagnetic force, weak force, and gravity[1]. It is quite amazing that so many different events may occur, yet only four forces are needed to describe them. It is even possible that only one force exists, and the four forces we know of today are just different manifestations of that same force.

Our discussion of forces will involve many different kinds of particles. It is less important that you memorize all of those different particles, and more important that you appreciate the different interactions. Our goal is to gain an understanding of how the physical universe works. We'll try not to get too far into the weeds with details and pay more attention to the bigger picture. But if you do memorize one type of particle, let it be the photon. A *photon* is a particle of light. It will come up countless times in this book (and in the universe at large!). The chapters that follow will get more into the mind-bending concepts of relativity and quantum physics.

The four fundamental forces

What exactly is a force? We have an intuitive understanding of forces on large scales, i.e. within interactions which are observable to the naked eye. For instance, when we push a shopping cart, we have to exert a force on it to move it across the floor. In this large-scale sense, a force is simply a 'push or pull' that a body experiences as a result of an interaction with something else. A force causes a body to change its state of motion [1].

[1] Note that I said the *physical* interactions can be explained by these four forces. As for interactions like love, or the creation of ideas, well those might have more going on than we think. We can reduce them to chemical interactions in the brain, but I would guess that's an oversimplification. Only time and discovery will tell.

doi:10.1088/978-1-6817-4513-8ch2

When we speak of the *fundamental* forces, our definition is a bit different. A force is fundamental if it cannot be explained by any simpler interactions. The large-scale forces that we experience can be explained by the microscopic, fundamental forces. For instance, when two billiard balls collide, both balls feel a force that causes them to bounce off each other. This large-scale force is a result of what's happening microscopically: the repulsive electric force is acting between particles within the billiard balls.

The strong force, electromagnetic force, and weak force are mediated via force-carrying particles. That means, in order for one of these forces to act between two matter particles, other force-carrying particles must be involved. These force-carrying particles are usually called 'exchange' particles since they are exchanged between matter particles. The forces themselves are the result of the exchanging of particles.

You might think of these forces in the same way you think of the interaction you experience when you play a game of catch. When you throw a ball to your partner, he catches it and throws it back. The two of you are connected by this game. If one of you doesn't throw the ball back, there is no longer a game of catch. Similarly, matter particles play catch with exchange particles, and they are bound together by this exchange. If they stop exchanging particles, they no longer experience a connection. There is no longer a force between the two matter particles when the exchanging stops.

As you might remember from science class, matter is anything that has mass and takes up space. Some force-carrying particles don't have any mass at all, such as photons or gluons. So those particles aren't really matter; they are the particles that allow matter to experience forces. Matter particles include quarks and leptons. The most important difference between quarks and leptons is that quarks can experience the strong force, while leptons cannot.

The strong force

Scientists used to think that protons and neutrons were fundamental particles which could not be broken down any smaller. They later discovered that there are quarks and gluons inside. Quarks are the matter particles, and gluons are their exchange particles. Quarks playing catch with gluons results in the strong force, which is (not surprisingly) the strongest of the four fundamental forces. When quarks exchange gluons, the quarks become bound together. For instance, inside a proton, three quarks exchange gluons (figure 2.1). So a proton is not a fundamental particle at all. Rather, it is a particle made up of three quarks which 'play catch' with gluons!

The quarks inside protons also play catch with the quarks that are inside *other* protons and neutrons. That's how protons and neutrons attract one another: their quarks exchange gluons. The image below may help illustrate these interactions in the nucleus of an atom (figure 2.2).

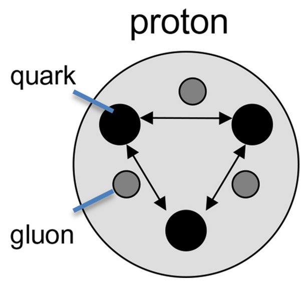

Figure 2.1. The proton contains three quarks (shown in black). They are bound together by exchanging gluons (shown in gray). This exchange results in the strong force. (This image is a simplification to show how quarks exchange gluons to form bonds. While all the quarks in the image appear to be of the same type and all the gluons also appear to be of one type, some are different from others in reality.)

