9.1: The Principles of Special Relativity

Learning Objectives

- You will know that the speed of light is the same for all observers.
- You will know that the laws of physics are the same for all observers in reference frames moving at constant velocity with respect to each other.

What Do You Think: Properties of Light

We have already seen how several unexplained experimental results led to the revolutionary ideas of quantum physics at the end of the 19th century, overturning longstanding notions about matter and energy. At around the same time, an apparent logical inconsistency in the theory of electromagnetism spurred a similar overturning of our notions about space and time. The classical theory of electricity and magnetism led to this revolution. The theory predicts the existence of waves of electromagnetic fields—electromagnetic waves. The waves themselves are not the problem, their speed is.

In the classical theory of electricity and magnetism, the speed of electromagnetic waves (i.e., the speed of light) is the product of two physical constants. One of the constants relates to the strength of electric fields; think static electricity. The other relates to the strength of magnetic fields, like the ones that stick magnets to a refrigerator door. These constants do not relate to the state of motion of either the source of the waves or to the motion of someone observing them; they are constants. So both moving and stationary observers should measure them to have the same value. And clearly, physical constants should not change if the source of electromagnetic waves, a light bulb, say, is moving fast, slow or not at all. This implies that all electromagnetic waves have the same speed, regardless of the state of motion of their source or of a person or device measuring the waves. This prediction relates to waves traveling through a vacuum. When the waves travel through a material, their interaction with that material can cause them to slow down in ways the depend in detail on the material and the frequency of the waves in question.

The constancy of the speed of electromagnetic waves (in vacuum), regardless of the motion of the source or the observer of the waves, is extremely unusual. This property is different from the way most things move. Some examples regarding the relative velocities of objects for different observers might help to clarify what we mean.

First, imagine you are standing on the side of a railroad track. You observe a train moving past, and a woman standing on the train throwing a ball in the direction of motion of the train. The woman measures a certain speed of the ball *relative to herself*. You will measure a different speed, *relative to yourself*. You must add the velocity of the train to whatever velocity the woman measures for the ball in order to get the speed you measure.

As another example, imagine you measure the speed of a horse galloping alongside a moving train. You will measure a different speed for the horse depending on whether you are riding on the train or standing beside the tracks. In particular, if the horse moves along the ground at the same speed that the train moves along the ground, and in the same direction, then someone on the train does not perceive that the horse is moving at all. The horse has zero velocity for such an observer.

Again, keep in mind that we are only talking about relative speeds here, not speeds along the ground. You are probably used to measuring all speeds relative to the ground, but this is done for convenience, so that everyone has a common reference point. But there is nothing special about the ground, so you can just as well measure all speeds relative to yourself or any other reference.

According to the theory of electromagnetism, electromagnetic waves do not share the property described above with horses and balls. If the ball or the horse were forms of light, both the observers on the ground and on the train would measure the same speed for them: 300,000 km/s. Strange.

Of course, it is possible that the theory of electromagnetism is not an adequate explanation of nature. Perhaps the form of the equations describing electromagnetic fields depends on the state of motion of the observer or the source of the fields. In that case, the equations might be modified depending on whether the source or observer of the waves is moving or stationary. Any such modification might predict that the speed of waves is different for different observers. However, no other laws governing physics require such modification, and physicists tend to think that laws that predict how nature behaves should be the same whether one is riding along in an automobile or sitting on the side of the road.

In the 1890s, a teenage Albert Einstein imagined what it might be like to move as fast as a light wave. He understood that the laws of electricity and magnetism predicted waves, and he also understood that if you could move along with a light wave, just as fast as the light itself, then the wave would seem to freeze. It would no longer oscillate, but would remain stationary. The electric fields might make a vertical sine wave, sort of like an artistically sculpted picket fence. The magnetic field would then make a horizontal sine wave, in phase with the electric field but rotated by 90 degrees from it. This configuration of the fields is shown in Figure 9.1. The motion of the wave is aligned with the spine of the wave, perpendicular to both the electric and magnetic fields.

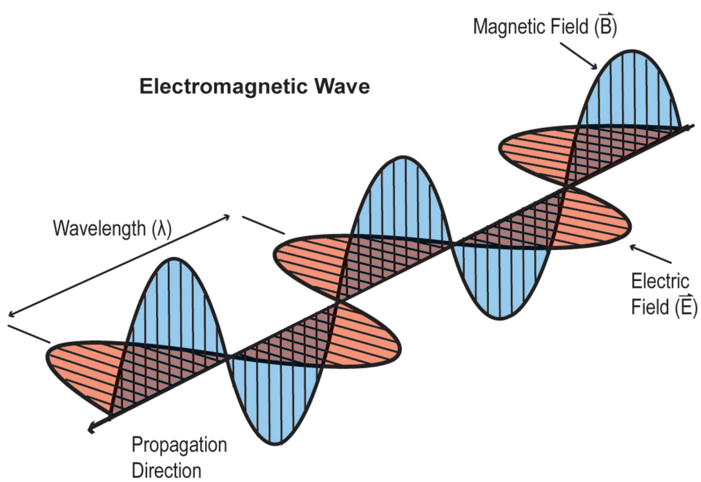

Figure 9.1: A frozen electromagnetic wave as seen by an observer moving along with the wave at the speed of light. Credit: NASA/SSU/Aurore Simonnet

Such a wave is not a wave at all, because it does not oscillate in time. Einstein knew that this idea was inconsistent with electromagnetic theory, and so he assumed that the situation he imagined was impossible. He also assumed that the laws of physics must be the same for all observers, regardless of their state of motion. He elevated the second of these two assumptions to a physical principle, called the *principle of special relativity*. Then he set about the task of seeing where they led. His work on this topic was published in 1905.

The relativity principle is often stated in the form of two separate postulates. Here they are in succinct form:

1. The laws of physics are the same for all observers who move at constant speed and in a constant direction, without any acceleration.
2. The speed of light is constant, regardless of the state of motion of the source or the observer.

The second of these postulates is actually contained within the first (because the laws of electromagnetism predict a constant speed of light), but we state it explicitly for clarity, just as Einstein did in his 1905 paper. The observers who move at constant speed and in a constant direction are often called inertial observers.

To date, all of the electromagnetic waves we have observed in a vacuum travel at this same speed, lending evidence to this idea. The prediction of classical electromagnetism is borne out.

For the rest of this chapter, we will explore some of the interesting consequences of the relativity principle. Again, Einstein simply assumed that it must be true, since to assume otherwise led to predictions that are at odds with experimental results. His resulting theory, The Special Theory of Relativity, though inconsistent with our common-sense notions of the world, has been shown to be entirely consistent with all experimental tests thus far - with one exception, that of certain quantum entangled states. Though these states are a fascinating aspect of the interplay of relativity and quantum mechanics, they are too far afield of our topic to explore here.
