Introduction to Special Relativity

PHYS 1301 F99
Prof. T.E. Coan
version: 20 Oct '98

Introduction

      This lab introduces you to special relativity and, hopefully, gives you some intuitive understanding of its basic phenomena of "time dilation," "Lorentz length contraction" and the special way speeds of fast moving objects add together. You will use a computer simulation during this session that lets you examine the behavior of simple objects (rods and clocks) when they travel at very large speeds along a straight line. All of the motion takes place along a straight highway and objects are allowed only to go forward or in reverse. You will control the speed and direction of motion of these objects, subject only to the constraints that the physics of special theory relativity imposes on them, first discovered by Einstein in 1905. In case you were wondering, the "special" in special relativity stands for "special case" and signifies that the theory of special relativity is a simplification of the more complete theory of "General Relativity."

      There are two main points to special relativity. First, imagine you and your lab partner are each in special rooms that contain all of your lab equipment. You look out the window of your room and see that your partner's room is moving at some constant speed with respect to you. She is either approaching or receding at a constant rate. After waving, you both close your respective windows so that neither of you can directly observe the outside world and perform all sorts of physics experiments. Based on the results of your experiments, you would not be able tell whether you were moving or your lab partner was moving. That is, the results of the experiments are the same whether you are moving or standing still. Similarly, your lab partner would not be able to tell if she were the moving one or the one at rest. This is the meaning of relativity.

      The second important point is that both you and your lab partner would measure the speed of light travelling through empty space as having the very **same** value, even though your lab partner is travelling with some speed with respect to you. Although not obvious, this implies that the speed of light is somehow the part of the essential fabric of the physical universe. The speed of light through empty space is typically given the symbol c and has been carefully measured to have the value $\mathbf{c = 3 \times 10^8}$ m/sec.

      Our simulation program automatically calculates all the numbers we require to develop an understanding of how time, length and speed are affected by SR. You need, however, to learn a small number of commands to manipulate the rods and clocks to send them on their way in the appropriate direction and with the appropriate speed. A detailed list of these commands is included in the lab. You only need to learn about 10 or so. Finally, it is important to understand that today you will perform a simulation of special relativistic effects. The simulation assumes that special relativity is correct and lets you explore the consequences of this assumption. **The**

software does not test whether or not special relativity is correct in the first place. What you do today is not really an experiment.

Procedure

1. Locate the folder <u>Spacetime</u>. The instructor will help you if you can't locate it. Double click (left mouse button) on the icon <u>Spacetime.</u>

2. In the reference material below, read the section <u>The Highway Window.</u> This will explain to you what you are staring at on the screen. You need to play a bit so that you learn a few commands to get something interesting to happen. Read and perform the <u>Tutorial</u>, which is also included in the reference section of this lab. What is most relevant to you is to know how to create rods, clocks, clock strings and so-called shuttles. Also, you will need to know where to look to find things like the speed and position of these things. You do not need to memorize every command. The point of the tutorial is to familiarize you with the program. This will probably take 20 minutes or so. Have fun.

3. Now we are ready to start by learning how lengths are modified by special relativistic effects. Create 4 rods at slightly different positions (x=0.5, 1.0,1.5 and 2.0) Give them 9 values of 9 = 0.6,0.8,0.95 and 0.99. I will refer to these rods as rod B (x=0.5) rod C (x=1.0) and so on.

4. **Question 1.** What is the corresponding value 1 for each value of 9?

5. Fill in data table 1 below. On a piece of graph paper, plot 1 v. 9. (This mean that the vertical axis should be 1 and the horizontal axis should be 9. Draw a **smooth** curve through the 5 points. (You can use the clock at the origin even though it isn't a rod because we are only interested right now in the relationship between 9 and 1.) **Question 2.** What do you notice about the apparent length of the rods?

6. Fill in data table 2 below. Can you make a general statement about the lengths of objects when they are moving very rapidly with respect to you?

