9.7: Faster Than Light?

Learning Objectives

- You will understand the fundamental reasons why particles cannot travel faster than the speed of light.

What Do You Think: Traveling Faster Than Light?

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The discussion in Section 9.6 has, we hope, helped you to understand why no particles can be accelerated from our frame of reference to a speed equal to (or in excess of) the speed of light: Sufficient energy is not available to move any material particles to such a speed. However, other even more fundamental reasons explain why particles cannot exceed the speed of light. We will perform another thought-experiment to understand why this is so.

We are familiar with the idea of causality in our daily world. This is just the notion that some events are the causes of other events. For instance, you flip on a light switch and then the light begins to stream from the bulb; you push a button on your iPod, and the music begins playing; a glass of milk slips from your hand, and then it falls to the floor and shatters. Conversely, we never see milk collect itself from a puddle on the floor and arrange itself into a glass, as the glass itself spontaneously assembles from scattered shards.

These sorts of events never happen in the reverse order. There is nothing in the laws of physics, not the ones we have discussed so far, that would prevent these "backwards" events from happening. Yet, they never do. To reverse the order of causally connected events is easily seen to be completely absurd. With that in mind, we will examine the causal relationships between two events as observed in two different reference frames in uniform motion.

Causal Relationships

Imagine the following thought-experiment: We flip a switch, and a signal is conveyed to a bulb at a speed 5/3 the speed of light—nearly 70% faster than light could transmit the signal. We will compare this situation with signals moving at the speed of light and slower than the speed of light.

Play Activity

1. To begin, use the *Spacetime Diagram Tool* to plot several events.

- It will be easier to understand this example if the first event (call it A), flipping on the switch, occurs at the origin.
- Now plot an event, assuming that the signal from the switch travels to the bulb at 3/5 the speed of light. This signal can travel 3 light-seconds of distance in 5 seconds, so an event at $x = 9$, $t = 15$ can represent this case. Call this Event B.
- Next, plot an event to represent the case where the signal travels at the speed of light. The signal will travel 3 units of space in 3 units of time, so an event at $x = 9$, $t = 9$ can represent it. Call this Event C.
- The final event to plot should occur at a point with $x = 15$ and $t = 9$; at the speed $v = 5/3c$, the signal would travel 15 light-seconds of distance in 9 seconds of time. This is farther than light could travel in the same amount of time. We will call this Event D.

For an observer at rest, Event B occurs 15 seconds after the switch is flipped. The other two events occur only 9 seconds after. But, what about for a moving observer? Imagine that an observer comes flying past, moving in the x-direction, and passes you just as you flip the switch. Then Event A will also occur at the origin for the moving observer, and so the switch is flipped at t' = 0. We can explore when the other events occur.

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In the last activity, you should have noticed that if you increase the speed of the observer enough, you can make the flip of the switch and the lighting up of the bulb simultaneous. A real light switch seems simultaneous to us because the delay is so short. But, in the case we are studying, the two events actually occur at exactly the same time. If you keep going even faster, you seem to be able to make the light turn on before the switch is flipped!

Another example might be even more instructive. Imagine that, rather than turning on a light, our switch connects to a valve for a container of air (Figure 9.19). Imagine also that the valve separates this container from a second container that is completely empty. In the rest frame of the containers, opening the valve will allow the air in the first container to flow into the empty container. Afterward, there will be air in both containers. (For dramatic effect, you can imagine that someone's life depends on getting the air into the second container.)

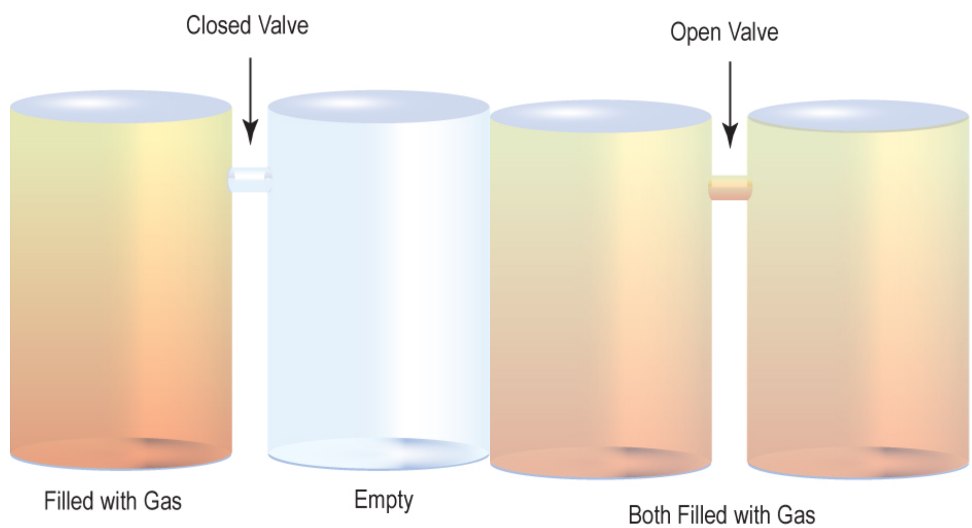

Figure 9.19: (a) One container is full of air and the other is empty. The containers are separated by a valve, which is closed to begin with. (b) After the valve is opened, air flows from the full container to the empty one until they contain the same amount of air. This process increases the entropy of the air, and so is extremely unlikely to spontaneously reverse. Credit: NASA/SSU/Aurore Simonnet

If this scenario played out as with the light bulb above, with the signal traveling from the switch to the valve at $5/3c$, then we could witness the following strange sequence of events: In a moving frame of reference, the air at first would be occupying both containers. At some point the air would spontaneously empty from one container into the other. After that, the valve separating the containers would close, leaving one container empty and the other one full.

