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I.1
CHAPTER

Matter and the forces that move it

The prologue to the book gave you a preview of our quest, something like the video a tour agency might show you. Now we embark on the actual trip.

Where do forces come from?

In just about any physics course, the professor would be talking about forces, the force of gravity, the electric force, so on and so forth. I am here to tell you that, until quantum field theory was invented, physicists did not really know where these forces came from. Sure, they could describe the forces, but that was about it.

So, that was a fairly big deal: quantum field theory could explain how forces arise.

Matter

First, I have to remind you that matter consists of molecules, and molecules are built out of atoms. An atom consists of electrons whirling around a nucleus, which in turn consists of protons and neutrons, collectively known as nucleons. The nucleons are made of quarks. That's what we know.[1]

The universe also contains dark matter and dark energy. Indeed, by mass, the composition of the universe is 27% dark matter, 68% dark energy, and only 5% ordinary matter. To first approximation, the universe may be regarded as one epic cosmic struggle between dark matter and dark energy.[2] The matter we know and love and of which we are made hardly matters. Unhappily, at present we know little about the dark side. Nevertheless, essentially all reputable speculations about the dark side are based on quantum field theory.

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Forces

We know of four fundamental forces between these particles. When particles come into the vicinity of each other, they interact, that is, influence each other. Here is a handy summary of the four forces, known as gravity, electromagnetism, the strong interaction, and the weak interaction:

G: Gravity keeps you from flying up[3] to bang your head on the ceiling or from floating off like a space cadet.
E: Electromagnetism prevents you from falling through the floor and dropping in on your neighbors if you live in an apartment.*
S: The strong interaction causes the sun to provide us light and energy free of charge.
W: The weak interaction stops the sun from blowing up in our faces.

While we all have to come to terms with gravity, we know electromagnetism best, as our entire lifestyle is based on enslaving electrons.

Only four forces!

The world appears to be full of mysterious forces and interactions. Only four?

As you toddled, you banged your head against a hard object. What is the theory behind that? Well, the theory of solids can get pretty complicated, given the large variety of solids. But a simple cartoon picture suffices here: the nuclei of the atoms comprising the solid are locked in a regular lattice, while the electrons cruise between them as a quantum cloud. A collective society in which all individuality is lost! The atoms no longer exist as separate entities. The arrangement is highly favorable energetically; that is jargon for saying that enormous energy is required to disturb that arrangement. Revolution is costly. It takes quite a tough guy to crack a rock into halves.

So, the myriad interactions we witness in the world, such as solid banging on solid, could all be reduced to electromagnetism. What we see in everyday life is by and large due to some residual effect of the electromagnetic force: since common everyday objects are all electrically neutral, consisting of equal numbers of protons and electrons, the electromagnetic force between these objects almost all cancel out. Even the steel blade of a jackhammer smashing into rock is but a pale shadow of the real strength of the electromagnetic force.[4]

When you first emerged into this world, you might have thought that there must be thousands, if not millions, of forces in the world. Thus, to be able

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*Plus a lot of other good deeds. Electromagnetism holds atoms together, governs the propagation of light and radio waves, causes chemical reactions, and last but not least, stops us from walking through walls.

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to state that there are only four fundamental forces is totally awesome, a feat summarizing centuries of painstaking investigations. For example, realizing that light is due to electromagnetism stands as a towering achievement.

No contact necessary

Our common everyday understanding of force involves contact: we can exert a force on an object only if we are in contact with it. In a contact sport such as American football, without tackling the ball carrier, a linebacker could hardly exert anything on him. And in the movies, a slap is not a slap until the leading lady's palm makes contact with the leading cad's cheek. At the supermarket, you can push the shopping cart only if you grip the handle. If you could just hold out your hands and command the shopping cart to move, a crowd would gather and honor you as a wizard.

Everyday forces, except for gravity, are short ranged, indeed zero ranged on the length scales of common experience. These forces are but pale vestiges of the electromagnetic force, as I've just said. The palm molecules have to be practically on top of the cheek molecules before the latter could acquire any carnal knowledge of the former.

Gravity is the glaring exception. When the earth pulls Newton's apple down, no hand comes out of the earth grabbing the apple as in a horror movie. Gravity is invisible, thus all the more horrifying as we age.

