THE FUNDAMENTAL FOUR

SRINIVASAN KRISHNAN

Four fundamental forces in Nature decide all known interactions in the world. What are these four forces? How do they arise? Why four and not more? This article explores some of these questions, describing the properties of the fundamental four and looking at how they shape our daily life.

Forces are all around us. They come in various types and sorts. For example, objects that are thrown up invariably come down due to the force of gravity; there are pushes and pulls that we exert on each other; springs, that operate, say, in vehicle suspensions, which cushion the painful effects of bumps; magnetic forces that appear to act mysteriously to always align the needle of a compass towards the North; forces exerted by hurricanes; the amazingly powerful forces of disintegration unleashed by nuclear bombs and so on. The list is practically endless!

However, there is overwhelming evidence to show that all of these varied forces are, in fact, manifestations of just **four** fundamental forces (although there is enough theoretical evidence to reduce this number to just two, that is a story best left for later). Why just four? The straightforward answer is that this is what we have evidence for. These four fundamental forces in nature are (in order of the strongest to the weakest) called - strong force, electromagnetic force, weak force and gravitational force. We've known of the electric and magnetic forces (now regarded as two aspects of a single force called electromagnetic force), as well as gravitational force from antiquity. In contrast, the other two forces - the strong and weak forces - were only discovered in the previous century. This discovery has dramatically changed the way we look at the world of elementary particles (protons, neutrons, electrons as well as their interactions), and most crucially, our ability to harness nuclear power.

The idea of forces has now been largely replaced by the concept of **fields**. A field is an influence, produced by one or many particles in a certain region of space that can exert a force on other particles. For an example of a field, take a look at the following activity involving magnets.

Experiment: Magnetic influence at a distance

Take two magnets. Mark their respective North and South poles. Place the magnets on the table with the North poles (or South poles) of both magnets facing each other. Ensure that they are sufficiently far away from each other so that neither moves. Then, begin to move them closer till you begin to feel a palpable repulsion between the two magnets, and they show a tendency to move away from each other on their own. Note this distance down. Repeat this experiment for stronger and weaker magnets. A variation of this experiment can be carried out with opposite poles facing each other (be careful here because the magnets can easily break apart if they are strong enough). In this case, observe how far away the two magnets need to be so that they just begin to move towards each other.

From these experiments, it will become clear that the two magnets can feel each other's presence even without there being any physical contact between them. This non-physical influence of a magnet is what is called its **magnetic field**. Once the first magnet enters the field of the second magnet, it experiences a force (and vice versa). **Seeing** this field is also quite easy. Put the magnet under a stiff piece of paper and sprinkle iron filings on it. The fillings will arrange themselves in patterns that clearly point out the shape of the field in two dimensions. One can play with using two or more magnets and iron filings to get pictures as shown in Figure 1.

One of the most important reasons for replacing the concept of forces with that of fields is that the latter provides a rather elegant way to explain how **quickly** any change in a configuration, say, of masses or charges, can be felt somewhere else. For instance, if the Sun were to disappear suddenly, its gravitational pull on the earth would fall to zero. But we would get to know of it only about 8 minutes later (the time taken for light to travel the distance between the two) and not instantaneously, as this **change** is transmitted through the previously existing gravitational field between the Sun and Earth, at the speed of light.

Figure 1. Some pictures of magnetic field lines using iron filings and magnets placed under a sheet of paper. Can you spot opposite poles facing each other above?

The field of properties and elementary particles

Each of the four forces actually refers to a specific property that particles which produce and are affected by them possess. For instance, gravitational force only acts between particles that have a property called **mass**; electromagnetic force only acts on particles that have **electrical charge**; strong force acts only on particles that have a property that we happen to call **colour** (not to be confused with our usual sense of colour as perceived by our eyes - but those who were doing the naming clearly did not think of interesting enough names) and finally, weak force acts only on particles that have a property that we choose to name as **flavour** (again not to be confused with our usual definition of flavour). These properties are assumed to be independent of each other, i.e., a gravitational field cannot interfere with a colour property, and a magnetic field cannot interfere with the mass possessed by a particle. However, the energy that each type of field can generate can easily be converted from one form to another. For example, gravitational energy can be converted into magnetic energy, or the energy produced by the strong force can be transformed into electrical energy (as in a nuclear reactor) and so on.

