Answer to Essential Question 26.2: The spacetime diagram is drawn for your reference frame, so you remain at $x = 0$ at all times. Thus, your worldline is a straight line up the ct axis, as shown in Figure 26.8.

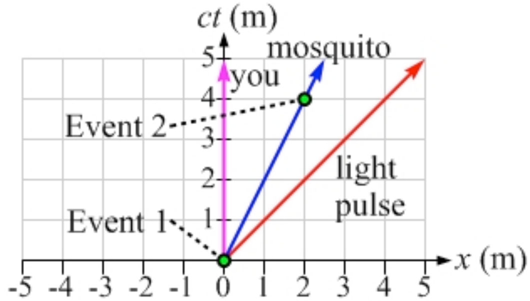

Figure 26.8: The spacetime diagram from Figure 26.7, updated to show your worldline.

26-3 Time Dilation – Moving Clocks Run Slowly

In Sections 26-1 and 26-2, we looked at situations in which time passes at different rates in different reference frames. This may be at odds with your own experience of time. However, we are not used to dealing with speeds that are significant fractions of the speed of light, so perhaps we should not be too surprised that time has such an interesting behavior when we compare reference frames that are moving at high speed with respect to one another.

The time-honored statement summarizing how time behaves is that "moving clocks run slowly." In this section, we will investigate how a clock that uses light pulses behaves when it is viewed from a moving reference frame. We will also discuss some of the experimental evidence supporting this behavior of time.

EXPLORATION 26.3 – A light clock

Figure 26.9 shows a light clock, which has a source (or emitter) of light pulses (at the bottom), a mirror at the top to reflect the light, and a detector at the bottom to record the pulses. The clock runs at a rate equal to the rate at which the pulses are received by the detector.

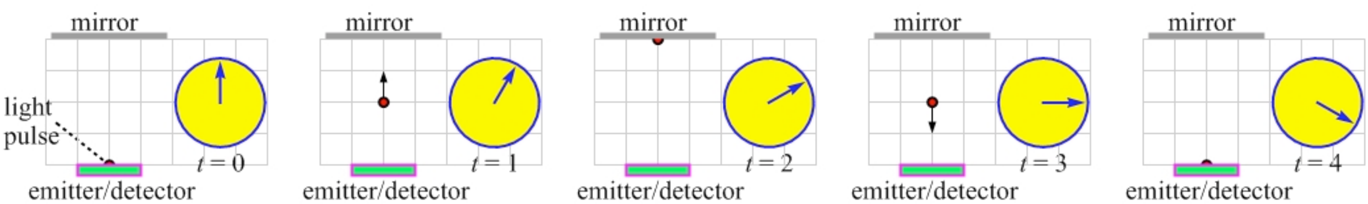

Figure 26.9: A clock that uses light pulses to measure the passage of time.

Step 1 – ***Let's say the clock above belongs to Jack. Relative to Jack, Jill moves to the right at a constant speed of 60% of the speed of light in vacuum. Jill's light clock is identical to Jack's. Sketch a diagram, similar to that in Figure 26.9, showing how the light pulses in Jill's clock travel from emitter to mirror to detector, according to Jack.*** According to Jack, Jill's clock is moving, so a light pulse in Jill's clock travels farther to reach the mirror after leaving the emitter than does a light pulse in Jack's clock. When Jack's clock reads 1 unit, Jill's clock is reading 0.8 units, according to Jack. This pattern continues, with Jill's clock continuing to show time passing by at 80% of the rate at which Jack's clock measures time passing, according to Jack.

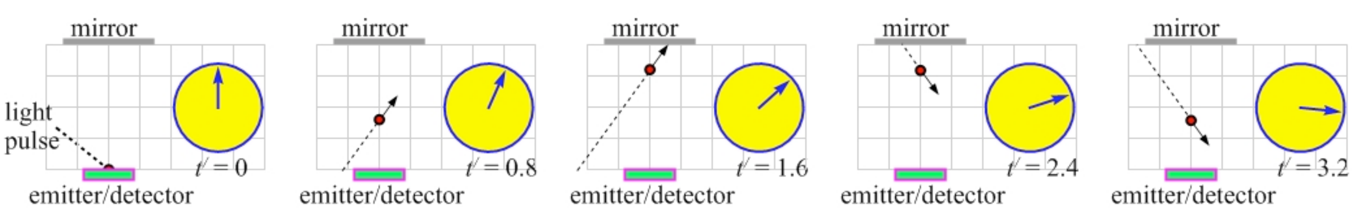

Figure 26.10: What Jill's light clock looks like, according to Jack. Compare this figure to Figure 26.9 to see what Jack sees on his clock and Jill's clock at the same instants.

