PART I

Kinematics: Relativity without any equations

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978-0-521-14100-0 - An Illustrated Guide to Relativity
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Excerpt
More information

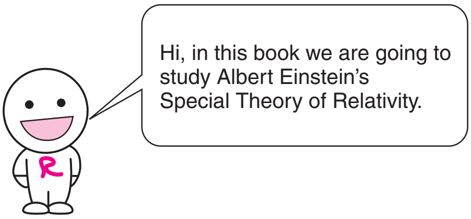
1

Welcome to the world of relativity

Albert Einstein's Special Theory of Relativity, or Special Relativity for short, came into being in 1905 in a paper with the unassuming title of "On the electrodynamics of moving bodies."[1] As the title suggests, Special Relativity is a theory of "moving bodies,"[2] that is: motion. In particular, it is a theory of how motion is perceived differently by different observers. Since motion is the process in which an object's location in *space* changes with *time*, any theory of motion is also a theory of *space* and *time*. Therefore, Special Relativity can be said to be a theory of how *space* and *time* are perceived differently by different observers. The "electrodynamics" part of the paper title refers to the fact that the theory has something to do with *light*, which is an electromagnetic wave. As we will learn in this book, the speed of light in vacuum, which we will call c,[3] plays a very special role in the theory of relativity.

Einstein (1879–1955) was not the first to construct a successful theory of motion. Building upon pioneering work by Galileo Galilei (1564–1642),[4] Sir Isaac Newton (1642–1727) had constructed theories of motion and gravity which were spelled out in his famous book *Philosophiae Naturalis Principia Mathematica*,[5] which is so famous that when people say *the Principia*,[6] it is understood that they are referring to Newton's book. First published in 1687, English translations and commentaries are still widely available in print [5]. Newton's theory worked perfectly well for over 200 years (and still does today in most applications) and succeeded in explaining the motions of objects both in Heaven (the planets, moons, comets, etc.) and on Earth (everything you see around you). However, toward the end of the nineteenth century, a certain mystery was discovered concerning the speed of light which could not be understood within the Galilei–Newton theory. The theory that provided a clear and illuminating resolution to the mystery, and became the theory to supersede that of Galilei–Newton, was Einstein's Special Theory of Relativity.

In this book, we will look at what that mystery was, why the Galilei–Newton theory was in trouble, how Einstein solved the mystery, and what the consequences of Einstein's discovery were. But before we can do that, we need to learn the basics of the study of motion.



Notes

1 "Zur Elektrodynamik bewegter Körper" in the original German. The German word "Körper" shares the same etymology as the English "corpse." They both come from the Latin word "corpus," which means "body." For an English translation of the paper, see [4].
2 Note that the word "bodies" here does not refer to human bodies, but to objects in general. So the expression "moving bodies" should be interpreted simply as "moving objects."
3 The letter c has been traditionally used as the symbol for the speed of light in vacuum because it is the first letter in *celeritas*, which is the Latin word for speed.
4 Galileo's discoveries concerning motion are described in his book *Dialogues Concerning Two Sciences*, the English translation of which can also be found in [4].
5 In English, the title translates to *Mathematical Principles of Natural Philosophy*. Both the title and content were in Latin.
6 The "c" in "Principia" is hard and should be pronounced like a "k."

2
Basics

2.1 Questions about motion

When studying the motion of an object, the most basic questions we would like to ask are things like:

Q1: Is it moving or is it at rest (not moving)?
Q2: If it is moving, what is its direction of motion?
Q3: What is its speed in that direction?

In order to answer these questions, we need to know the object's *location in space* at each *instant in time*, so that we can keep track of how it is changing as *time* progresses. If we find that the object's location in space is not changing with time, that is, if it stays *at the same place*, then we can say that it is "at rest," while otherwise we can say that it is "moving." If the object is "moving," we can specify its direction of motion by saying things like "it is moving to the left" or "it is moving to the right," and we can figure out its speed by determining by how much its location in space is changing per unit time.

Once we have these basic questions under control, we can then start to ask more advanced questions like:

Q4: Is the direction of motion changing with time?
Q5: Is the speed changing with time?
Q6: If they are changing, what is causing it?

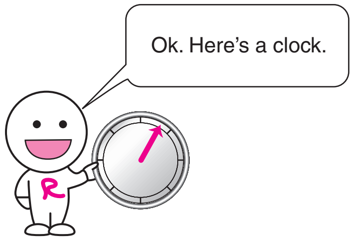
and so on. Questions 2 and 3, and questions 4 and 5, are often combined into the questions

Q2+Q3: If it is moving, what is its *velocity*?
Q4+Q5: Is the *velocity* changing with time?

The term *velocity* means something like "speed and/or direction of motion." When we say "the *velocities* are the same" we mean that both the speeds and the directions of motion are the same. When we say "the *velocities* are different" we mean that either the speeds or the directions of motion, or both, are different.

