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Gravity on Earth:

the inescapable force

Gravity is everywhere. No matter where you go, you can't seem to escape it. Pick up a stone and feel its weight. Then carry it inside a building and feel its weight again: there won't be any difference. Take the stone into a car and speed along at 100 miles per hour on a smooth road: again there won't be any noticeable change in the stone's weight. Take the stone into the gondola of a hot-air balloon that is hovering above the Earth. The balloon may be lighter than air, but the stone weighs just as much as before.

This inescapability of gravity makes it different from all other forces of nature. Try taking a portable radio into a metal enclosure, like a car, and see what happens to its ability to pick up radio stations: it gets seriously worse. Radio waves are one aspect of the *electromagnetic force*, which in other guises gives us static electricity and **magnetic fields**. This force does not penetrate everywhere. It can be excluded from regions if we choose the right material for the walls. Not so for gravity. We could build a room with walls as thick as an Egyptian pyramid and made of any exotic material we choose, and yet the Earth's gravity would be right there inside, as strong as ever. *Gravity acts on everything the same way.*

Every body falls *toward* the ground, regardless of its composition. We know of no substance that accelerates *upwards* because of the Earth's gravity. Again this distinguishes gravity from all the other fundamental forces of Nature. **Electric charges** come in two different signs, the "+" and "-" signs on a battery. A negative **electron** attracts a positive **proton** but repels other electrons.

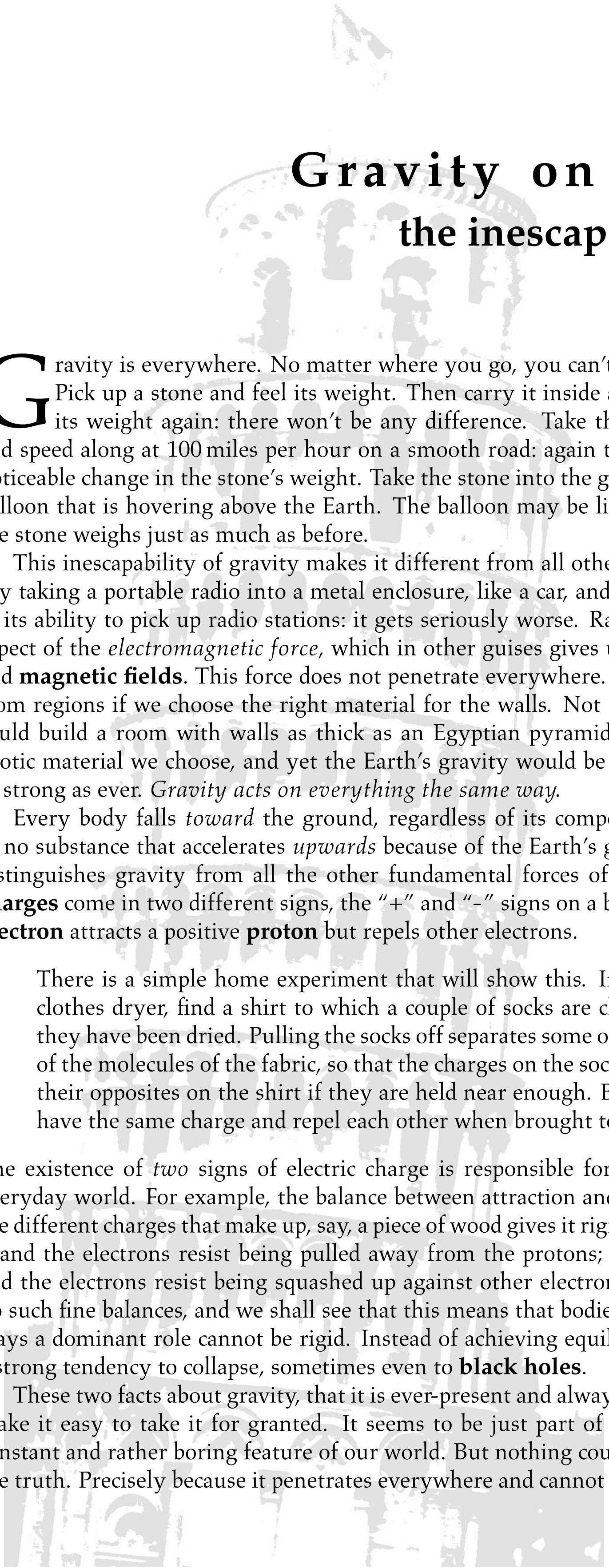
> There is a simple home experiment that will show this. If you have a clothes dryer, find a shirt to which a couple of socks are clinging after they have been dried. Pulling the socks off separates some of the charges of the molecules of the fabric, so that the charges on the sock will attract their opposites on the shirt if they are held near enough. But the socks have the same charge and repel each other when brought together.

The existence of *two* signs of electric charge is responsible for the shape of our everyday world. For example, the balance between attraction and repulsion among the different charges that make up, say, a piece of wood gives it rigidity: try to stretch it and the electrons resist being pulled away from the protons; try to compress it and the electrons resist being squashed up against other electrons. Gravity allows no such fine balances, and we shall see that this means that bodies in which gravity plays a dominant role cannot be rigid. Instead of achieving equilibrium, they have a strong tendency to collapse, sometimes even to **black holes**.