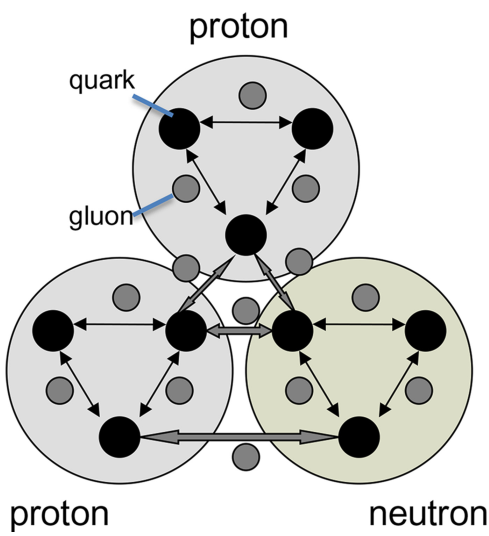

Figure 2.2. Protons and neutrons are bound together as their quarks exchange gluons. (This image is a simplification to show how quarks exchange gluons to form bonds. While all the quarks in the image appear to be of the same type and all the gluons also appear to be of one type, some are different from others in reality.)

Hang on, it looks like the protons can attract each other. This might seem strange to you if you remember the saying, ‘same charges repel, and opposite charges attract’. Two protons have the same positive charge, so shouldn’t they repel? Well, that saying applies to the *electric* force. Here, we are talking about a different type of interaction—the *strong* force. It is true that opposite charges attract and same charges repel by means of the electric force. But it is also true that quarks exchange gluons, causing protons to attract via the strong force. So both the electric and strong forces act at the same time. The strong force is a very short-range force, so it is only significant between two particles that are both inside the same nucleus. It is *very* strong, so it overpowers the repulsive electric force that the protons also experience.

Now, back to quarks and gluons. These particles are subject to ‘confinement’, which means they are confined within the larger particles that they make up. We can never observe a single one of them standing alone! There are six types, or ‘flavors’, of quarks, while gluons do not have flavor. The physicists who discovered the six flavors of quarks playfully named them strange, charmed, up, down, top, and bottom (bottom is sometimes called beauty instead).

Each quark or gluon can come in a variety of ‘color states’ (or ‘colors’ for short). There are rules for the possible combinations of quarks and gluons based on their colors. The ‘color’ of a quark or gluon is nothing like color as we think of it visually. Rather, the so-called colors are associated with a property called *color charge*. Color charge is kind of like a secret language that only quarks and gluons know how to speak. It is a unique property which allows quarks and gluons to be the only particles that can experience the strong force [2].

The electromagnetic force

The next strongest fundamental force is the electromagnetic force, a combination of electric and magnetic forces. It is about 100 times weaker than the strong force. This is the force that keeps the negatively-charged electrons orbiting the positively-charged nucleus of an atom. As we discussed, protons repel other protons via the electric force, but their quarks cause them to attract one another via the strong force. Since the strong force is so much stronger than the electric force at short distances, the protons are able to remain bound together within the nucleus.

We are also familiar with the magnetic force that causes magnetic materials to attract or repel one another. The magnetism of a material is actually caused by the motions of the charged particles in the material. Each electron, proton, and neutron is a small moving charge, and it generates a tiny magnetic field. Collectively, the magnetic fields of all the charged particles produce the magnetic field of the total material. A material’s total magnetic field then produces a magnetic force which can act on other magnets.

We have mentioned that electrons, protons, and neutrons are moving charges which produce magnetic fields. Evidently then, there is a connection between electric charge and magnetism. The connection between electricity and magnetism was discovered through experiments involving currents through wires in circuits. Experimentalists discovered that running an electric current through a wire produces a magnetic field which circles around that wire (figure 2.3).

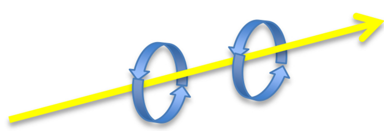

Figure 2.3. Electric current running through a wire (shown in yellow) produces a magnetic field around the wire (shown in blue). This is one of the effects that signifies an intimate relationship between electricity and magnetism.

They also discovered that a magnetic field can act on an electrically charged particle if the particle is in motion. This means that a moving electric charge (such as an electron) must have some kind of magnetic property. Additionally, a changing magnetic field produces an electric field, and a changing electric field generates a magnetic field. When all of these relationships were written in mathematical formalism, it became clear that the electric and magnetic forces were simply different aspects of the same force. We now call this force the electromagnetic force [3].

According to quantum mechanics, an electromagnetic force occurs due to the exchange of photons, the particles of light. The photons in these processes are considered 'virtual' photons. They are virtual because we cannot detect them in a laboratory. We know that they exist only from their effects. For instance, we observe that the proton and electron attract one another, and this attraction is due to the exchange of virtual photons. So the electromagnetic force is experienced by charged particles playing catch with photons. All particles which have an electric charge associated with them are subject to electromagnetic forces; they all can play catch with particles of light.

