1
Introduction

> *The job of science is to enable the inquiring mind to feel at home in a mysterious universe.*
> Lewis Carroll Epstein, *Relativity Visualized*

1.1
The Meaning of Relativity

The theory of relativity (special and general) is one of the cornerstones of modern physics. Its basic element is the principle of relativity. The word “relativity” here reflects only one, although very important, aspect of this principle: certain physical characteristics of a system are relative, in the sense that a numerical value of such characteristic measured by one observer may be different from the value measured by another observer moving with respect to the first one. The second aspect, inseparable from the first one, is that all laws of Nature are independent of the observer’s motion. This statement reflects the “absolute” aspect of the principle of relativity, namely, that the *physical laws are the same for all observers*. And the two aspects are inseparable because one directly follows from the other. Indeed, the relativity of motion (“the states of rest and motion do not have the absolute meaning”) follows immediately from absoluteness of natural laws (they are the same regardless of the state of motion of an observer).

We will start here with the relativity aspect. And a good starting point may be the discussion of such familiar characteristics of motion as velocity. Even a person with only rudimentary education can easily understand that velocity is a relative characteristic. If you are riding on a train and see another passenger passing from the rear of the train car to her seat in the front, you could estimate her velocity as about 2 miles/h. But an observer outside the train may estimate her velocity as 42 miles/h, owing to the additional 40 miles/h made by the train.1) The velocity of an object acquires exact meaning only when we specify relative to what it is measured. In this respect, it is a “flexible” characteristic. An object that is perceived by a ground-based observer to be moving is at rest to another observer moving together with this object. A third observer, moving in the same direction, but faster than the second one, will see the

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1) We will see later that this simple addition of velocities is only an approximation to the more general rule.

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same object moving in the opposite direction. We will call such quantities as velocity "observer-dependent," or relative.

Not all physical quantities are relative, however. Some of them are observer-independent, or absolute. Here is a simple example: if a car with three passengers has a velocity 45 miles/h, then the fact of it having this velocity is of a quite different category than the fact of it having three passengers inside. The latter is absolute because it is true for anyone regardless of one's state of motion. The former is relative because it is only true for those standing on the ground. But it is false, say, for a driver in another car moving along the same straight road. The driver will agree with you on the number of passengers in the first car but disagree on its velocity. He may hold that the first car has zero velocity because it has always been at the same distance from him.

Who is right – you or the second driver? Both are. And there is no contradiction here, because each observer relates what he sees to his own "reference frame."

Moreover, even one and the same observer can measure different velocities of the same object, depending on the observer's state of motion. A policeman in a car, using radar for measuring speeds of moving objects, will record two different values for the velocity of a vehicle, if he measures this velocity first time when his own car just stands on the road and the second time when his car is moving. We emphasize that nothing happens to the observed vehicle, it remains in the same state of motion with constant speed on a straight highway. And yet the value of this speed as registered by the radar is different for the two cases.

We thus see that the value of a speed does not by itself tell us anything. It only becomes meaningful if you specify *relative to what* this speed is measured. This is what we mean by saying that speed (more general, velocity) is a relative physical quantity.

Understanding the relative nature of some physical quantities (and absolute nature of some others) is the first step to acquiring the main ideas of special relativity.

Let us start with the widespread public perception of the theory of relativity: "Einstein has proved that everything is relative. Even time is relative."

One of these statements is true and profoundly deep; the other one is totally misleading.

The true statement is: *time is relative*. The realization of relative nature of time was a revolutionary breakthrough in our understanding of the world.

The wrong statement in the above "popular" account of relativity is that *everything* is relative. We already know that, for instance, the number of passengers in a car (or the chemical composition of a certain material) is not relative. One of the most important principles in relativity is that, together with natural laws, *certain physical quantities are absolute (invariant)*. One of such invariable quantities is the speed of light in vacuum. Also, a certain combination of time and distance turns out to be invariant. We will discuss these absolute characteristics in the next chapters. They are so important that we might as well call the theory of relativity the theory of absoluteness. It all depends on which aspect of the theory we want to emphasize.

We will now discuss in more details the relativity aspect, but keep in mind that, as emphasized above, its essence is the absolute status of the laws of Nature.