7. This exercise illustrates that if we take into account special relativity, "moving objects" appear shorter than they do when their length is measured in their own rest frame. These objects are "Lorentz contracted" by an amount that depends on their speed. The greater their speed, the greater their contraction. It is important to understand that I am NOT talking about an optical illusion. I am talking about the length you would measure with a plain old ruler or similar device.

8. We now examine how time behaves when we take into account special relativistic effects. Delete the rods you have previously created and start with a fresh screen. Create 4 clocks (C, D, E and F) at x=0.5, 1.0, 1.5 and 2.0, and give them the 9 values of 0.6(clock C), 0.8 (D), 0.95 (E) and 0.99 (F). You should see a total of 5 clocks on your screen, including the one (clock B) that is at rest (9=0). Make certain you are in the reference frame of clock B (that's the one at rest) and advance the time on clock B until it reads 10.0 seconds. Examine the times on all the other clocks. Fill in data table 3. You may find it useful to use the so-called Object Table found under menu Windows.

9. **Question 3.** What clock seems to be running the slowest? Write down a general statement about the rate at which a clock "runs" and the speed of a clock.

10. Jump to the reference frame of clock F. Advance clock F until it reads 10.0 seconds. Examine the object table. **Question 4.** Is there any difference between the Object Table now and when you were in reference frame B? Why do you think that is?

11. This exercise illustrates the phenomenon that according to special relativity, "moving clocks run slow." Actually, moving clocks do not run any slower than they should, unless they are mechanically defective. It is just that what we mean by a "second of time" depends on the reference frame we are in.

12. We will now examine how speeds add when we take into account special relativistic effects. Delete all the clocks you made previously. We will create 5 rods in succession, each with a speed 0.5c faster than the rod before it. All of the rods will be at x=0. First, create rod A with 9=0. Next, create rod B with 9=0.5 also at x=0. Jump to reference frame B and create a new rod C at x=0 that has a speed 0.5c with resect to rod B. This means that somebody standing on rod C will see rod B move away from them with a speed equal to half that of light's. Continue by "transforming" (jumping) to rod C and creating a rod D that has speed 0.5c with respect to rod C. Finally, transform to rod D and create a rod E with 9=0.5 with respect to D.

13. Transform to reference frame E (the frame of the last rod you made).

14. **Question 5.** What is the speed of rod D as seen from rod E? (Express your answer as 9= ...)

15. **Question 6.** What is the speed of rod A as seen by somebody standing on rod E?

16. Transform back to frame A, the original frame. **Question 7.** What is the speed of rod E as seen from A? **Question 8.** What is the speed of rod B as seen from A? **Question 9.** What is the similarity between the object tables when you are standing on rod E and when you are standing on rod A? Try to be as specific as possible about what this similarity is.

Did you notice that even though you kept creating rods that were moving with half the speed of light (9=0.5) with respect to the preceding rod, you were never able to create

a rod moving faster than the speed of light? Doesn't this seem strange? This exercise illustrates that c is a limiting speed for all objects in the universe.

Reference Material

About the Program

■ THE *HIGHWAY* ▬▬▬▬▬▬▬▬▬▬

The *Highway* Window

When the program starts, you see the *Highway* window, a "superhighway" running from left to right across the screen (see Figure 1). Different lanes on the highway are for objects moving at different speeds. Objects lying on the dashed horizontal line through the middle of the screen are on the center strip of the highway and do not move. Objects above the center move to the right; the farther above the center, the faster they move. Objects in the very top lane move to the right with the speed of light; only light flashes (and neutrinos) can occupy this lane.
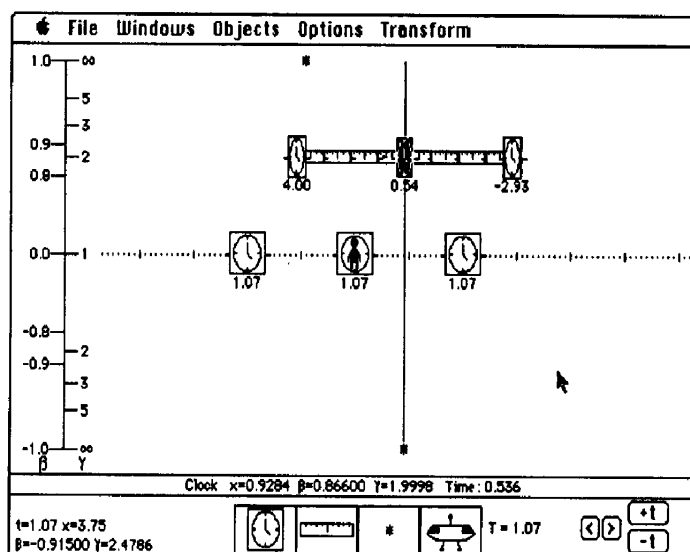

