3.1: The Principle of Relativity

> *The name relativity theory was an unfortunate choice: The relativity of space and time is not the essential thing, which is the independence of laws of Nature from the viewpoint of the observer.*
>
> *- Arnold Sommerfeld*

Fundamental Science needs only a Closed Room

How do you know you are moving? Or at rest? In a car, you pause at a stoplight. You see the car next to you easing forward. With a shock you suddenly realize that, instead, your own car is rolling backward. On an international flight you watch a movie with the cabin shades drawn. Can you tell if the plane is traveling at minimum speed or full speed? In an elaborate joke, could the plane actually be sitting still on the runway, engines running? How would you know?

Principle of Relativity: With shades drawn you cannot tell your speed

Everyday observations such as these form the basis for a conjecture that Einstein raised to the status of a postulate and set at the center of the theory of special relativity. He called it the **Principle of Relativity**.[1] Roughly speaking, the Principle of Relativity says that without looking out the window you cannot tell which reference frame you are in or how fast you are moving.

Galileo; First known formulation of Principle of Relativity

Galileo Galilei made the first known formulation of the Principle of Relativity. Listen to the characters in his book:

> SALVATIUS: Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish in it; hang up a bottle that empties drop by drop into a wide vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something to your friend, you need throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction. When you have observed all these things carefully (though there is no doubt that when the ship is standing still everything must happen in this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that. You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still.[2] In jumping, you will pass on the floor the same spaces as before, nor will you make larger jumps toward the stern than toward the prow even though the ship is moving quite rapidly, despite the fact that during the time that you are in the air the floor under you will be going in a direction opposite to your jump. In throwing something to your companion, you will need no more force to get it to him whether he is in the direction of the bow or the stern, with yourself situated opposite. The droplets will fall as before into the vessel beneath without dropping toward the stern, although while the drops are in the air the ship runs many spans. The fish in their water will swim toward the front of their bowl with no more effort than toward the back, and will go with equal ease to bait placed anywhere around the edges of the bowl. Finally the butterflies and flies will continue their flights indifferently toward every side, nor will it ever happen that they are concentrated toward the stern, as if tired out from keeping up with the course of the ship, from which they will have been separated during long intervals by keeping themselves in the air . . .

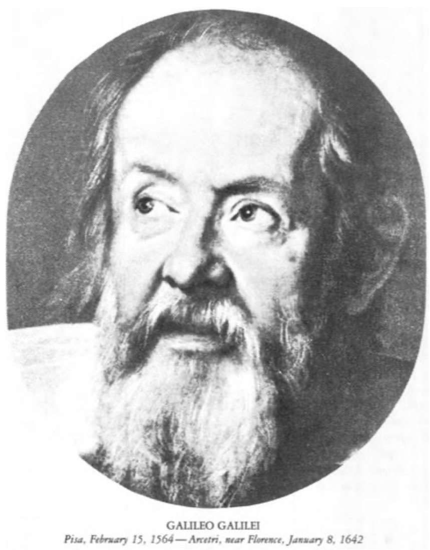

Figure 3.1.1 : Pisa, February 15, 1564—Arcetri, near Florence, January 8, 1642
"My portrait is now finished, a very good likeness, by an excellent hand."— September 22, 1635

> *"If ever any persons might challenge to be signally distinguished for their intellect from other men, Ptolemy and Copernicus were they that had the honor to see farthest into and discourse most profoundly of the World's systems."*

> *"My dear Kepler, what shall we make of all this? Shall we laugh, or shall we cry?"*

> *"When shall I cease from wondering?"*

> SAGREDUS: Although it did not occur to me to put these observations to the test when I was voyaging, I am sure that they would take place in the way you describe. In confirmation of this I remember having often found myself in my cabin wondering whether the ship was moving or standing still; and sometimes at a whim I have supposed it to be going one way when its motion was the opposite . . .

The Galilean Principle of Relativity is simple in this early formulation, yet not as simple as it might be. In what way is it simple? Physics looks the same in a ship moving uniformly as in a ship at rest. Relative uniform motion of the two ships does not affect the laws of motion in either ship. A ball falling straight down onto one ship appears from the other ship to follow a parabolic course; a ball falling straight down onto that second ship also appears to follow a parabolic course when observed from the first ship. The simplicity of the Galilean Principle of Relativity lies in the equivalence of the two Earthbound frames and the symmetry between them.

Extension of Galileo's reasoning from ship to spaceship

In what way is this simplicity not as great as it might be? In Galileo's account the frames of reference are not yet free-float (inertial).[3] To make them so requires only a small conceptual step; from two uniformly moving sea-going ships to two unpowered spaceships. Then up and down, north and south, east and west, all become alike. A ball untouched by force undergoes no acceleration. Its motion with respect to one spaceship is as uniform as it is with respect to the other. This identity of the law of free motion in all inertial reference frames is what one means today by the Galilean Principle of Relativity.