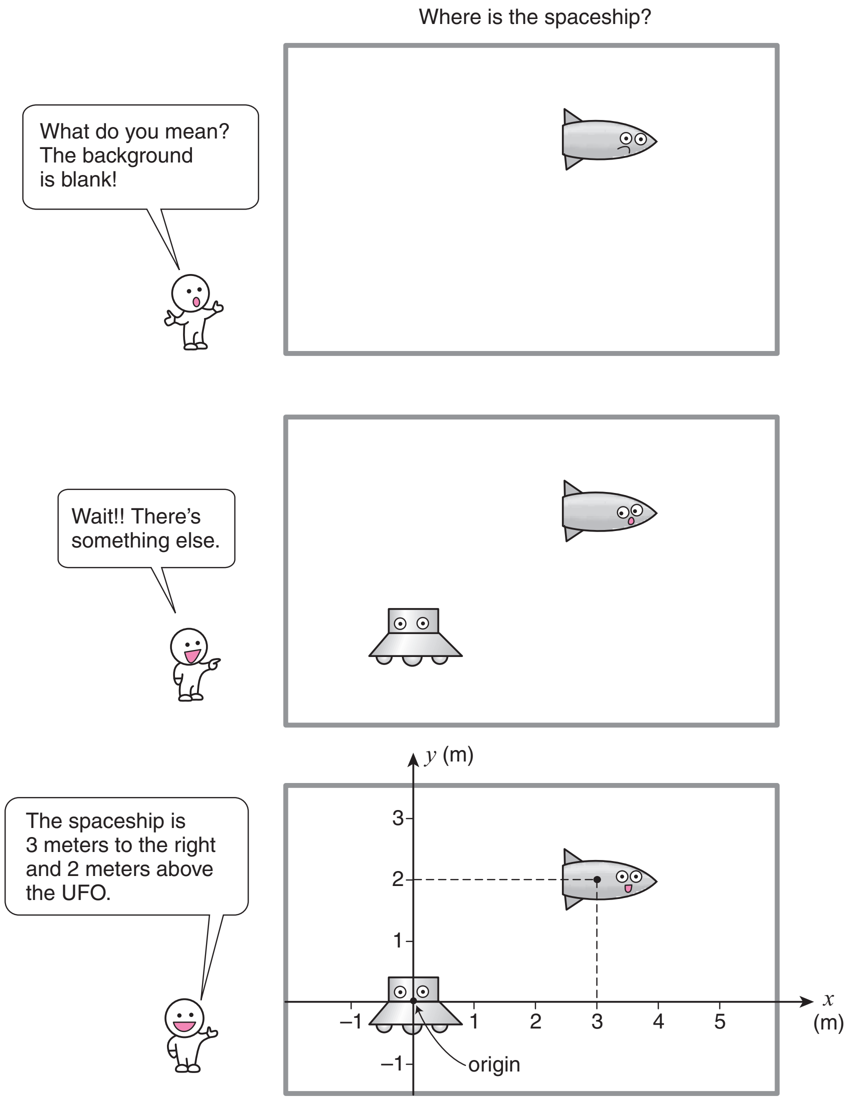
2.2 Frames of reference

Now, what are the tools we need to actually keep track of how an object's *location in space* is changing with *time*? First, and foremost, we obviously need a *clock* to keep track of the *time*. The reading of the clock will give us a number t, which labels each *instant in time*. If we are using SI units,[1] t will be given in seconds. We will be using a different unit later on.



Next, we need to specify the object's *location in space* at each *instant in time*. But the only way to do this is to specify it *relative* to something else. To see this, imagine a spaceship traveling in an empty universe which is devoid of anything else but the spaceship. I am sure you would agree that it would be impossible to state *where* the spaceship is. In fact, the concept of *location* itself does not make much sense in that situation. It is only when there are stars or planets or some other object, like another spaceship, present in the universe that we can specify the location of the spaceship *relative* to the other object.

To be more specific, what we need is *a reference point* fixed to some object to define our positions from. Once we have chosen such a reference point, which we will call the *origin*, we can specify the location of the object by saying, for instance, that the object is x meters to the east, y meters to the north, and z meters up from the origin. In other words, we can attach a set of numbers (x, y, z) as a label to each point in space. Of course, we need a ruler to measure these distances, and we also need to specify (or be able to specify) what we mean by east–west, north–south, and up–down.