Fig. 1. Objects moving in one dimension are displayed in the Highway window on a left-to-right "superhighway" with objects moving at different velocities spread out vertically into different "lanes." Shown here is the classic Train Paradox scenario at the moment the backward-moving light flash (at the bottom of highway) reaches the center of the train moving to the right. The features of this window are described below in the section "Exploring the Highway."

Objects below the center of the screen move to the left; the farther below the center, the faster they move. Objects in the very bottom lane move to the left with the speed of light; only light flashes (and neutrinos) can occupy this lane.

The highway convention is British, but modified; vehicles drive on the left side, but slow lanes are near the center strip, fast lanes near the edge of the road.

To understand what appears on the highway, think of it as a movie of all the objects traveling along the highway. At any given instant, you are looking at a single "still" of the movie. As you click the buttons labeled "+t" and "−t" at the lower right corner of the window you simulate the passage of time by looking at the next or the previous still-frame of the movie. You are going to learn how to make such movies.

A vertical ruler at the left of the screen shows β (Greek beta), the velocity as a fraction of the speed of light: $\beta = v/c$. The range of β extends from +1 at the top (light moving to the right), through 0 at the center, to −1 at the bottom (light moving to the left). Notice that this is not a linear scale; equal vertical lane separations do not correspond to equal changes in β. This is done so that more of the interesting velocities near $\beta = v/c = \pm 1$ can fit on the screen.

There is a scale on the screen labeled γ next to the β scale. Ignore this second scale for now.

The numbers at the lower left corner of the screen describe the position of the pointer on the screen. The first number, t, is the time as measured in the current reference frame. This number stays constant as you move the mouse and changes only as you step through time. The number next to it, x, is the right-left position of the pointer on the highway. The second line shows the β and γ (Greek gamma) of the velocity of the lane to which the pointer is pointing.

Before learning more details of the *Highway* window, take a quick spin to get the feel of it. The next section is a tutorial to introduce you to SPACETIME.

TUTORIAL

This fifteen-minute tutorial introduces you to the program by guiding you through an example journey on the highway.

To start SPACETIME, do the following:

1. Turn on your Macintosh

Spacetime

2. Insert the SPACETIME disk into a disk drive

3. When the directory window opens, double-click the icon labeled SPACETIME

The program displays the title of the program and the name of the author.

Click the OK button to proceed

The naked-eye star nearest to our sun is Alpha Centauri, about four-and-a-half light-years distant from us. Assume that the distance units shown along the center strip are light-years and the time units on the clocks are years. The "reference clock" in the center of the screen represents Earth with observer. Now create a second clock to represent Alpha Centauri. At the bottom of the screen in the objects palette is a clock icon. It looks like this:

You create an object by dragging the corresponding icon onto the highway. To aid you in positioning objects, the numbers at the lower left corner of the window show the position of the pointer when the pointer is on the highway.

Drag a clock icon to the position x = +4.5 and velocity β = 0.0. This clock represents Alpha Centauri.

Next, prepare a shuttle for the trip to Alpha Centauri. The initial position of the shuttle is the same as Earth (x = 0) and its initial velocity is β = 0.9. The shuttle icon looks like this:

Drag the shuttle icon to the position x = 0.0 and velocity $\beta = 0.9$

Now start the shuttle on its journey by stepping time forward. The buttons for changing the time are located in the lower right corner of the screen.