Let us first recall the classical principle of relativity in mechanics. Suppose you are inside a train car that moves uniformly along a straight track. If the motion is smooth enough, then, unless you look out of the window, you cannot tell whether the train moves or is at rest on the track. For instance, if you drop a book, it will fall straight down with acceleration, as it would do on the stationary platform. It will hit the floor near your feet, as it would do on the platform. If you play billiards, the balls will move, and collide, and bounce off in precisely the same manner as they do on the platform. And all other experiments will be indistinguishable from those on the platform. There is no way to tell, whether you are moving or not, by performing mechanical tests. This means that the states of rest and uniform motion are equivalent for mechanical phenomena. There is no intrinsic, fundamental difference between them. This general statement was formulated by Galileo and it came to be known as his principle of relativity. According to this principle, the statement "My train is moving" has no absolute meaning. Of course, you can find out that it is moving, the moment you look out of the window. But the moment you do it, you start referring all your observations to the platform. You then can say: "My car is moving relative to the platform." Platform constitutes your reference frame in this case. But you may as well refer all your data to the car you are in. Then the car itself will be your reference frame, and you may say: "My car is at rest, while the platform is moving relative to it." Now, pit the last two quoted statements against each other. They seem to be in contradiction, but they are not, because they refer to different reference frames. Each statement is meaningful and correct, once you specify the corresponding frame of reference.

We see that the concept of reference frame plays a very important role in our description of natural phenomena. We can even reformulate the principle of relativity in terms of reference frames. To broaden the pool of examples (and make the further discussion more rigorous!), we will now switch from jittering trains, and from spinning Earth with its gravity, far into deep space. A better, and more modern, realization of a suitable reference frame would be a nonrotating spaceship with its engines off, coasting far away from Earth or other lumps of matter. Suppose that initially the ship just hangs in space, motionless with respect to distant stars. You may find this an ideal place to check the basic laws of mechanics. You perform corresponding experiments and find all of them confirmed to even higher precision than those on Earth.

If you release a book, it will not go down; there is no such thing as "up" or "down" in your spaceship, because there is no gravity in it. The book will just hang in air close by you. If you give it an instantaneous push, it will start moving in the direction of the push. Inasmuch as you can neglect air resistance, the book will keep on moving in a straight line with constant speed, until it collides with another object. This is a manifestation of Newton's first law of motion – the famous law of inertia. Then you experiment with different objects, applying to them various forces or combination of forces. You measure the forces, the objects' masses, and their response to the forces. In all cases, the results invariably confirm Newton's second law – the net force accelerates an object in the direction of the force, and the magnitude of the acceleration is such that its product by the mass of the object equals the force. This explains why the released book does not go down – in the absence of gravity it does not know where "down" is. With no gravity, and possible other forces balanced, the net force on the book and thereby its acceleration is zero. Then you push against the wall of your compartment and immediately find yourself being pushed back by the wall and flying away from it. This is a manifestation of Newton's third law: forces always come in pairs; to every action there is always equal and opposite reaction.

Let us now stop for a while and make a proper definition. Call a system where the law of inertia holds, an inertial system or inertial reference frame. Then you can say that your ship represents an inertial system. So does the background of distant stars relative to which the ship is resting.

Suppose now that you fall asleep and during your sleep the engines are turned on. The spaceship is propelled up to a certain velocity, after which the engines are turned off. You are still asleep, but the ship is now in a totally different state of motion. It has acquired a velocity relative to the background of stars, and it keeps on coasting with this velocity due to inertia. The magnitude of this velocity may be arbitrary. But even if it is nearly as large as that of light, it will not by itself affect in any way the course of events in the ship. After you have woken up and checked if everything is functioning properly, you do not find anything unusual. All your tests give the same results as before. The law of inertia and other laws hold as they had done before. Your ship therefore represents an inertial reference frame as it had been before. Unless you look outside and watch the "sky" or measure the spectra of different stars, you would not know that your ship is now in a *different state of motion* than it had originally been. The reference frame associated with the ship is therefore also different from the previous one. But, according to our definition, it remains inertial.

What conclusions can we draw from this? First, any system moving uniformly relative to an inertial reference frame is also an inertial reference frame. Second, all the inertial reference frames are equivalent with respect to all laws of mechanics. The laws are the same in all of them. The last statement is the classical (Galilean) principle of relativity expressed in terms of the inertial reference frames.

The classical principle of relativity is very deep. It seems to run against our intuition. In this era of computers and space exploration, I have come across a few students in my undergraduate physics class who argued that if a passenger in a uniformly moving subway car dropped an apple, the apple would not fall straight down, but rather would go somewhat backwards. They reasoned that while the apple is falling down, the car is being pulled forward from under it, which causes the apple to hit the floor closer to the rear of the car. This argument, which overtly invokes the platform as a fundamental reference frame, overlooks one crucial detail: before being dropped, the apple in the passenger's hand was moving forward together with the car. This preexisting component of the motion persists in the falling apple due to inertia and exactly cancels the effect described by the student, so that the apple as seen by an observer in the car will go down strictly along its vertical path (Figure 1.1). This conclusion is confirmed by innumerable observations of falling objects in moving cars. It is a remarkable psychological phenomenon that sometimes not even such strong evidence as direct observation can overrule the influence of a more ancient tradition of thought. About a century and a half ago, when the first railways and trains appeared, some people were afraid to ride in them because of their great speed. The same story repeated at the emergence of aviation. Many people were afraid to board a plane not only because of the altitude of flight, but also because of its