Where is the spaceship?
What do you mean? The background is blank!
Wait!! There's something else.
The spaceship is 3 meters to the right and 2 meters above the UFO.
y (m)
3
2
1
–1
–1
1
2
3
4
5
x (m)
origin

As an example, consider the motion of a car moving along a straight horizontal road as shown in the figure. To specify the position of the car, we can use its distance from some fixed object along the road, say a tree, and say, for instance, that "the car is 5 meters to the right of the tree," or "the car is 3 meters to the left of the tree." To simplify things, we can assign positive numbers to the distance from the tree when the car is to the right of the tree, and negative numbers to the distance when the car is to the left of the tree and say "the car is at $x = +5$ meters" instead of "the car is 5 meters to the right of the tree," and "the car is at $x = -3$ meters" instead of "the car is 3 meters to the left of the tree." This frees us from the need to specify "left" or "right." This procedure allows us to assign a number x (in meters) to the position of the car. The tree, in this case, is the *origin*.

When we have a clock to specify the time, and the origin and the directions in which to measure the distance from the origin set up, we say that we have a *frame of reference*, or simply a *frame*. A *frame of reference* allows us to specify any point in *space* and *time* with a set of numbers. In the *frame* fixed to the tree, it is the reading of the clock t and the distance from the tree x.

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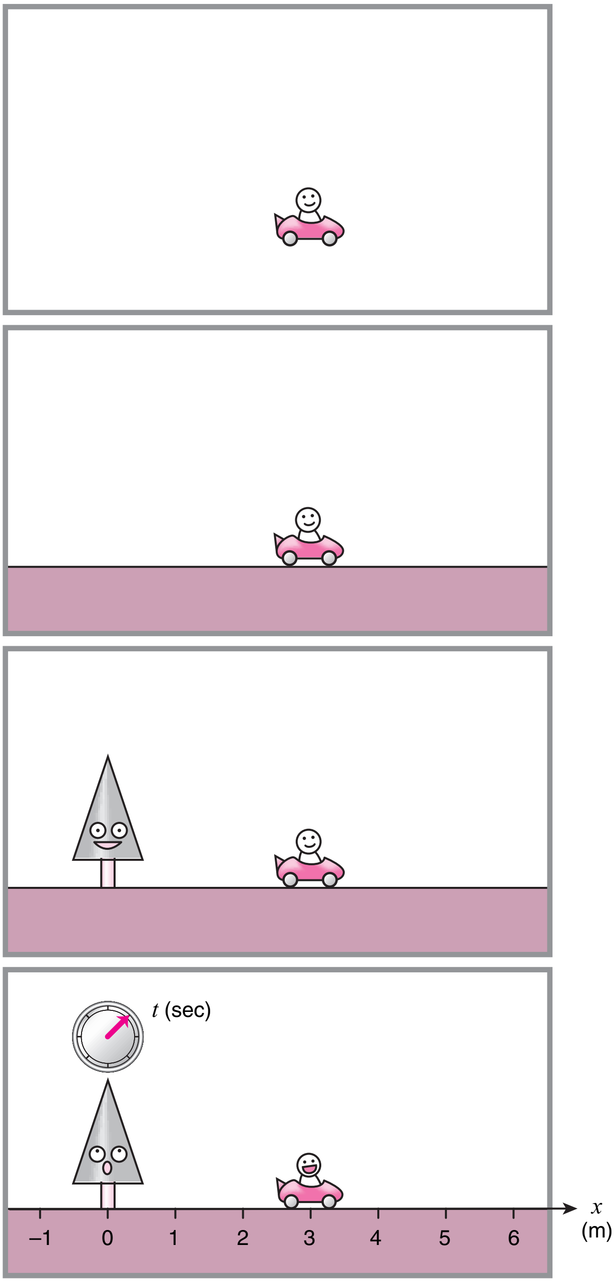
A car...

on a straight
horizontal road...

with a tree...

The tree-frame!



Actually, even in the lone-spaceship-in-the-universe case, there is an *origin* we can use to set up a *frame of reference* since the universe must contain in it, in addition to the spaceship, the clock we use to specify the time (with ourselves to read it, for that matter). It could be that the clock is fixed to the spaceship, in which case we have a *frame* in which the spaceship's position does not change at all with time. It's a boring choice of *frame*, but a *frame* nevertheless.

In effect, the choice of *origin* is equivalent to choosing which object we are going to consider to be at rest, that is "not moving," in that frame. Anything that maintains a constant distance and direction from the origin is also at rest. In other words, the choice of *origin* defines what we mean for an object to be *at the same place*.

Since a clock is always necessary to specify the time, the clock itself is the logical choice for the origin in any frame. We will assume throughout the rest of the book, without comment, and even if the clock is not drawn explicitly in my drawings, that the clock is always fixed at the origin, that is, the clock is always at rest in its frame. In the tree-frame we discussed above to describe the motion of the car, the clock is assumed to be fixed to the tree. If we fix the clock to the car instead, it will move with the car. In that case, we will specify the location of objects relative to the car, and we will have a different *frame of reference* from the tree-frame, which we will call the car-frame.