Click the +t button twice

The shuttle has moved closer to Alpha Centauri. It arrives when it lines up vertically with the clock located at x = 4.5. You need to see detailed, numerical information about the shuttle as it moves.

Click the shuttle (on the highway)

The icon changes to white on black. A line of information across the bottom of the highway shows the shuttle's

position, speed, and the reading on its clock. This information is updated as you move the shuttle toward Alpha Centauri.

Click the +*t* button three times

The shuttle has arrived at Alpha Centauri. Now move the shuttle into a lane moving to the left so it is heading home, as follows:

Choose Program Shuttle from the Objects menu

A box appears with numbers and buttons in it. Find the buttons that look like this:

$$\bullet \quad \beta > 0$$
$$\bigcirc \quad \beta < 0$$

These buttons determine whether the shuttle is moving to the right (with a positive velocity $\beta > 0$), or moving to the left (with a negative velocity $\beta < 0$). The black dot in the circle means that the positive velocity is selected right now.

Click the $\beta < 0$ button

The black dot moves to the lower circle.

Click the OK button

The shuttle is now programmed to turn around when it reaches Alpha Centauri. Now bring the shuttle home:

Click the +*t* button five times

Welcome the shuttle home. You observed everything while standing on the center strip, so you did not move! To record the arrival as an event:

Choose Object Event from the Objects menu

The event is displayed as a vertical line across the highway. This emphasizes that the objects are actually located on a single line in space—the vertically separated velocity-lanes are just a way of avoiding screen clutter.

Compare the time on the Earth clock to the time on the shuttle clock. Each clock shows the number of years that has passed. Who is younger, the shuttle pilot or the stay-at-home twin? This is called the Twin Paradox. For a further analysis of the Twin Paradox, see "Some Relativistic Effects."

Now repeat the journey while you, the observer, are riding on the shuttle. First reset the time to zero:

Choose $t = 0$ from the Options menu

Now climb onto the shuttle (if the shuttle is not still shown as white-on-black, click it to select it):

Choose Jump to Object from the Transform menu

You are now riding on the shuttle. With respect to you (the observer) the shuttle is at rest so the shuttle is on the center-strip of the highway. Earth is lined up with you but below you, in a leftward-moving lane. Alpha Centauri is in the same lane as Earth, located to the right of Earth. Because Earth and Alpha Centauri are moving in your rest frame, the distance between them is contracted according to the laws of special relativity.

Noticed that when observed from the shuttle, the Earth clock has a different reading than the clock on Alpha Centauri. This is due to the relativistic effect called "relative synchronization of clocks." When two clocks are both at rest on the center strip, they *do* have the same reading— they are "synchronized" with one another. This is discussed in "Some Relativistic Effects."

Click the +*t* button seven times

The "movie" of the trip to Alpha Centauri and back to Earth is replayed as observed while riding on the shuttle. The shuttle automatically turns around when it reaches Alpha Centauri and stops when it reaches Earth. Welcome home.

Choose Quit from the File menu

A dialog box appears asking if you want to save your work.

Click the No button

This concludes the tutorial.

■ EXPLORING THE *HIGHWAY* ███████████████████████

You have already used many of the most important *Highway* window commands. Now it is time to examine the *Highway* window more closely. The *Highway* window (shown in Figure 1) automatically appears when you start SPACETIME. When you view another window, the *Highway* window becomes hidden.

