

STOP TO THINK 37.4

A tree and a pole are 3000 m apart. Each is suddenly hit by a bolt of lightning. Mark, who is standing at rest midway between the two, sees the two lightning bolts at the same instant of time. Nancy is at rest under the tree. Define event 1 to be “lightning strikes tree” and event 2 to be “lightning strikes pole.” For Nancy, does event 1 occur before, after, or at the same time as event 2?

37.5 The Relativity of Simultaneity

We’ve now established a means for measuring the time of an event in a reference frame, so let’s begin to investigate the nature of time. The following “thought experiment” is very similar to one suggested by Einstein.

FIGURE 37.16 shows a long railroad car traveling to the right with a velocity v that may be an appreciable fraction of the speed of light. A firecracker is tied to each end of the car, right above the ground. Each firecracker is powerful enough so that, when it explodes, it will make a burn mark on the ground at the position of the explosion.

Ryan is standing on the ground, watching the railroad car go by. Peggy is standing in the exact center of the car with a special box at her feet. This box has two light detectors, one facing each way, and a signal light on top. The box works as follows:

1. If a flash of light is received at the right detector before a flash is received at the left detector, then the light on top of the box will turn green.
2. If a flash of light is received at the left detector before a flash is received at the right detector, or if two flashes arrive simultaneously, the light on top will turn red.

The firecrackers explode as the railroad car passes Ryan, and he sees the two light flashes from the explosions simultaneously. He then measures the distances to the two burn marks and finds that he was standing exactly halfway between the marks. Because light travels equal distances in equal times, Ryan concludes that the two explosions were simultaneous in his reference frame, the reference frame of the ground. Further, because he was midway between the two ends of the car, he was directly opposite Peggy when the explosions occurred.

FIGURE 37.17a shows the sequence of events in Ryan’s reference frame. Light travels at speed c in all inertial reference frames, so, although the firecrackers were moving, the light waves are spheres centered on the burn marks. Ryan determines that the light wave coming from the right reaches Peggy and the box before the light wave coming from the left. Thus, according to Ryan, the signal light on top of the box turns green.

How do things look in Peggy’s reference frame, a reference frame moving to the right at velocity v relative to the ground? As **FIGURE 37.17b** shows, Peggy sees Ryan moving to the left with speed v . Light travels at speed c in all inertial reference frames, so the light waves are spheres centered on the ends of the car. If the explosions are simultaneous, as Ryan has determined, the two light waves reach her and the box simultaneously. Thus, according to Peggy, the signal light on top of the box turns red!

Now the light on top must be either green or red. *It can’t be both!* Later, after the railroad car has stopped, Ryan and Peggy can place the box in front of them. Either it has a red light or a green light. Ryan can’t see one color while Peggy sees the other. Hence we have a paradox. It’s impossible for Peggy and Ryan both to be right. But who is wrong, and why?

What do we know with absolute certainty?

1. Ryan detected the flashes simultaneously.
2. Ryan was halfway between the firecrackers when they exploded.
3. The light from the two explosions traveled toward Ryan at equal speeds.

The conclusion that the explosions were simultaneous in Ryan’s reference frame is unassailable. The light is green.

FIGURE 37.16 A railroad car traveling to the right with velocity v .

The firecrackers will make burn marks on the ground at the positions where they explode.