Elementary particle physics was born, possibly in 1897, with the discovery of the electron by J. J .Thomson. Then, in 1914, Rutherford experimentally showed that the positive charge (and almost all of the mass) of an atom was concentrated in a tiny core at its centre, called the nucleus. Once the neutron was discovered much later by Chadwick in 1932, the answer to "What was matter made of?" could be answered very simply as "Electrons, protons and neutrons". See Figure 2 for a view of a generic atom.

You might wonder how protons could be lumped together inside the nucleus (with a size of the order of 10^{-15} metres) given that they repulsed each other very strongly. Yukawa[1], in 1934, postulated that this was possible because of an exchange interaction of mediator particles called **strong** force as it had to overcome this (Coulomb) repulsion. Similarly, in attempting to explain beta decay in radioactive nuclei, which resulted in the emission of electrons from the nucleus, Fermi postulated another exchange

For a wonderful introduction to elementary particle, refer:

1. Particle Data Group of the Lawrence Berkeley National Laboratory (LBNL). URL: http://particleadventure.org/, or,
2. CERN outreach site. URL: http://home.cern/students-educators

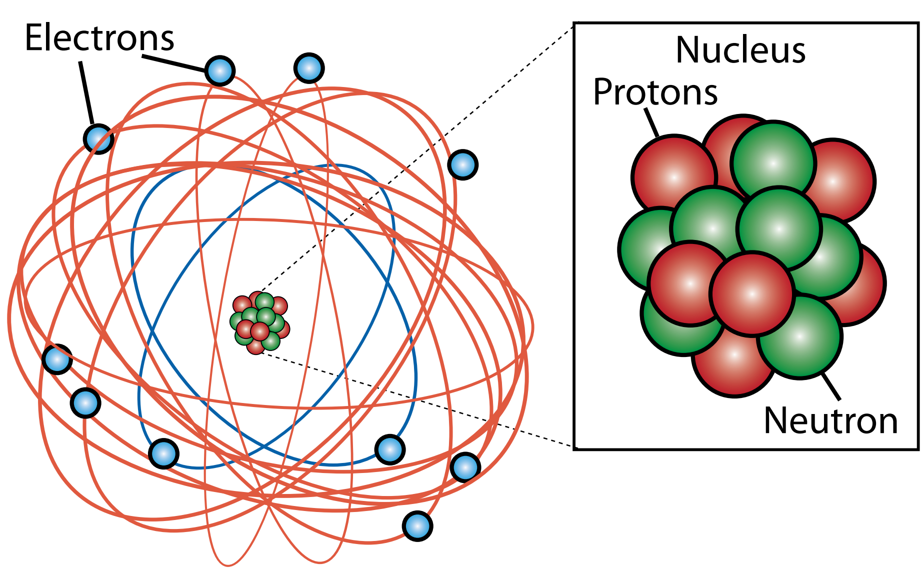


Figure 2. A generic atom. Note that the electron orbits are not circular in shape. The nucleus consists of only the protons and neutrons with the electrons orbiting outside. This drawing is not to scale and the orbital shapes are only representative.

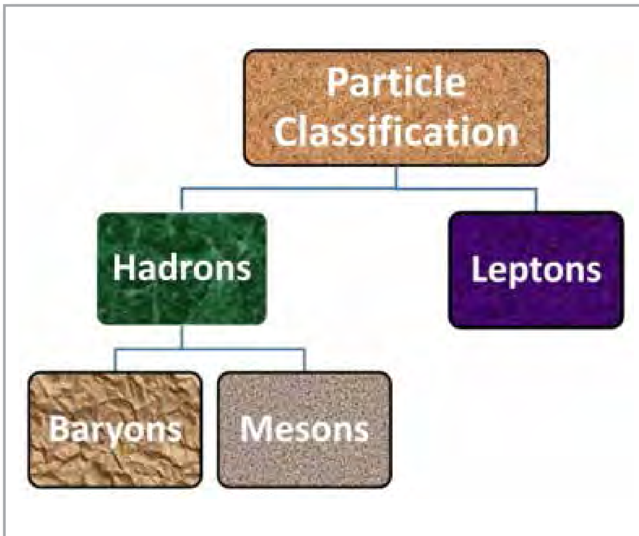


Figure 3. Given here is the really simple classification of all the particles (many hundreds have been observed in the lab) known to us. What is remarkable is that all particles fit the above scheme without fail.