To view the *Highway* window, choose Highway from the Windows menu (or press ①)

This section of the manual describes the following:

• The concept of the highway

• Things that can appear on the highway

• How to create things on the highway

• How to change things on the highway

• How to delete things from the highway

- How to change the time
- How to change the reference frame
- How to change the view of the highway

The Concept of the Highway

one-dimensional

The vertical separation of objects by velocity on the highway is just for analysis. In reality all the objects are moving along a single line, a single dimension in space. SPACETIME artificially separates them vertically on the screen in order to analyze their relative motions without screen clutter. An event is represented as a vertical line across the entire highway to remind you of the artificial vertical separation in the window.

units

The short vertical lines along the center strip of the highway are one unit of distance apart. SPACETIME uses abstract units. You may choose any units to measure time and space that suit your purposes. The only constraint is that light move 1 unit of distance in 1 unit of time. Hence, consistent units might be years of time and light-years of distance, or minutes of time and light-minutes of distance (one light-minute equals the distance that a flash of light moves in one minute), or meters of distance and meters of light-travel time (one meter of light-travel time equals the time it takes for a light flash to move one meter), etc. Thus, you control the scale of events.

gamma scale

Immediately to the right of the β scale (described above in "The *Highway* Window") is a second scale labeled γ that gives the value of γ(Greek gamma), sometimes called the *time stretch factor*.

$$\gamma \equiv \frac{1}{\sqrt{1-\beta^2}} \qquad (1)$$

Moving clocks appear to run slow by the factor γ and moving rods appear to be contracted by a factor γ along their direction of motion. The factor γ, which is always positive, ranges from the value infinity at the top of the screen, through the value 1 at the center, to the value infinity again at the bottom of the screen.

animation vs. observation

You cannot run time backward in real life. Thus, you must always remember that the highway does not show events as they are occurring, even in principle. Rather it replays data gathered from remote locations, transported to a central information processing facility, and assembled into a picture-by-picture animation, which can be run backward or forward in time at your pleasure.

command menus   The titles of the pull-down menus appear across the top of the screen. Commands are grouped by function, so, for example, filing operations can be found in the menu titled File.

command keys   Many of the menu commands have keyboard equivalents. These are listed beside the command within the menu. In this program it is *not* necessary to hold down the ⌘ key while pressing the keyboard equivalent of a menu command.

help   At any time you can obtain on-screen help about the commands by either pressing ? or choosing Help from the ⌘ menu. A different help screen appears for each window. Click anywhere to resume using the program.

Things That Can Appear on the Highway

clock

A clock appears as an icon that looks like the face of a clock. Since moving objects appear to be shortened, the icon of a moving clock appears narrowed on the screen. The time reading of the clock is shown below the icon.

Each clock ticks at its regular rate in the frame of reference in which the clock is stationary, but to an observer in relative motion, the clock appears to run slow.

The clocks in a given frame are said to be "synchronized" when the following is true: Jump to their frame so that all the clocks are at rest. If all the clocks read the same time, they are synchronized. A clock on the highway is automatically synchronized in its rest frame unless you manually set its time. The time on an *unsynchronized* clock is shown in outlined numbers (e.g., 4.00).

When two synchronized clocks are both at rest on the center strip, they read the same time. However, two synchronized clocks moving in the same highway lane do not read the same time. This is due to a relativistic effect called the "relative synchronization of clocks." Most people have trouble understanding this relativistic effect. For more on relative synchronization of clocks, see "Some Relativistic Effects."

clock string
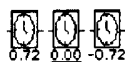
A clock string can be attached to a clock, rod, or shuttle. The clock string is an infinite set of synchronized clocks spaced regularly in the same lane as the object to which the clock string is attached. To avoid screen clutter caused by the Lorentz contraction, moving clock strings are displayed with some of the clocks omitted. The spacing between clocks in a clock string is 1 unit (in the rest frame of the object) if the object is moving with a γ between 1 and 2. The spacing is 2 if γ is between 2 and 3, and so on. Thus, the

apparent distance between adjacent clocks in the string does *not* correctly follow Lorentz contraction.

rod

A rod appears as an icon that looks like a ruler. The length of the rod in its rest frame is the distance a flash of light travels in one unit of time. A rod always has the same length in the frame of reference in which it is stationary, but is observed to be shortened in a frame in which the rod is moving.