If you find it difficult to form a mental image of how these microscopic forces exist within the observable world around you, you're not alone. They are not visible to the naked eye, making them difficult to believe. Imagine looking at a marble under a very strong microscope. The marble appears to be one small solid ball to the naked eye. But under the microscope, you see that it is made up of many smaller balls (electrons) and those balls are orbiting around small lumps (the nuclei of atoms). Even more surprising to you are the distances between the electrons and the nuclei. They are so far apart that the majority of the marble is empty space! The moral of the story is, the quantum world hides many secrets since it operates on such small scales. When we zoom out to large scales, the quantum mechanical under-workings are invisible.

Antiparticles

Before we move on to the next fundamental force, there is something else worth mentioning. Our discussion of fundamental forces and particles would be incomplete without antiparticles. Antiparticles have the same mass but opposite electric charge to their corresponding regular particles. The interesting thing about antiparticles is that they can annihilate their corresponding particles. An electron's antiparticle is a positron; if an electron and positron collide, they annihilate and turn into a burst of photons.

Antiparticles play a role in one of the unsolved mysteries of the universe. Scientists have not figured out why we observe more matter than antimatter. If there were equal amounts of matter and antimatter created, then all particles would have annihilated in the early universe. Our universe would be full of radiation created by those annihilations, and nothing else. In other words, we wouldn't be here today if there were an equal amount of matter and antimatter. Something must have happened—some physical phenomenon, or some physical law must exist—to explain why there is more matter than antimatter. Scientists have their theories, but there is no conclusion on this one yet.

The Higgs boson

On the other hand, there *is* one mystery that physicists were able to solve recently, and it involved the discovery of the Higgs boson. Scientists wondered why certain particles, like the W and Z bosons, have mass. They expected those particles to be massless. The conclusion was that those particles could have mass if they were moving through some kind of 'condensate' that fits into their model. The so-called condensate would be something like a liquid, but invisible. This condensate was theorized to be made up of Higgs bosons. They would be everywhere in the universe. Other particles move through the condensate and do not lose energy, but they are affected in some way. Peter Higgs himself, the proponent of the theory, said moving through the Higgs condensate is not really like experiencing drag, but more like how light is bent when it moves through water. He admits the Higgs mechanism is difficult to describe. The important thing is that the Higgs boson was found, and the Standard Model of particle physics would be nonsense without it [4].

The weak force

The weak force, also called the weak interaction, is somewhat unique compared to the strong and electromagnetic forces. It is mediated by different exchange particles called W and Z bosons. This force differs from the others since the exchange particles involved are usually released from a single matter particle rather than transferred from one particle to another. The weak force causes a quark or a lepton to transform into another type of particle. A quark turns into another type of quark by releasing a W or Z boson, or a lepton turns into another lepton in the same manner.

One notable example of a weak interaction is known as beta decay. It is a process that turns a neutron into a proton. What happens is, a down quark inside a neutron emits a W boson. The emission causes the down quark to turn into an up quark. The result is that the neutron turns into a proton. Meanwhile, the W boson decays into an electron and an antineutrino (a type of lepton). The resulting electron is called a beta particle, so that's why this is called beta decay (figure 2.4). Why do we care?

Figure 2.4. Beta decay is a weak interaction where a neutron turns into a proton. This happens when one of the down quarks in the neutron turns into an up quark by emitting a W boson. The W boson decays into an electron and an antineutrino.

Well, the older an atom gets, the more times it will have undergone beta decay. Thus, by detecting beta particles, scientists are able to determine the age of substances or objects. This process is known as 'radiometric dating'. It has been used to determine the age of many fossils and artifacts [1].

Physicists have used particle accelerators to explore the weak force further. They discovered that, at high energies, there were similarities between the function of photons in electromagnetism and the W and Z bosons in the weak interaction. They were able to unify the electromagnetic force and the weak force into the electroweak force. At high energies, they also observed that the electroweak force becomes stronger and the strong force becomes weaker. The quarks of the strong force appear to move more freely than they did at lower energies. Their exchange particles (gluons) begin to operate like the photons, W, and Z bosons of the electroweak force. In theory, at the 'unification energy', the strong and electroweak forces also become unified.

We are not able to reach this energy in the laboratory because our particle accelerators are not large enough to accelerate particles to high enough speeds. However, the Standard Model mathematically predicts this unification, and it has not been proven wrong. Many scientists believe that, at the beginning of the universe, all of the four fundamental forces were unified into one. In fact, if we look far back in time, the Standard Model predicts the unification of three forces: the strong force, the electromagnetic force, and the weak force. But theorists have not yet found a way to incorporate the fourth force: gravity.

