End-of-Chapter Exercises

Exercises 1 – 8 are primarily conceptual questions designed to see whether you understand the main concepts of the chapter.

1. Return to the Jack and Jill situation in Exploration 26.1. Let's now add a third observer, Martin, who, according to Jack, is traveling in the same direction as Jill but at a different speed. From Martin's point of view, the charges in Jack's reference frame move apart at the same rate that the charges in Jill's reference frame move apart. Explain qualitatively how this is possible.

2. If magnetism is a relativistic phenomenon, then we should be able to explain effects that we previously attributed to magnetic interactions without resorting to magnetism. An example is the situation shown in Figure 26.15, in which an object with a negative charge has an initial velocity v directed parallel to a long straight wire. The current in the long straight wire is directed to the left. (a) First, use the principles of physics we discussed in Chapter 19 to explain how to determine the direction of the force exerted by the wire on the moving charge, and state the direction of that force. (b) Now, we'll work through the process without magnetism. Imagine that the current in the wire is associated with electrons flowing to the right with the same speed, v, that the charged object has. The wire, when no current flows, has an equal amount of positive and negative charge. We can imagine the positive charges to be at rest in the original frame of reference, shown in Figure 26.15(b). If we look at the situation from the point of view of the charged object, however, which charges in the wire are moving, the positive charges or the negative charges? (c) From the frame of reference of the charged object, will the distance between the electrons in the wire be length-contracted? What about the distance between the positive charges in the wire? (d) Again from the frame of reference of the charged object, will the wire appear to be electrically neutral, or will it have a net positive or net negative charge? (e) Looking at the electric interactions only, will the wire exert a net force on the charged object? If so, in what direction is it, and is this direction consistent with the answer to part (a)?

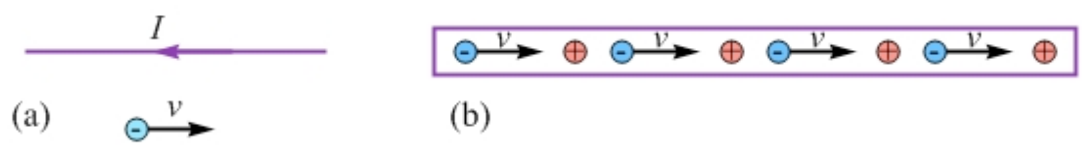

Figure 26.15: (a) A negatively charged object near a long straight current-carrying wire, and (b) a close-up of the wire showing the moving electrons and stationary positive charges making up the wire, for Exercise 2.

3. According to Michael, two events take place at the same location, but are separated in time by 5 minutes. Jenna is moving at a reasonable fraction of the speed of light with respect to Michael. According to Jenna, (a) do the events take place at the same location, and (b) is the time interval between them longer than, equal to, or shorter than 5 minutes?

4. When you and your rocket are at rest on the Earth, you measure the length of your rocket to be 60 m. When you and your rocket are traveling at 80% of the speed of light with respect to the Earth, how long do you measure your rocket to be?

5. Consider events A and B on the spacetime diagram shown in Figure 26.16. Do the events occur at the same time, or at the same location, for any of the four observers? Explain.

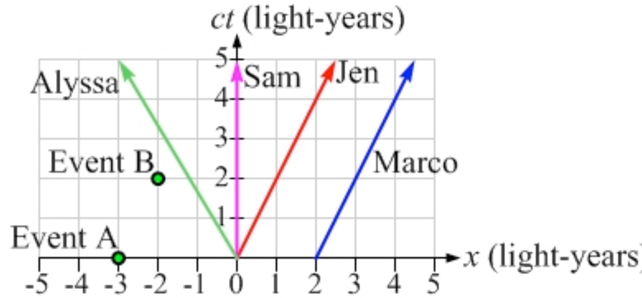

Figure 26.16: This spacetime diagram shows worldlines for four observers, whose motion is confined to the *x*-axis, as well as the spacetime coordinates of two events, in Sam's frame of reference. For Exercise 5.

6. You are on a train that is traveling at 70% of the speed of light relative to the ground. Your friend is at rest on the ground, a safe distance from the track, watching the train go past. Which of you measures the proper length for the following? (a) The length of the train. (b) The distance between the two rails the train is riding on. (c) The distance between the two cities the train is traveling between.