flash of light

A flash of light appears as an icon that looks like an asterisk. All flashes of light move at the same speed in *all* inertial frames of reference. On the one-dimensional highway, a flash of light can have a velocity of either $\beta = +1$ or $\beta = -1$. Hence, flashes appear only in the two outermost lanes.

beacon

A beacon can be attached to a clock or a rod, but not to a flash or the shuttle. Starting at time zero, each time the clock *of the object to which the beacon is attached* increases by one unit the beacon emits two flashes of light, one forward and one backward.

shuttle

The shuttle icon represents a clock that you can program to follow a planned trip by changing its velocity lane on the highway. (How to program the shuttle is explained later in this section.) For example, the shuttle enables you to measure the time of a round-trip journey. Only one shuttle is allowed on the highway.

When you create a shuttle, its clock is synchronized and set to time zero. From that time on the shuttle's clock runs continuously. Unlike an ordinary clock, when you change lanes the shuttle's clock is not synchronized with the "local clocks" in its new lane. To remind you of this, the shuttle's time is displayed in outlined numbers (for example, 4.00) whenever it is unsynchronized in its rest frame. Whenever you wish, you can re-synchronize the shuttle to the time as measured at its position in its local frame by selecting it and using the Synchronize clock command in the Objects menu. However, it will then be out of synchronization when it jumps to other frames (including earlier frames).

event

An event is defined by both a particular time and a particular location. On the highway, an event appears as a vertical line and is displayed only at the time (in the frame of the observer) when that event occurs. (Events are listed on the *Table* window and continuously shown on the *Spacetime Diagram* window.) When you incrementally change time, the clock automatically stops at the time of every event, even if the event occurs within a time step, to avoid skipping over an event (unless you toggle this feature off in the Options menu).

Events are numbered 1, 2, 3, and so on in the order you create them (not necessarily in chronological order). The event 0 (event number zero) is a special one: by definition it occurs at $t = 0$ and at $x = 0$ in all reference frames. Event 0 is called the *reference event* because it is the starting gun from which clocks are synchronized in every reference frame. Event 0 is created automatically when you start the program.

Examples of other possible events include a collision, the emission of a flash of light, or a coincidence (the place and time at which two objects have the same position).

Creating Objects Using the Mouse
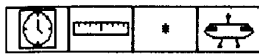
To place an object, you simply drag the appropriate icon from the object palette at the bottom of the screen onto the highway.

1. Use the mouse to position the pointer over the object's icon (the pointer changes to look like a hand)

2. Press and hold down the mouse button

3. Use the mouse to drag the icon up onto the highway

As you move the object, its position and velocity coordinates are displayed at the bottom left corner of the screen (for example, $x = 4.00$ and $\beta = -0.50000$ $\gamma = 1.1547$). The position coordinate is automatically rounded to the nearest multiple of 0.25 units. (If you wish to position objects more precisely, toggle off the Round Coordinates option of the Options menu.)

4. When the object is where you want it, release the mouse button

If you change your mind and do not want to create the object, simply drag the object off the highway before releasing the mouse button.

Clocks and rods are shown Lorentz-contracted by an amount appropriate for the velocity of the lane. Flashes of light can travel only at the speed of light and so can be placed only in the two outermost lanes.

Creating Objects Numerically

An alternative way to create an object is to enter numerical values for its position and velocity.

1. Choose Enter Object from the Objects menu

A dialog box appears on the screen as shown in Figure 2.

Set the object's parameters:
Speed: ◉ ß   ◉ ß>0   Position:
0.0000   ○ Gamma ○ ß<0   4.3301
Time on clock:
                ⊠ Synchronize   ○ Rod   ○ Flash
                                ◉ Clock ○ Shuttle
□ Clock String □ Beacon
Enter Description:
Distant star

        Cancel   Ok

Fig. 2. The object parameters dialog box enables you to create or modify an object numerically.

You can move around within the dialog box by clicking what you want to select or enter.