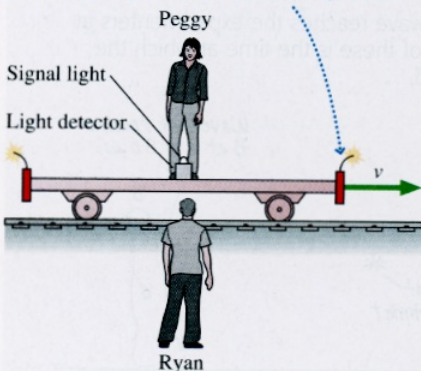
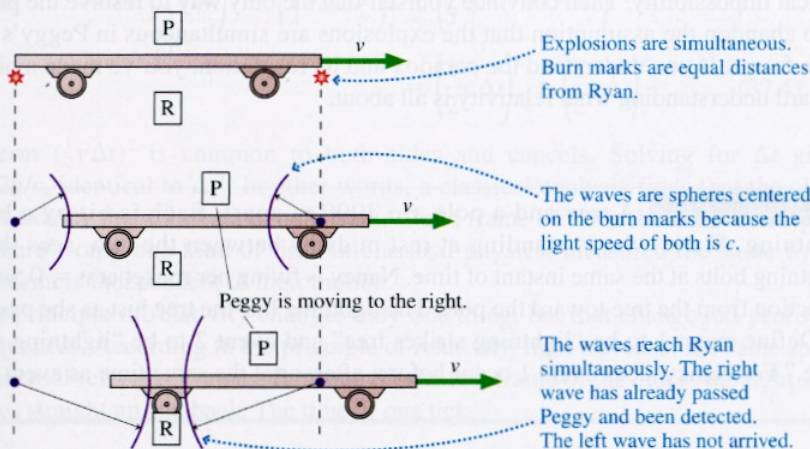
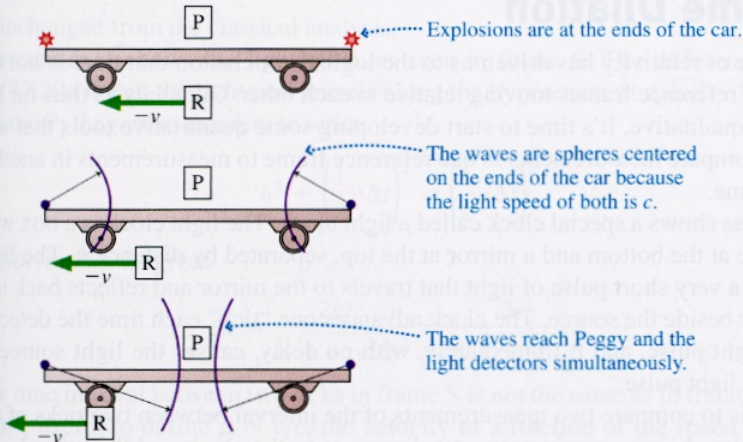


FIGURE 37.17 Exploding firecrackers seen in two different reference frames.

(a) The events in Ryan's frame



(b) The events in Peggy's frame



Peggy, however, made an assumption. It's a perfectly ordinary assumption, one that seems sufficiently obvious that you probably didn't notice, but an assumption nonetheless. Peggy assumed that the explosions were simultaneous.

Didn't Ryan find them to be simultaneous? Indeed, he did. Suppose we call Ryan's reference frame S , the explosion on the right event R , and the explosion on the left event L . Ryan found that $t_R = t_L$. But Peggy has to use a different set of clocks, the clocks in her reference frame S' , to measure the times t'_R and t'_L at which the explosions occurred. The fact that $t_R = t_L$ in frame S does *not* allow us to conclude that $t'_R = t'_L$ in frame S' .

In fact, in frame S' the right firecracker must explode *before* the left firecracker. Figure 37.17b, with its assumption about simultaneity, was incorrect. FIGURE 37.18 shows the situation in Peggy's reference frame, with the right firecracker exploding first. Now the wave from the right reaches Peggy and the box first, as Ryan had concluded, and the light on top turns green.

One of the most disconcerting conclusions of relativity is that **two events occurring simultaneously in reference frame S are *not* simultaneous in any reference frame S' moving relative to S .** This is called the **relativity of simultaneity**.

The two firecrackers *really* explode at the same instant of time in Ryan's reference frame. And the right firecracker *really* explodes first in Peggy's reference frame. It's not a matter of when they see the flashes. Our conclusion refers to the times at which the explosions actually occur.

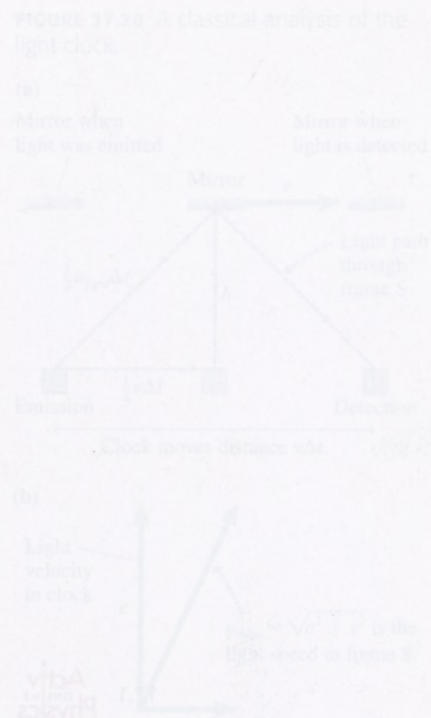
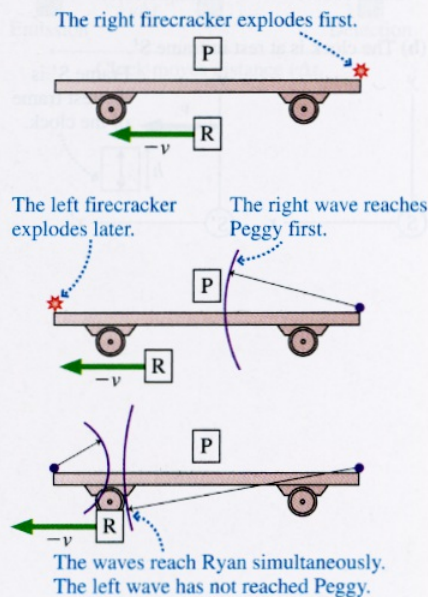