7. Return to the Earth, Zorg, you and Isabelle situation from Exploration 26-4, and the spacetime diagram for this situation that was drawn for it, from your frame of reference, in Figure 26.14. Now sketch the spacetime diagram for this situation from Isabelle's frame of reference.

8. One way that observers in the same reference frame can synchronize their clocks is to use a light pulse. For instance, you and your friend, who is located some distance from you, might agree to both set your clocks to read zero when you each observe a light pulse that is emitted from a source exactly halfway between you and which spreads out uniformly in all directions. Comment on this possible alternate method of clock synchronization. Your friend can bring his clock to where you are, you can synchronize them, and then your friend can carry his clock back to his original location. What, if anything, is wrong with that method?

Exercises 9 – 13 involve the spacetime interval.

9. According to you, two events take place at the same location, with a time interval of 60 meters of time between them. According to a second observer, the time interval between the events is 75 meters of time. (a) How many nanoseconds does 60 meters of time represent? (b) What is the distance between the locations of the two events, according to the second observer?

10. Four observers watch the same two events. The time interval and spatial separation between the events, according to each of the observers, is shown in Table 26.1. Fill in the blanks in the table.

Table 26.1: The time interval and spatial separation between the same two events, according to four different observers, for Exercise 10.

Observer	Time interval	Spatial separation
Anna		7.0 m
Bob		14.0 m
Caroline	35.7 meters of time	21.0 m
Dewayne	50.0 meters of time	

11. According to you, two events take place simultaneously at locations that are 100 m apart. According to a second observer, the spatial separation between the locations of the events is 150 m. What is the time interval between the events, according to the second observer?

12. According to you, two events take place 100 ns apart with a spatial separation between them of 18 m. (a) What is the spacetime interval for the two events? (b) For a second observer, the two events occur at the same location. What is the time interval between them, in nanoseconds, according to the second observer?

13. The spacetime diagram in Figure 26.17 shows three events. Determine the spacetime interval between (a) Event 1 and Event 2, (b) Event 1 and Event 3, and (c) Event 2 and Event 3.

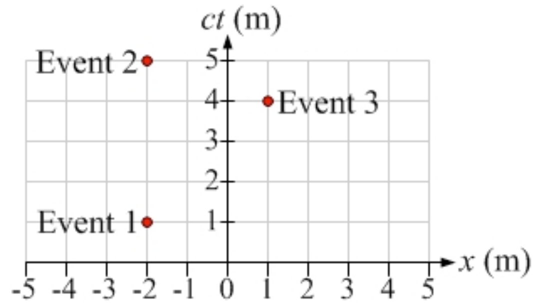

Figure 26.17: A spacetime diagram showing three events, for Exercise 13.

Exercises 14 – 18 involve drawing and interpreting spacetime diagrams.

14. Consider the spacetime diagram shown in Figure 26.18, for four people whose motion is confined to the *x*-axis. The squares on the grid measure 1 m × 1 m. (a) Which worldline is impossible? Why? (b) What is Keith's velocity with respect to Erica? (c) What is Sai's velocity with respect to Erica?

15. Consider the spacetime diagram shown in Figure 26.18. (a) What are the coordinates of events A and B, according to Erica? (b) What is the spacetime interval for these two events? (c) According to Sai, what is the spatial separation between events A and B? (d) According to Sai, what is the time difference between the events?

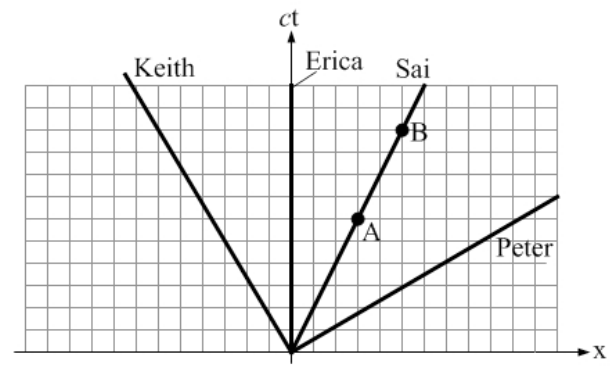

Figure 26.18: A spacetime diagram showing worldlines for four people and two events, A and B. For Exercises 14 and 15.