interaction over a very short range, also mediated by mediator particles, called **weak** interaction (would you be tempted then to think that electrons exist within the nucleus? This is just not true. No electrons have ever been seen experimentally within the confines of the nucleus and yet they are emitted from there). These Strong and Weak interactions play crucial roles in the (nuclear) reactions that occur in nuclear reactors and in nuclear bombs. In the core of the Sun, for example, these forces facilitate the formation of Helium nuclei out of four Hydrogen nuclei, thereby releasing energy which is crucial to life on Earth. We will look at these exchange interactions in more detail in a later section.

In 1932, the number of elementary particles observed was just three. But by 1960, this number had grown into a veritable jungle. What's more, it was hypothesized that each particle would have a corresponding **antiparticle**. An antiparticle is such that were it to meet its particle, the two would annihilate each other to produce electromagnetic radiation. These were also being discovered experimentally. Thankfully, all these particles could be categorised into three major groups called the Baryons ('heavyweights'), Mesons ('middle weights') and Leptons ('lightweights'). Baryons and Mesons are collectively known as the Hadrons.

Some examples of Baryons include the well-known protons and neutrons and the less-known Lambda, Sigma and Delta particles. Some examples of Mesons include Pions, Kaons, Etas and others. Lastly, some examples of the Leptons include electrons as well as the less familiar muons, tauons, electrons, neutrinos and so on. Do remember that all these particles have their corresponding antiparticles[2].

It was to make sense of all these particles (and anti-particles) as well as the interactions that govern their behaviour, that the **Standard Model** of particle physics was proposed. This model postulates that all the Hadrons are composed of even more fundamental particles, called Quarks, which came in six major types or **flavours**. These flavours were called Up (U), Down (D), Strange (S), Charm (C), Beauty (B) and Truth (T). Each of these flavours of quarks is believed to come in three 'colours', Red, Green and Blue. The anti-quarks are given anti-colours, i.e., anti-Red (also termed minus-Red or Cyan), anti-Green (minus-Green or Magenta) and anti-Blue (minus-Blue or Yellow). In this model, therefore, the total number of quarks (and also that of antiquarks) is 18.

All Baryons are believed to be composed of three quarks bound together. Similarly, anti-Baryons are naturally made up of three anti-quarks. Mesons are believed to be composed of a quark and anti-quark pair bound together. All **observed** particles are thought to have a net 'colour', which is either **white**, i.e., equal amounts of Red, Green and Blue or their anti-colours, or zero where there are equal amounts of the Red and anti-Red, and so on for other colours. Look at Figure 4 for some examples.

Leptons do not have colour. It is because of this that the strong force has no effect on leptons, even though

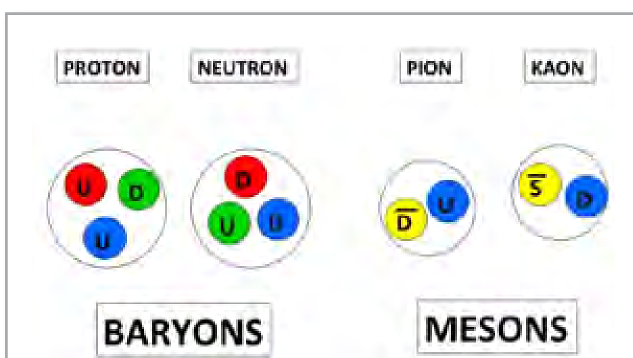


Figure 4. The examples above show the composition of some baryons and mesons in terms of quarks. The confining boundary shows that these quarks are actually bound together. The quarks shown here are the U, D and S quarks, and the anti-quarks $\bar{D}$ and $\bar{S}$.

these particles are influenced by weak, gravitational and electromagnetic forces.