Gravity

Gravity is the weakest of the fundamental forces. For particles like protons and electrons, the gravitational force is practically negligible. The other forces overwhelm it. Gravitation has some interesting properties of its own, though. It operates at infinite distances (although this is also true of the electromagnetic force). That means you are experiencing the gravitational effects of bodies on the other side of the galaxy and beyond. And all particles experience gravitational effects of massive bodies. Table 2.1 summarizes the elementary particles and the different forces that they experience.

Right now, gravity is described by two different theories that don't match up. One is Einstein's general theory of relativity, which claims that gravity is not a 'real' force like the other three fundamental forces; rather, gravity is the result of the curvature of spacetime induced by the presence of mass. This will be discussed in detail in chapter 4. The other theoretical framework is quantum mechanics, which predicts that the force of gravity is transmitted by an exchange particle called the graviton. We have not yet discovered the graviton, but physicists like to think that it exists since the other three fundamental forces all operate due to exchange particles. The existence of the graviton is also predicted within the mathematics of quantum theory. However, when physicists try to combine the general theory of relativity with quantum mechanical theory, the equations break down. They produce non-physical answers, like infinity when a finite number is expected. One of the great tasks of modern physics is to find a theory which can describe gravity on both microscopic and large scales, unifying general relativity and quantum mechanics [5].

Table 2.1. A table summarizing elementary particles and fundamental forces that have been discovered.

Type of Particle	Name	Antiparticle	Relation to Forces	Unique Properties
Quark	Up	Antiup	Experiences strong, electromagnetic, weak, & gravity	Color charge, cannot be isolated
	Down	Antidown		
	Strange	Antistrange		
	Charmed	Anticharmed		
	Top	Antitop		
	Bottom	Antibottom		
Lepton	Electron	Positron	Experiences electromagnetic, weak, & gravity	Lepton number
	Muon	Antimuon		
	Tauon	Antitauon		
	Electron neutrino	Positron neutrino	Experiences weak, & gravity	Lepton number, no electric charge
	Muon neutrino	Antimuon neutrino		
	Tauon neutrino	Antitauon neutrino		
Guage boson (exchange particle)	Gluon	Gluon	Mediates strong	Massless, no electric charge
	Photon	Photon	Mediates electromagnetic	
	W^- boson	W^+ boson	Mediates weak	Can change quark flavor
	Z boson	Z boson	Mediates weak	No electric charge
Higgs boson	Higgs boson	Higgs boson	Accounts for mass	No electric charge, recently discovered

Einstein's general theory of relativity was nothing less than revolutionary. Before Einstein's lifetime, the Newtonian description of gravity was accepted as universal law. Newton's equations accurately describe gravitational effects on Earth, but when we look to very large scales, his equations make inaccurate predictions. General relativity makes the correct predictions, and better yet, it illuminates the unity of space and time: they operate as one fabric which can curve and warp when matter is present (figure 2.5).

A few years before Einstein wrote his general theory of relativity, he devised the special theory of relativity, which was equally astounding. We'll begin our discussion of Einstein's theories with the special theory of relativity in the following chapter. If you think that time passes at the same rate for all people and objects everywhere, or that space is uniform and unchanging, you're in for an enlightening surprise.

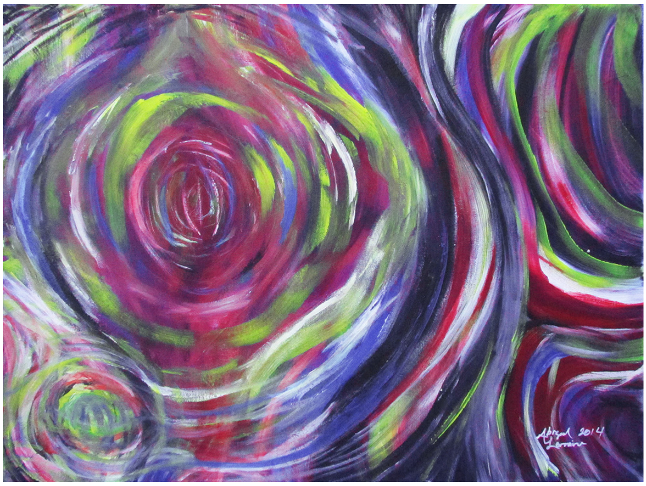

Figure 2.5. Since we can only see three spatial dimensions, spacetime curvature cannot be realistically envisioned. This is an artist's (the author's) depiction of spacetime curvature around spheres. It is a three-dimensional representation of a four-dimensional phenomenon (three spatial dimensions and one time dimension).

References

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