16. Consider the spacetime diagram in Figure 26.19, which shows worldlines for you and for two other astronauts. All the motion is confined to the *x*-axis. (a) What is Sasha's velocity with respect to you? (b) What is Michel's velocity with respect to you? (c) What is your velocity with respect to Michel?

17. Consider the spacetime diagram shown in Figure 26.19. (a) Add two events to the spacetime diagram that, according to you, happen at a distance of 5 light-years from you, but which are separated by a time interval of 4 years. (b) Add two events to the spacetime diagram that happen at different times, but at the same location, according to Sasha.

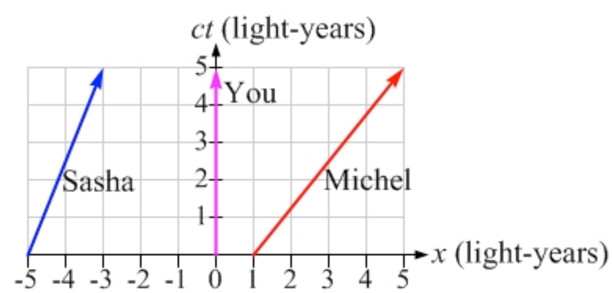

Figure 26.19: A spacetime diagram showing worldlines for three astronauts, for Exercises 16 and 17.

18. Draw a spacetime diagram, with units of meters, showing (a) your worldline, and (b) the worldline of a rocket that, according to you, passes through $x = +100$ m at $t = 0$ and travels in the positive *x*-direction at 60% of the speed of light. (c) According to you, what is the rocket's location at $t = +600$ meters of time?

Exercises 19 – 22 involve time dilation.

19. According to you, an astronaut's trip from Earth to a distant planet takes 50 years. The distant planet is in the same frame of reference as the Earth, and the astronaut travels at constant velocity between the two planets. (a) How long does the trip take, according to the astronaut, if the astronaut's speed with respect to you is (i) 5% of the speed of light, (ii) 50% of the speed of light, and (iii) 95% of the speed of light? (b) What is the distance between the planets, according to you, for the three different cases in part (a)?

20. Light takes 500 s to travel from the Sun to Earth. In the frame of reference of the light, how much time does the trip take?

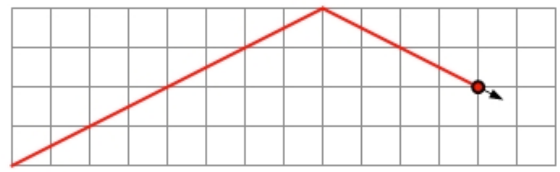

Figure 26.20: The path followed by a light pulse in Randi's clock, as observed by you. For Exercise 21. The grid on the diagram is square, according to you.

21. Figure 26.20 shows the path followed by a light pulse in Randi's light clock. Randi and her clock are moving at constant velocity to the right with respect to you. What is Randi's speed with respect to you?

22. According to you, the distance between the Earth and a distant star is 1000 light-years. You and the star are in the same reference frame as the Earth. (a) According to you, what is the shortest time a message could be sent from the Earth to the star? (b) In the frame of reference of Megan, who is traveling at constant velocity between the Earth and the star, could the trip take only 10 years? If not, explain why not. If so, determine Megan's speed with respect to you. (c) Which observer, you or Megan, measures the proper time between the two events of Megan passing Earth and Megan passing the distant star? Explain.

Exercises 23 – 25 involve length contraction.

23. According to you, the distance between the Earth and a distant star is 1000 light-years. You and the star are in the same reference frame as the Earth. (a) In the frame of reference of Rajon, who is traveling at constant velocity between the Earth and the star, could the Earth and the star be separated by a distance of only 5 light-years? If not, explain why not. If so, determine Rajon's speed with respect to you. (b) Which observer, you or Rajon, measures the proper length between the Earth and the star? Explain.