Step 2 – *Sketch a diagram showing how the light pulses in Jack's clock travel from emitter to mirror to detector, according to Jill.* According to Jill, her clock is working fine (she sees her clock as in Figure 26.9), but Jack's clock is running slowly. All observers see light traveling at the speed of light, so Jill sees Jack's clock running slowly because the light pulses in Jack's clock, shown in Figure 26.11, travel farther to reach the mirror than do the pulses in Jill's clock.

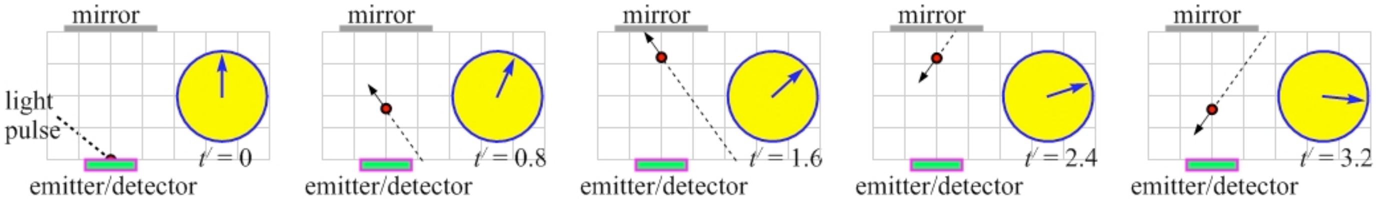

Figure 26.11: What Jack's light clock looks like, according to Jill. Compare this figure to Figure 26.9 to see what Jill sees on her clock and Jack's clock at the same instants.

Proper time and time dilation: An observer measures the proper time interval Δt_{proper} between two events when that observer is present at the location of both events. Observers for whom the events take place in different locations measure a longer time interval Δt between the events.

$$\Delta t = \frac{\Delta t_{proper}}{\sqrt{1 - \frac{v^2}{c^2}}} = \gamma \ \Delta t_{proper} ,$$ (Equation 26.2: **Time dilation**)

where v is the relative speed between the two reference frames.

Key ideas: The faster a clock moves with respect to an observer, the more slowly it ticks off time, according to that observer. All time-keeping devices, including beating hearts, act this way, not just the light clocks we explored here. **Related End-of-Chapter Exercises: 19 – 22, 34.**

Experimental evidence for time dilation

In 1941, Bruno Rossi and David Hall compared the rate at which muons (essentially heavy electrons) entering the Earth's atmosphere passed through their detectors when they were at the top of Mt. Washington in New Hampshire, at an altitude of 6300 feet. They also measured the rate at which muons passed through the detectors at sea level. For an observer at rest on the Earth, these muons take 6.4 μs to cover 6300 feet, considerably longer than the 2.2 μs average lifetime of muons created in the laboratory. Thus, one would expect almost all the muons to decay before reaching sea level. Rossi and Hall's measurements showed that significantly more muons reached sea level than would be expected. This can be explained by time dilation. According to an Earth-based observer, time passes more slowly for these muons, which travel at over 99% of the speed of light. When 6.4 μs has elapsed for us, we observe clocks in the muons' frame of reference to be running more slowly, explaining why they last longer than we expect.

Another experiment was carried out in 1971 by J. C. Hafele and R. E. Keating. They flew four atomic clocks eastward around the world, and then flew the clocks westward around the world. After each trip, the clocks were compared to an identical clock that remained at the United States Naval Observatory. Both the effects of general and special relativity were important in this experiment, but the observed results (a loss of 59 ± 10 ns for the eastward trip, and a gain of 273 ± 7 ns for the westward trip) were in agreement with the predictions of relativity.

Essential Question 26.3: Return to Exploration 26.3. Who is aging more slowly, Jack or Jill?