These two facts about gravity, that it is ever-present and always attractive, might make it easy to take it for granted. It seems to be just part of the background, a constant and rather boring feature of our world. But nothing could be further from the truth. Precisely because it penetrates everywhere and cannot be cancelled out, it

In this chapter: the simplest observations about gravity – it is universal and attractive, and it affects all bodies in the same way – have the deepest consequences. Galileo, the first modern physicist, founded the equivalence principle on them; this will guide us throughout the book, including to black holes. Galileo also introduced the principle of relativity, used later by Einstein. We begin here our use of computer programs for solving the equations for moving bodies.

▷Remember, terms in **boldface** are in the glossary.



▷The picture underlying the text on this page is of the famous bell tower at Pisa, where Galileo is said to have demonstrated the key to understanding gravity, that all bodies fall at the same rate. We will discuss this below. Photo by the author.

is the engine of the Universe. All the unexpected and exciting discoveries of modern astronomy – **quasars**, **pulsars**, **neutron stars**, black holes – owe their existence to gravity. It binds together the gases of a **star**, the stars of a **galaxy**, and even galaxies into **galaxy clusters**. It has governed the formation of stars and it regulates the way stars create **chemical elements** of which we are made. On a grand scale, it controls the **expansion of the Universe**. Nearer to home, it holds planets in orbit about the Sun and satellites about the Earth.

The study of gravity, therefore, is in a very real sense the study of practically everything from the surface of the Earth out to the edge of the Universe. But it is even more: it is the study of our own history and evolution right back to the **Big Bang**. Because gravity is everywhere, our study of gravity in this book will take us everywhere, as far away in distance and as far back in time as we have scientific evidence to guide us.

Galileo: the beginnings of the science of gravity

In this section: Galileo laid the foundations for the scientific study of gravity. His demonstration that the speed of fall is independent of the weight of an object was the first statement of the principle of equivalence, which will lead us later to the idea of black holes.

We will begin our study of gravity with our feet firmly on the ground, by meeting a man who might fairly be called the founder of modern science: Galileo Galilei (1564–1642).

In Galileo's time there was a strong interest in the trajectories of cannonballs. It was, after all, a matter of life and death: an army that could judge how far gravity would allow a cannonball to fly would be better equipped to win a battle over a less well-informed enemy. Galileo's studies of the trajectory problem went far beyond those of any previous investigator. He made observations in the field and then performed careful experiments in the laboratory. These experiments are a model of care and attention to detail. He found out two things that startled many people in his day and that remain cornerstones of the science of gravity.

> First, Galileo found that the rate at which a body falls does not depend upon its weight. Second, he measured the rate at which bodies fall and found that their acceleration is constant, independent of time.

After Galileo, gravity suddenly wasn't boring any more. Let's look at these two discoveries to find out why.

The story goes that Galileo took two iron balls, one much heavier than the other, to the top of the bell tower of Pisa and dropped them simultaneously. Most people of the day (and even many people today!) would probably have expected the heavier ball to have fallen much faster than the lighter one, but no: both balls reached the ground together.

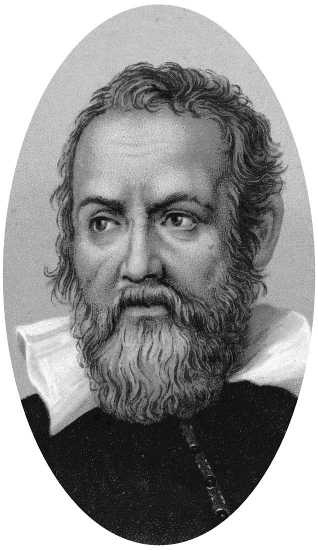


Figure 1.1. *Galileo Galilei moved science away from speculation and philosophy and toward its modern form, insisting on the pre-eminence of careful experiment and observation. He also introduced the idea of describing the laws of nature mathematically. Meeting strong religious opposition in his native Italy, his ideas stimulated the growth of science in northern Europe in the decades after his death. Image reproduced courtesy of Mary Evans Picture Library.*

The equality of the two balls' rates of fall went against the intuition and much of the common experience of the day. Doesn't a brick fall faster than a feather? Galileo pointed out that air resistance can't be neglected in the fall of a feather, and that to discover the properties of gravity alone we must experiment with dense bodies like stones or cannonballs, where the effects of air resistance are small. For such objects we find that speed is independent of weight.

But surely, one might object, we have to do much more work to lift a heavy stone than a light one, so doesn't this mean that a heavy stone "wants" to fall more than a light one and will do so faster, given the chance? No, said Galileo: weight has nothing to do with the speed of fall. We can prove that by measuring it. We have to accept the world the way we find it. This was the first step towards what we now call the *principle of equivalence*, which essentially asserts that gravity is indistinguishable from uniform accleration. We shall see that this principle has a remarkable number of consequences, from the weightlessness of astronauts to the possibility of black holes.