Galileo could not by any stretch of the imagination have asked his hearer to place himself in a spaceship in the year 1632. Yet he could have described the greater simplicity of physics when viewed from such a vantage point. Bottles, drops of water, and all the other test objects float at rest or move at uniform velocity. The zero acceleration of every nearby object relative to the spaceship would have been intelligible to Galileo of all people. Who had established more clearly than he that relative to Earth all nearby objects have a common acceleration?

Einstein's Principle of Relativity is a generalization of such experiments and many other kinds of experiments, involving not only mechanics but also electromagnetism, nuclear physics, and so on.

Principle of Relativity

All the laws of physics are the same in every free-float (inertial) reference frame.

Einstein's Principle of Relativity says that once the laws of physics have been established in one free-float frame, they can be applied without modification in any other free-float frame. Both the mathematical form of the laws of physics and the numerical values of basic physical constants that these laws contain are the same in every free-float frame. So far as concerns the laws of physics, all free-float frames are equivalent.

We can tell where we are on Earth by looking out of the window. Where we are in the Milky Way we can tell by the configuration of the Big Dipper and other constellations. How fast and in what direction we are going through the larger framework of the universe we measure with a set of microwave horns pointed to pick up the microwave radiation streaming through space from all sides. But now exclude all information from outside. Screen out all radiation from the heavens. Pull down the window shade. Then do whatever experiment we will on the movement and collision of particles and the action of electric and magnetic forces in whatever free-float frame we please. We find not the slightest difference in the fit to the laws of physics between measurements made in one free-float frame and those made in another. We arrive at the Principle of Relativity in its negative form:

Principle of Relativity, negative form

No test of the laws of physics provides any way whatsoever to distinguish one free-float frame from another.

Box 3-1

THE PRINCIPLE OF RELATIVITY RESTS ON EMPTINESS!

In his paper on special relativity, Einstein says, "We will raise this conjecture (whose intent will from now on be referred to os the 'Principle of Relativity') to o postulate ... " Is the Principle of Relativity just o postulate? All of special relativity rests on it. How do we know it is true? What lies behind the Principle of Relativity?

This is a philosophical question, not a scientific one. You will have your own opinion; here is ours. We think the Principle of Relativity as used in special relativity rests on one word: emptiness.

Space is empty; there are no kilometer posts or mileposts in space. Do you want to measure distance and time? Then set up a latticework of meter sticks and clocks. Pace off the meter sticks, synchronize the clocks. Use the lattice- work to carry out your measurements. Discover the laws of physics. This latticework is your construction, not Nature's. Do not ask Nature to choose your latticework in preference to the similar latticework that I have constructed. Why not? Because space is empty. Space accommodates both of us as we go about our constructions and our investigations. But it does not choose either one of us in preference to the other. How can it? Space is empty. Nothing whatever can distinguish your latticework from mine. If we decide in secret to exchange latticeworks. Nature will never be the wiser! It follows that whatever laws of physics you discover employing your lattice- work must be the same laws of physics I discover using my latticework. The same is true even when our lattices move relative to one another. Which one of us is at rest? There is no way to tell in empty space! This is the Principle of Relativity.

But is space really empty? "Definitely not!" says modern quantum physics. "Space is a boiling cauldron of virtual particles. To observe this cauldron, sample regions of space much smaller than the proton. Carry out this sampling during times much shorter than the time it takes light to cross the diameter of the proton." These words are familiar or utterly incomprehensible, depending on the amount of our experience with physics. In either case, we can avoid dealing with the "boiling cauldron of virtual particles" by observing events that are far apart compared with the dimensions of the proton, events separated from one another by times long compared with the time it takes light to cross the diameter of the proton.

In the realm of classical (nonquantum) physics is space really empty? "Of course not!" says modern cosmology. "Space is full of stars and dust and radiation and neutrinos and white dwarfs and neutron stars and (many believe) black holes. To observe these structures, sample regions of space comparable in size to that of our galaxy. These structures evolve and move with respect to one another in times comparable to millions of years."

So we choose regions far from massive structures, avoid dust, ignore neutrinos and radiation, and measure events that take place close together in time compared with a million years.

Notice that for the very small and also for the very large, the "regions" described span both space and time — they are regions of spacetime. "Emptiness" refers to spacetime. Therefore we should have said from the beginning, "Spacetime is empty" — except for us and our apparatus — with limitations described above.

In brief, we can find "effectively empty" regions of spacetime of spatial extent quite a few orders of magnitude larger and smaller than dimensions of our bodies and of time spread quite a few orders of magnitude longer and shorter than times that describe our reflexes. In spacetime regions of this general size, empty spacetime can be found. In empty spacetime the Principle of Relativity applies. Where the Principle of Relativity applies, special relativity correctly describes Nature.

1 Principle of Relativity: With shades drawn you cannot tell your speed

2 Galileo: First known formulation of Principle of Relativity

3 Extension of Galileo's reasoning from ship to spaceship