Free quarks have **not been observed in nature**. However, experiments have shown that protons and neutrons have a micro-structure composed of three parts, which gives some credence to the quark model. Predictions made using this model have all been experimentally validated, and it is generally accepted that the Standard Model describes elementary particles and their interactions very well.

The nature of interactions: messengers and fabrics

How do electromagnetic, weak and strong fields arise, and how do they facilitate interactions between particles? It is postulated that every field can be thought to act with the aid of exchanging particles called 'messengers' which carry the force back and forth between two interacting particles. Photons act as messengers for electromagnetic fields by moving back and forth between two charges that are influencing each other (can you see how this picture can be used to explain both attraction and repulsion between charges?). For the strong force, there are eight messenger particles called **gluons**. For the weak force, there are just three messenger particles called **vector bosons**. See the table below for a summary of these messengers.

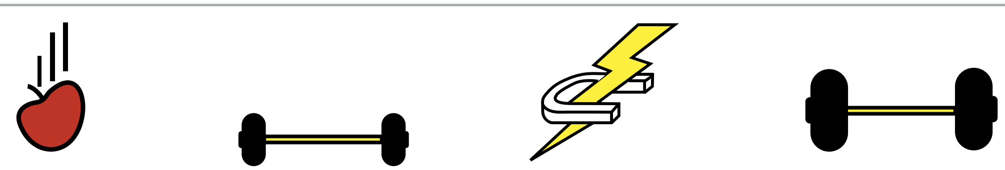
How is the gravitational field described nowadays? Just as for the other three fields, it is postulated that gravity is also carried by a messenger called the Graviton but this has not been discovered yet. However, gravity is really quite different from the other three fields. To see why, let us look at a simple experiment described below.

Experiment: How does one cancel gravity?

It is amazingly easy. Look at the left panel of Figure 5. It shows a slotted mass hanging from a spring inside a closed bottle. Since gravity is acting on the mass, it is clear that the spring is stretched. When the bottle is now released and allowed to freely fall, the mass moves up and stays there as though the spring was not being stretched at all, till it hits the ground. This shows that there is no force of gravity, **relative to the spring and bottle**, acting on the mass as long as it is falling. So, in general, to cancel gravity on any object relative to its immediate surroundings, one must enable it and its surroundings to enter a state of free fall. This is what happens in space, inside, say, a manned satellite, where the astronaut and the satellite are orbiting the earth, and are therefore in a state of free fall. Hence, the astronaut feels no gravitational force with respect to the satellite and can float about inside it with abandon.

It was based on the result of this experiment, among other things, that Einstein formulated his notion of the General Theory of Relativity. This states that gravity is just a contortion of the **fabric** of space–time by a mass. You can understand this by placing a heavy object like a basketball, say, on a stretched membrane like a trampoline. The trampoline is now deformed or acquires a curvature such that if you roll marbles near it, they will tend to fall towards the basketball in paths other than straight lines. These could either be in the form of curved paths that go around the basketball, or in the form of straight lines.

Carrying this analogy to the solar system and elsewhere, planetary orbits then are just paths that arise due to the curvature of the fabric of space itself by the sun and there is thus no actual force (or field) of gravity present. Gravity can



	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried by	Graviton (not yet observed)	w^+ w^- z^0	Photon	Gluon
Acts on	All	Quarks & Leptons	Quarks & Charged Leptons & w^+ w^-	Quarks & Gluons

Table 1. The second row lists mediators that create the forces that we experience as well as those (that operate at the sub-atomic level) that we don't. Why do we need so many mediators for the strong and weak forces?