3. Make the desired selections and entries as described below:

Choose whether to specify the speed as a β or a Gamma by clicking the appropriate button

Type the speed value (β between –1.0 and 1.0, or Gamma any positive value greater than or equal to 1.0)

Choose the direction of motion by clicking $\beta < 0$ for motion to the left or $\beta > 0$ for motion to the right

Type the desired position coordinate

Type the desired time (to synchronize the clock with other clocks in the same lane, click the Synchronize box)

Choose the type of object by clicking the Clock, Rod, Flash, or Shuttle button

Attach a clock string or beacon to the object by clicking the corresponding box

You can annotate the object if necessary by typing up to 255 characters in the Description box (for display in the *Table* window)

4. When you have made all your choices and entries, click the OK button

The dialog box disappears and the object appears on the highway.

Selecting an Object

To select an object, simply click it. The icon of the object inverts, becoming a white outline on a black background.

When two icons are overlapping, be careful that you click the object you really want.

When an object is selected, information about its speed, position, etc. is displayed near the bottom of the screen, just below the highway.

To have no object be selected, click anywhere on the highway that there is no object. When no object is selected, the message "No object is currently selected" appears below the highway.

Adjusting an Object

Sometimes by accident you place a clock, rod, or flash on the screen in a slightly different location than you want it to be. For example, you may accidentally place an object with β = 0.81 when you wanted it to have β = 0.80. You can edit this and other object parameters in either of two ways. The first way is to do the following:

1. Hold down (Shift)

The pointer shape changes to a hand.

2. Drag the object to its new location

3. Release the mouse button and release (Shift)

The object appears in the new location.

Alternatively, you can change an object the following way:

1. Select the object by clicking it

2. Choose Edit Object Details from the Objects menu (or press (E))

A dialog box appears enabling you to alter the object (see Figure 2 above). You can move around within the dialog box by clicking what you want to change.

3. Make the desired changes as described below:

The method of specifying speed is changed by clicking either β or a Gamma

The speed is changed by typing the new speed value ($-1.0 \leq \beta \leq 1.0$ or $1.0 \leq$ Gamma)

The direction of motion is chosen by clicking β <0 for motion to the left or β >0 for motion to the right

The position is changed by typing the position coordinate desired

The time on the clock is set by typing the time desired (to synchronize the clock with other clocks in the same lane, click the Synchronize box)

The type of object is changed by clicking the Clock, Rod, Flash, or Shuttle button

A clock string or beacon is attached to the object by clicking the corresponding box

An annotation to the object (up to 255 characters) can be typed in the Description box (for display in the *Table* window)

4. When you have made all the changes you want, click the OK button

Creating a Clock String or Beacon

To create a clock string or beacon, first create a clock, rod, or shuttle and then attach the clock string or beacon to the object.

1. Select the object by clicking it

2. Choose Beacon or Clock String from the Objects menu

Deleting an Object

You can delete an object from the scenario. If you delete an object, any events, clocks strings, or beacons associated with that object are also deleted.

To delete a particular object, do the following:

1. Select the object by clicking it

2. Choose Delete from the Objects menu

You can delete all of the objects to clear the scenario. This also resets the time to zero.

To delete all the objects and reset the time to zero, do either of the following:

Choose Clear All from the Objects menu (or press Ⓐ)

OR

Choose New from the File menu (or press Ⓝ)

Creating an Event at an Object

You can create an event at the current location of any object.

To create an event at an object, do the following:

1. Click the object to select it

2. Choose Object Event from the Objects menu

The time of the event is set to the time as measured in the current reference frame.

You can also create an event at any position and time using the Enter Event... command described in the next section, "The *Spacetime Diagram*."

Programming the Shuttle

The shuttle is simply a clock that follows a series of programmed velocity changes (in other words, a script) that is replayed as you change the time.

To program the shuttle, do the following:

1. Create the shuttle and click on it to select it (see "Creating Objects" above)

2. Change the time (see "Changing Time" below) to the time you want the velocity change to occur

3. Choose Program Shuttle from the Objects menu (or press ⌘)

A dialog box identical to the one used to edit objects appears (see Figure 2).