Just about the only commonplace example of a force acting without contact is the refrigerator magnet: You can feel the refrigerator pulling on the magnet before the magnet makes contact with the refrigerator. This shows that the electromagnetic interaction, like gravity, is also long ranged.

Hence, in quantum physics, the word "interaction" is preferred rather than the word "force." No contact is necessary for particles to interact with each other. Indeed, the very concept of "contact" is problematical in the quantum world.

The universe as a finely choreographed dance

While the proverbial guy and gal on the street are plenty acquainted with gravity and electromagnetism, they have no personal experience with the strong and the weak interactions. But in fact, the physical universe is a finely choreographed dance starring all four interactions.

Consider a typical star, starting out in life as a gas of protons and electrons. Gravity gradually kneads this nebulous mass into a spherical blob, in which the strong and the electromagnetic forces stage a mighty contest.

The electric force causes like charges to repel each other. Thus, the protons are kept apart from each other by their mutual electric repulsion. In contrast,

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the strong force, also known as nuclear attraction, between the protons tries to bring them together. In this struggle the electric force has a slight edge, a fact of prime importance to us.[5] If the nuclear attraction between protons were a tiny bit stronger, two protons could get stuck together, thus releasing energy. Nuclear reactions would then occur very rapidly, burning out the nuclear fuel of stars in a short time, thereby making steady stellar evolution, let alone civilization, impossible.

In fact, the nuclear force is barely strong enough to glue a proton and a neutron together, but not strong enough to glue two protons together. Roughly speaking, before a proton can interact with another proton, it first has to transform itself into a neutron. This transformation necessitates the intervention of the weak interaction. Processes effected by the weak interaction occur extremely slowly, as the term "weak" suggests. As a result, nuclear burning in a typical star like the sun occurs at a stately pace, bathing us in a steady, warm glow.

Short and long ranged

The reason that the proverbial guy and gal in the street do not feel the strong and the weak interactions is because these two interactions are short ranged. The strong attraction between two protons falls abruptly to zero as soon as they move away from each other. The weak interaction operates over an even shorter range. Thus, the strong and weak interactions do not support propagating waves.

In contrast, the gravitational force between two masses and the electric force between two charges both fall off with the separation r between the two objects like $1/r^2$, the famous inverse square law of Newton. Gravity and electromagnetism are long ranged, as was mentioned earlier, and thus can and do support propagating waves. We will see how quantum field theory could explain this curious state of affairs in chapter III.2.

For r large, these forces still go to zero, but slowly enough that we can feel the tug of the sun, literally an astronomical distance away.[6] For that matter, our entire galaxy, the Milky Way, is falling toward our neighbor, the Andromeda galaxy.

Thus, in the contest between the four interactions, brute strength is not the only thing that counts: many phenomena depend on an interplay between range and strength. A case in point is fusion versus fission in nuclear physics. When two small nuclei get together, each consisting of a few protons and some neutrons, the strong attraction easily overwhelms the electric repulsion and they want to fuse. In contrast, in a large atomic nucleus, famously, the uranium nucleus, the electric repulsion wins over the strong attraction. Each proton only feels the strong attraction of the protons or neutrons right next to it, but each proton feels the electric repulsion from all the other protons in the nucleus. The nucleus wants to split into two smaller pieces, accompanied by the release of energy.

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Notes

[1] Whether or not quarks and electrons are tiny bitty strings is an intriguing, but at the moment purely speculative, possibility.

[2] See *GNut,* chapter VIII.2.

[3] You know how fast the earth is spinning to cover about 24,000 miles in 24 hours. Anybody who has studied some physics could calculate what the centrifugal acceleration would be.

[4] Just about the only time the true fury of electromagnetism shakes us is when thunder and lightning fill the sky. While we modern dudes have totally enslaved electromagnetism, all ancient people attribute its occasional bursts of temper to the gods. We still devote one day a week to electromagnetism: Thursday is Thor's day.

[5] Quantum mechanics enters crucially here. The protons are not energetic enough to climb over the repulsive barrier set up by the electric force but have to tunnel through. See the discussion about Gamow tunneling in my book *Fly by Night Physics* to be abbreviated henceforth as *FbN*. See the bibliography.

[6] Of course, the feebleness of gravity compared to the other three interactions is also compensated for by the enormous number of particles contained in the sun and in the earth.

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