24. A rocket is passing by the Earth traveling at 80% of the speed of light in a direction parallel to the length of the rocket. As the rocket passes, you measure the rocket's length to be precisely 100 m, using a tape measure in which lines are marked every millimeter. According to an observer moving with the rocket, (a) what is the length of the rocket, and (b) how far apart are the marks on your tape measure?

25. If you examine Figures 26.9 and 26.10 carefully, you will notice that the images of the mirror, and the images of the emitter/detector, are shorter in Figure 26.10 than they are in Figure 26.9. (a) What is the explanation for this? (b) For the particular situation described in Exploration 26.3, how much shorter are the mirrors in Figure 26.10 compared to those in Figure 26.9?

Exercises 26 – 31 involve ideas from General Relativity. In case you are intrigued by Einstein's ideas and you would like to know more, these exercises will give you some starting points for further reading.

26. These days, GPS (Global Positioning System) units can be carried by hikers and sailors, and are built into cars and airplanes, to provide accurate information about someone or something's position on Earth. Do some research regarding how and why the clocks on the GPS satellites are corrected for effects associated with General Relativity, and write a couple of paragraphs about this.

27. In 1960, Robert Pound and Glen Rebka did an interesting experiment at Harvard University to prove that the frequency of light is affected by gravity. Do some reading about their experiment, describing how gravity affects the frequency of light, and how the Pound and Rebka experiment verified the effect.

28. Joseph Taylor and Russell Hulse won the Nobel Prize for Physics in 1993. Do some reading about their research, and write a couple of paragraphs about it. Be sure to mention how their work is connected to General Relativity.

29. LIGO and LISA are acronyms for two large physics experiments that relate to General Relativity. Do some research about them, first to determine what these acronyms stand for, and then so you can write up a couple of paragraphs about how the experiments are designed to work and what they are trying to find.

30. A famous experiment in 1973 to test the predictions of relativity theory involved atomic clocks, which are incredibly accurate time-keepers. One atomic clock was placed on an airplane that circled the Earth going eastward. A second clock was placed on a plane that went westward around the Earth. A third clock was left at the US Naval Observatory. When the clocks were all brought back together, they showed that slightly different time intervals had gone by. Could the principles of physics be used to explain the observations? Was it Special Relativity or General Relativity that was more important in the experiment? Do some reading about the experiment, and write a couple of paragraphs describing the implications of the results.

31. In 1919, Arthur Eddington led an expedition to the island of Príncipe in an effort to test one of Einstein's predictions regarding how light is influenced by gravity. What did the expedition determine, and why did they have to go to Príncipe to do this?

General problems and conceptual questions

32. The spacetime interval between two events is 40 m. The events have a spatial separation of (1) 18 m, according to Gary, (2) 8 m, according to Megan, and (3) 0 m, according to Shawn. What is the time interval, in meters of time, between the events, according to (a) Gary, (b) Megan, and (c) Shawn.

33. Review the discussion of the Rossi and Hall experiment in Section 26.3, and assume that the muons are traveling at 99% of the speed of light. (a) From the point of view of an observer at rest on the Earth, how much time elapses on the clock of an observer who is in the reference frame of the muons? (b) From the point of view of an observer in the reference frame of the muons, what is the vertical distance between the top of Mt. Washington and sea level, and how long does it take a muon to traverse that distance?

34. Let's investigate a light clock that is moving with respect to you, but moving in a direction perpendicular to the mirror instead of parallel to it as in Exploration 26.3. The clock is shown in Figure 26.21. You observe the emitter and the mirror to be separated by 90 cm, and the clock to be moving at 50% of the speed of light. Note that this situation parallels the Brandi and Mia situation from Chapter 4, in which Mia ran on a moving sidewalk. (a) How long does a light pulse take to travel from the emitter to the mirror, according to you? (b) How long does the pulse take to travel back from the mirror to the detector, according to you? (c) What is the total round trip time for the light pulse in the clock, according to you? (d) If you have an identical clock, what is the round trip time for a light pulse in your clock? (e) Is the time dilation equation (Equation 26.2) valid for this situation? Explain why or why not.