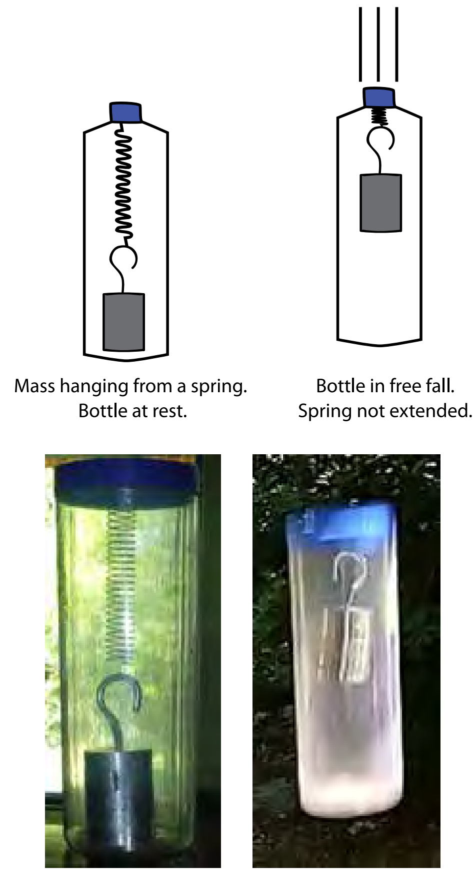


Figure 5. Top panel: Experimental set up. Bottom panel: Actual experiment. The figures in the left panel show a Mass hanging from a spring inside a bottle that is at rest. The figures in the right panel show the same bottle in free fall – note that the spring is not extended. This shows that the pull of gravity on the Mass is cancelled with respect to the bottle and spring.

be seen, as shown in Figure 6, as a distortion of space–time.

The nature of the interactions: strength and range

What is the strength of the four fields? How weak or strong are they with respect to each other? Do they vary with distance? Let us rank the four fields in the following way. Imagine that two elementary particles, like protons, were to be placed next to each other. If the strong force acting between them is given a notional value of 1, we will find that the electromagnetic repulsive force has a value of 0.001, i.e., it is one thousand times weaker. The weak force will have a relative value of 10^{-14}, i.e., it is about hundred trillion times weaker. Finally, the gravitational force between the two protons will have

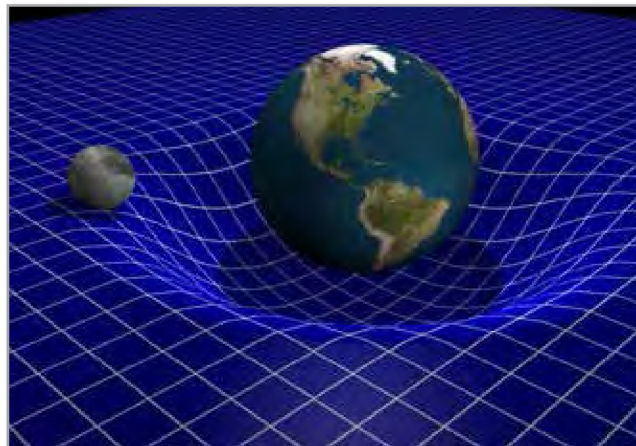


Figure 6. Gravity is a distortion of space-time which is depicted here as a coordinated system (look at the grid lines). It is this coordinate system that is distorted by the mass of the planet
Source: This has been taken from https://i.ytimg.com/vi/cxgHz5H4AHA/maxresdefault.jpg and https://www.youtube.com/watch?v=cxgHz5H4AHA.

a relative value of 10^{-43}, i.e., it is ten tredecillion times weaker!

The electromagnetic force is probably the most significant force in our lives. This is primarily because the electrons, which orbit the nucleus, repel each other. This in turn implies that two atoms which try to come too close simply cannot do so. All the properties of matter, which produce the pushes and pulls that are most familiar to us, arise primarily from this effect between atoms. Since it dwarfs the gravitational effect by a factor of 10^{40}, it follows that we need a huge mass like the earth, which is also largely charge neutral, to produce a strong enough Gravitational pull to keep us down. Look at Figure 7 for a comparison between the electrical and gravitational force.

Both gravitational and electromagnetic fields have a range that is infinite. There is no way to escape these forces by moving away from them. It just becomes weaker the farther away you go, but can never become zero (one can, of course, cancel the force out at specific points but that is a different thing since one needs to use other masses or charges to do so). The strong and weak fields, in contrast, have a very short range, which acts only across distances typically the size of the nucleus, about 10^{-15} metres. Beyond this distance, they fall to zero. So for either of these two forces to come into effect, elementary particles must be forced to interact at very short distances. Since atoms cannot come that close to each other under ordinary circumstances of temperature and pressure, we cannot experience these forces in a direct way.