FIGURE 37.18 The real sequence of events in Peggy's reference frame.



The paradox of Peggy and Ryan contains the essence of relativity, and it's worth careful thought. First, review the logic until you're certain that there *is* a paradox, a logical impossibility. Then convince yourself that the only way to resolve the paradox is to abandon the assumption that the explosions are simultaneous in Peggy's reference frame. If you understand the paradox and its resolution, you've made a big step toward understanding what relativity is all about.

STOP TO THINK 37.5 A tree and a pole are 3000 m apart. Each is hit by a bolt of lightning. Mark, who is standing at rest midway between the two, sees the two lightning bolts at the same instant of time. Nancy is flying her rocket at $v = 0.5c$ in the direction from the tree toward the pole. The lightning hits the tree just as she passes by it. Define event 1 to be “lightning strikes tree” and event 2 to be “lightning strikes pole.” For Nancy, does event 1 occur before, after, or at the same time as event 2?

37.6 Time Dilation

The principle of relativity has driven us to the logical conclusion that time is not the same for two reference frames moving relative to each other. Our analysis thus far has been mostly qualitative. It's time to start developing some quantitative tools that will allow us to compare measurements in one reference frame to measurements in another reference frame.

FIGURE 37.19a shows a special clock called a light clock. The light clock is a box with a light source at the bottom and a mirror at the top, separated by distance h . The light source emits a very short pulse of light that travels to the mirror and reflects back to a light detector beside the source. The clock advances one “tick” each time the detector receives a light pulse, and it immediately, with no delay, causes the light source to emit the next light pulse.

Our goal is to compare two measurements of the interval between two ticks of the clock: one taken by an experimenter standing next to the clock and the other by an experimenter moving with respect to the clock. To be specific, **FIGURE 37.19b** shows the clock at rest in reference frame S' . We call this the **rest frame** of the clock. Reference frame S' moves to the right with velocity v relative to reference frame S .

Relativity requires us to measure *events*, so let's define event 1 to be the emission of a light pulse and event 2 to be the detection of that light pulse. Experimenters in both reference frames are able to measure where and when these events occur *in their frame*. In frame S , the time interval $\Delta t = t_2 - t_1$ is one tick of the clock. Similarly, one tick in frame S' is $\Delta t' = t'_2 - t'_1$.

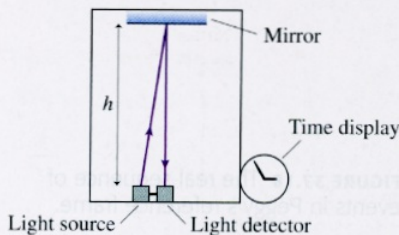
To be sure we have a clear understanding of the relativity result, let's first do a classical analysis. In frame S' , the clock's rest frame, the light travels straight up and down, a total distance $2h$, at speed c . The time interval is $\Delta t' = 2h/c$.

FIGURE 37.20a shows the operation of the light clock as seen in frame S . The clock is moving to the right at speed v in S , thus the mirror moves distance $\frac{1}{2}v(\Delta t)$ during the time $\frac{1}{2}(\Delta t)$ in which the light pulse moves from the source to the mirror. The distance traveled by the light during this interval is $\frac{1}{2}u_{\text{light}}(\Delta t)$, where u_{light} is the speed of light in frame S . You can see from the vector addition in **FIGURE 37.20b** that the speed of light in frame S' is $u_{\text{light}} = (c^2 + v^2)^{1/2}$. (Remember, this is a classical analysis in which the speed of light *does* depend on the motion of the reference frame relative to the light source.)

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FIGURE 37.19 The ticking of a light clock can be measured by experimenters in two different reference frames.

(a) A light clock



(b) The clock is at rest in frame S' .