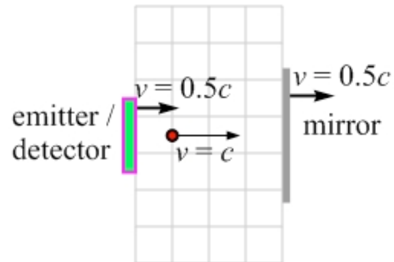

Figure 26.21: A light clock that is moving in a direction perpendicular to the plane of its mirror. For Exercise 34.

35. A spacetime diagram, showing worldlines for four observers whose motion is confined to the x-axis, is shown in Figure 26.22. (a) Which two observers have the same velocity? What is the spatial separation between the two observers with the same velocity, according to (b) Sam, (c) Jen, and (d) Marco?

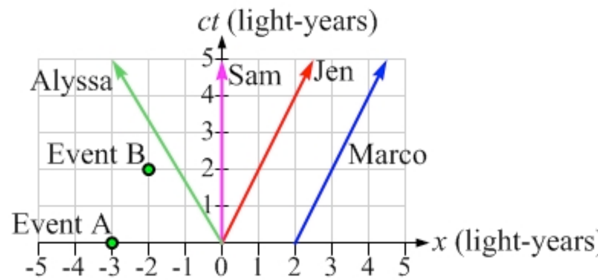

Figure 26.22: This spacetime diagram shows worldlines for four observers, whose motion is confined to the x-axis, as well as the spacetime coordinates of two events, in Sam's frame of reference. For Exercises 35 – 36.

36. (a) What is the spacetime interval between events A and B on the spacetime diagram in Figure 26.22? According to Jen, what is (b) the spatial separation between the two events, and (c) the time interval between the two events? (d) Do any of the other three observers agree with Jen on the answers to (b) and (c)? If so, who agrees with Jen?

37. The spacetime diagram in Figure 26.23 shows the spacetime coordinates of three events, as measured by a particular observer. Determine the spacetime interval between (a) events A and B, (b) events A and C, and (c) events B and C.

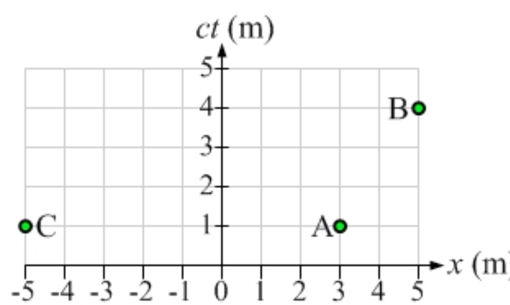

Figure 26.23: A spacetime diagram showing the spacetime coordinates of three events, as measured by a particular observer. For Exercises 37 and 38.

38. The spacetime diagram in Figure 26.23 shows the spacetime coordinates of three events, as measured by a particular observer whose worldline follows the ct axis. (a) According to a second observer, who is traveling at constant velocity along the x-axis with respect to the first observer, events A and B occur at the same location. What is the speed of the second observer with respect to the first observer? (b) According to a third observer, who is traveling at constant velocity along the x-axis with respect to the first observer, events C and B occur simultaneously. What is the speed of the third observer with respect to the first observer?

39. You are standing on a train platform that has a length of 150 m, according to you. According to a passenger on the train, the train has a length of 250 m. As the train passes through the station at very high speed, however, you observe the length of the train to be exactly the same as the length of the platform, 150 m. If we define event A to be the front of the train passing one end of the platform, and event B as the rear of the train passing the other end of the platform, you observe that the two events are simultaneous. (a) What is the speed of the train, according to you? (b) What is the spacetime interval between the events A and B? (c) What is the time interval between the two events, according to the passenger on the train?

40. You are on a train that is traveling at 70% of the speed of light relative to the ground. Your friend is at rest on the ground, a safe distance from the track, watching the train go past. According to you, the train has a length of 300 m, and the distance between the two cities the train is traveling between is 1200 km. What does your friend measure for (a) the length of the train, and (b) the distance between the two cities the train is traveling between.

41. Return to Exercise 40. Assuming the velocity of the train is constant, what is the time taken by the train to travel between the two cities according to (a) you, and (b) your friend?