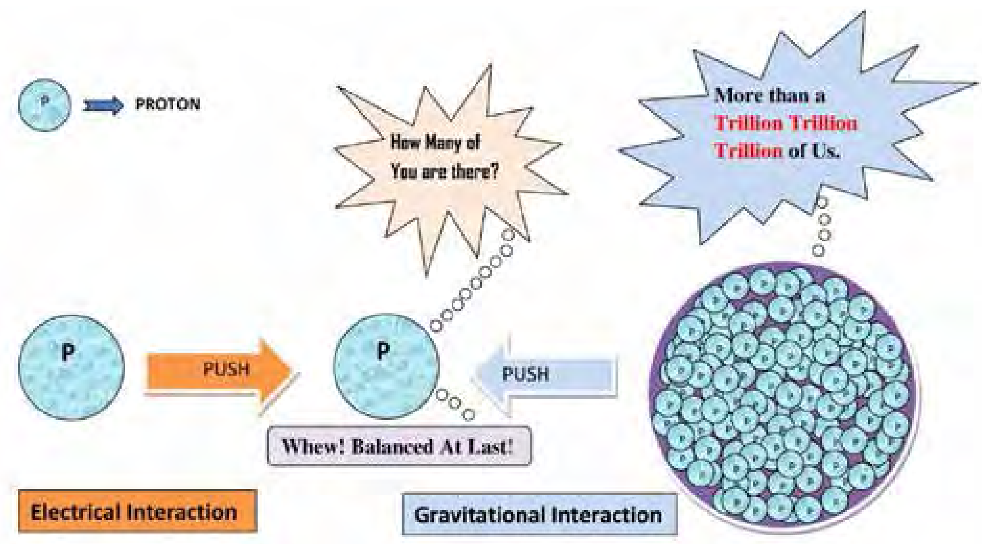


Figure 7. Comparing electrical and gravitational forces. The proton in the middle has no net force on it. On the left, it is being pushed by another proton using only the electrical Force. On the right, it is being pushed by a bunch of protons using only the gravitational Force. To balance the two forces, and provide the required gravitational force strength, the number of protons one needs on the right is more than 1.25 Trillion Trillion Trillion, i.e., 1.25 ×1036 protons.

To summarise, one sees that the electromagnetic field largely determines the size and composition of planets. Even commonplace technologies rely on this field. The strong and weak forces power the stars by enabling nuclear fusion at very high temperatures within their cores. They also power nuclear bombs and nuclear power plants. The gravitational force produces all the most important known structures, like stars, galaxies, galaxy clusters, etc. in the observable universe. These structures have stupendous quantities of largely charge-neutral matter present in them. Gravitational fields are also directly responsible for producing the most energetic events in the universe, like gamma ray bursts, supernovae and so on. This is because a large enough amount of matter can exert a force much stronger than the other three forces, and can paradoxically set into motion tremendous quantities of energy. There is something significant after all in being heavy enough.

Conclusion

These four fundamental interactions between particles have been sufficient to describe most of the observed properties of matter, but it is not impossible that some other forces can occupy such a fundamental position in the future. For example, recent cosmological evidence shows that 96% of the known universe may contain both a different sort of matter and energy called dark matter and dark energy respectively. It is speculated that dark matter has an attractive gravitational force, and dark energy has what looks like a repulsive gravitational force. They are termed dark because unlike ordinary matter, they do not absorb and emit electromagnetic waves. Knowledge of these forces may very well unlock many more kinds of fields. There appear to be surprises galore just waiting to be explored!

References

1. 'Introduction to Elementary Particles', by David Griffiths, John Wiley and Sons, New York.
2. Review of Particle Physics, Chinese Physics C Vol. 38, No. 9 (2014) 090001, Particle Data Group. See http://pdg.lbl.gov/2015/html/computer_read.html.

Srinivasan Krishnan completed his Ph.D. in astrophysics from IUCAA, Pune in 2000, after which he joined a small school as a physics and science teacher. His present interests include reading and designing lab equipment for young children. He can be contacted at ksrini69@gmail.com.