We know from experience that this scenario is completely absurd. It is like watching a movie backward; it does not make sense. We never see the air in a room spontaneously flow into a tiny volume up in one corner. This tendency of gases or liquids to expand and occupy more volume, cover more of the floor, etc., rather than contract into a tiny volume is part of a more general trend in nature, the increase of disorder or more technically, the increase of entropy. In fact, so basic is this tendency that it has its own law, called the Second Law of Thermodynamics. This law states that the total entropy for any process must always increase. To learn more, read Going Further 9.4: Entropy, Disorder, and the Second Law of Thermodynamics.

So, the reason that objects or signals cannot travel faster than light is not strictly the result of special relativity. It is special relativity (the speed of light is constant in all frames of reference in uniform motion) along with the second law of thermodynamics (the total entropy must increase for any process). Sending signals faster than the speed of light would force us to abandon at least one of these basic principles. Since they are so well grounded in experimental results, it is much simpler to assume that no signals can travel faster than light. The fact that none has ever been seen to do so suggests that this is the correct choice, but like all things in science, it is subject to modification if contradictory information becomes available.

Going Further 9.4 Entropy, Disorder, and the Second Law of Thermodynamics

Understanding why entropy must always increase is not too difficult. There are many more ways to arrange items so that they are in disarray than there are to arrange them in a nice orderly way. So, given free reign, things tend to get disorderly. As an example, consider a deck of cards.

It is possible to arrange a deck of cards so that all the suits are together and the cards are all in order, from ace to king. But, the number of ways to do so is pretty small. We could arrange them such that the spades were on top, followed by the hearts, then the clubs, and then the diamonds. Or, we could start with the clubs, then have the diamonds, clubs, and spades, and so on. Since this system is so simple, it is not difficult to calculate how many ways we can arrange the deck such that all the suits are collected together and the cards are ordered. We have four suits, so there are four choices for the suit we want to use first. For each of those choices, there are three remaining choices of which suit to place second. So, that is $4 \times 3 = 12$ choices of which suits to put in first and second place. For each of those choices, we have two remaining choices for the third position because there are only two suits left to be placed, so we have $4 \times 3 \times 2 = 24$ possibilities for the placement of the first three suits.

The final suit does not give us any more choices. We have already placed three of the four suits, so only one remains. Thus, the total number of possible ways we can stack a deck of cards such that all the suits are collected and the individual suits are ordered from ace to king is $4 \times 3 \times 2 \times 1 = 24$.

You can come up with other ways to order the cards, perhaps collecting all the aces together, and all the twos, threes, etc. You could go through a calculation similar to the one above to figure out how many ways the cards can be collected that way. Do you think you would have more ways, or fewer? If you like to play poker, then you might already be familiar with these sorts of calculations.

But, what if you want to arrange the cards in no particular order at all? How many ways are there to do that? Well, for the first card, we can choose any of the 52 in the deck (we are ignoring the jokers). For the second, we have one less, so there are 51 possibilities from which to choose. So, for the first two cards, we have $52 \times 51 = 2652$. We already have many more ways to place the first two cards than we had to place all four suits in the first example. How many choices do we have for placing a third card? Fifty, because that is how many cards are left to place. You can probably see the pattern here. To place all the cards, we will have a number of possibilities given by $52 \times 51 \times 50 \times 49 \times 48 \times \ldots \times 5 \times 4 \times 3 \times 2 \times 1$. We simply take one off the previous number of possibilities and multiply by that, repeating this pattern until we get down to one. Such a pattern, as you might already know, has a name. It is called the factorial function. We could shorten our calculation for the cards by saying that the number of ways of arranging the 52 cards in the deck is 52!, where the exclamation point means to take the factorial of 52. This is a huge number. It is almost 10^{68}.

Now imagine that instead of placing cards from a deck of cards, we are placing gas molecules in a box. Each has a position and a velocity. We can choose the x, y, and z components of the position and the x, y, and z components of the velocity independently. How many different ways are there to do that if the box contains a mole (6.02×20^{23}) of atoms? We will not compute it, but you probably see that the number is enormous, much larger than the ways we can place 52 cards.

As an example, we could imaging placing the molecules at random locations, with each of them moving in a random direction and with a speed taken from some random distribution of speeds. This would be a very disordered arrangement of molecules. How many ways are there to do that, do you imagine?

On the other hand, we could arrange the particles to be located on a regular grid, all with equal spacing between them. We could arrange for them to all move in the same direction and all have exactly the same speed. This would be a highly ordered arrangement. How many ways would there be to create a situation like this? It is still a lot given the large numbers or particles we are dealing with, but it is a much smaller number of possibilities than the previous case.

The analysis for molecules has to be slightly modified because, unlike cards in a deck, molecules are identical: every oxygen molecule is like every other oxygen molecule, every nitrogen is like every other nitrogen, and so on for carbon dioxide, etc. We have to take this notion into account, but it does not change the basic analysis. There are vastly more ways to arrange things such that they are disordered rather than ordered.

The second law of thermodynamics makes a very strong statement about this idea, saying that any change in the Universe always increases the total entropy of the Universe - the total amount of "disorderliness." Of course, physicists have a very precise mathematical expression to define what is meant by entropy, but we do not have to consider the details to that level. We should mention that an overall increase in “disorder” or “disarray” in the universe does not prohibit the growth of locally complex and orderly structures. It just means that the local increase in order is made up for, and then some, by disorder someplace else.