42. ***An introduction to the pole-and-barn paradox.*** A particular pole is 10 m long, according to Paul, who is at rest with respect to the pole. According to you, the distance between the front and back doors of a barn is only 5 m. However, Paul runs fast enough, while holding the pole parallel to the ground, that the pole appears to be just under 5 m long, according to you. Thus, with the barn's front door open and back door closed, Paul can run through the front door of the barn, and you can close the front door and your assistant can simultaneously open the back door so that Paul passes through the barn without any trouble. The apparent paradox comes when the situation is looked at from Paul's perspective. According to Paul, (a) what is the length of the pole, and (b) what is the distance between the two barn doors? (c) Is it possible for Paul's pole, according to Paul, to be entirely inside the barn, as you saw it to be? (d) According to you, Paul can pass through the barn without the pole hitting either door. According to Paul, is this possible? Either explain this apparent paradox yourself, or do some background reading about the barn and pole paradox to resolve it.

43. Table 26.2 gives the readings on the clocks of three observers, as recorded by one of the three observers. The relative velocities between the observers remain constant at all times. (a) Complete the table, filling in the missing readings. (b) Which of the three observers is recording the clock readings? Explain. (c) What is Sarah's speed with respect to Josh?

	Josh	**Rachel**	**Sarah**
Event A	2 hours	0	2 hours
Event B	5 hours		6 hours
Event C	11 hours	3 hours	

Table 26.2: A table of clock readings for various events, as recorded by one of the three observers.

44. Let's return to the Isabelle, you, and Yan situation that was introduced in Section 26-4, and elaborated on in Section 26-5. You and Yan, who are in the same reference frame but separated by 40 light-years, according to you, agree that you will set your clocks to zero when a light pulse, emitted from the point midway between you and Yan, reaches you. The light travels at the speed of light in vacuum. Isabelle, who is traveling at 80% of the speed of light while traveling from Earth, where you are, to Zorg, where Yan is, happens to pass you at the same time the light pulse reaches you, so she sets her clock to read zero at the same time you do. (a) According to you, how long does it take the light pulse to reach you after it is emitted? (b) According to Isabelle, how far is it from the point where the light pulse was emitted to you? Isabelle agrees that the point where the light pulse is emitted is halfway between you and Yan. (c) According to Isabelle, how long does the light pulse take, after being emitted, to reach Yan? Note that, according to Isabelle, the light pulse and Yan are both moving. (d) According to Isabelle, how long does the light pulse take, after being emitted, to reach you? (e) On Isabelle's clock, how much time elapses between the light pulse reaching Yan and the light pulse reaching you? (f) According to Isabelle, how much time elapses on Yan's clock between the light pulse reaching Yan and the light pulse reaching you? Note that this answer should agree with the information in Section 26-5.

45. Return to Exercise 44. Sketch a spacetime diagram, from your frame of reference, for the situation described in Exercise 44. Draw worldlines for you, Yan, Isabelle, the light pulse that travels from the midpoint between you and Yan to you, and the light pulse that travels from the midpoint between you and Yan to Yan.

46. Repeat Exercise 45, but now sketch the spacetime diagram for Isabelle's frame of reference.

47. You are traveling along the intergalactic freeway in your personal rocket. A large transporter in the next lane, which has the same velocity as you, is exactly 4 times the length of your rocket. An identical transporter in the oncoming lane, however, appears to be the same length as your rocket. Relative to you, at what speed is transporter in the oncoming lane traveling?

48. Two students are considering a particular question. Comment on the part of their conversation that is reported below.

Erin: The question says"As the rocket goes by at 75% of the speed of light, observers in the Earth's reference frame mark the locations of the tip and tail of the rocket at the same time. They then measure the distance between the marks to be 60 meters. What is the length of the rocket?" Uh, 60 meters, right?

Katie: Doesn't the speed have something to do with it? Don't we have to use the length contraction equation to find the length of the rocket in the rocket's frame of reference?

Erin: Well, the question doesn't really say, right? It asks for the length of the rocket, but according to who? Who's the observer?

Katie: What if we did two answers, one 60 meters, and the other the length that's seen by somebody in the rocket?

Erin: OK, I'll go with that. Now, length gets contracted, so the other length should be less than 60 meters, right?