4. Type the new velocity

5. Click OK

Alternatively, after step 2 you can do the following:

3. Hold down ⁅Shift⁆ and drag the shuttle to the lane of the new velocity

Two shuttles are now drawn on the screen: both at the same position but one at the velocity just before the jump and one at the new velocity. Only one shuttle exists, but it appears in two lanes because at the moment of the jump the velocity is undefined. At times prior to the jump, one shuttle appears in the old velocity lane; at times after the jump, one shuttle appears in the new velocity lane.

The shuttle can make as many velocity changes as you wish, but each velocity change must be made in chronological order. If you insert an additional velocity change into the shuttle's program, all subsequent velocity changes previously programmed are erased. A history of the velocity changes of the shuttle is listed in the *Table* window.

You cannot change the *spatial* position of the shuttle using either programming method. To do so would be to allow an instantaneous change in the location of the shuttle, which is physically impossible. If you find that you placed the shuttle in the wrong lane, delete it and create a new shuttle. By using the Enter Object command of the Objects menu, you can position the shuttle accurately.

Appendix A: How to . . .

This appendix lists commands by the actions they carry out (erase, create, etc.). Look for action verbs, listed alphabetically. Each description is very specific and brief—a quick reminder. Alternative ways to do the same thing are not listed. Fuller descriptions can be found in Appendix B under the menu that includes the command.

Align two objects	1. Click one object 2. Choose Align from the Objects menu 3. Click the other object (Does not work for Shuttle or for flashes emitted by a Beacon)
Annotate event	1. Choose Spacetime Diagram from the Window menu 2. Choose Select tool (an arrow) from the tool palette 3. Click the event 4. Choose Edit Event from the Objects menu 5. Type a comment in Description Window 6. Click the OK button (Comment appears in the *Table* window)
Annotate object	1. Choose Highway from the Window menu 2. Click the object 3. Choose Edit Object Details from the Objects menu 4. Type a comment in Description Window 5. Click the OK button (Comment appears in the *Table* window)
Call	See "Display"
Change frame	In *Highway*: 1. Click the object you want to jump to 2. Choose Jump to Object from the Transform menu

Create event	In *Highway*:

1. Change time (see above) to time when event is to occur
2. Select object at which event is to occur
3. Choose Object Event from Objects menu

In *Spacetime Diagram*:

1. Click the Event tool (top one; pointing finger)
2. Click the Create button
3. Position the pointer at the desired position x and time t (numerical values displayed at lower left)
4. Click mouse

Create flash	

1. Choose Highway from the Windows menu
2. Drag a flash icon from the bottom of the screen to the desired location on the top or bottom lanes of the highway (position x and velocity β are shown at bottom left corner)

Create hyperbola	

1. Choose Spacetime Diagram from the Windows menu
2. Click the Hyperbola tool (a curved line) from the tool palette
3. Click the Create button
4. Click the event the hyperbola should pass through

Create lightcone	

1. Choose Spacetime Diagram from the Windows menu
2. Click the Lightcone tool (two crossed lines) from the tool palette
3. Click the Create button
4. Click the event the lightcone should originate from

Create rod	

1. Choose Highway from the Windows menu
2. Drag a rod icon from the bottom of the screen to the desired location on the highway (position x and velocity β are shown at bottom left corner)

Create shuttle	

1. Choose Highway from Windows menu
2. Drag the shuttle icon from the bottom of screen to the desired location on the highway (position x and velocity β are shown at bottom left corner). Only one shuttle can be placed on the highway

|	
Delete connection	1. Choose Spacetime Diagram from Windows menu 2. Select Connect tool (a line connecting two dots) from tool palette 3. Select Delete button 4. Drag the pointer from one event to the other (the connection line disappears when the mouse button is released)
Delete event	1. Choose Spacetime Diagram from Windows menu 2. Select the Event tool (top one; pointing finger) from the tool palette 3. Select the Delete button 4. Click the event
Delete hyperbola	1. Choose Spacetime Diagram from Windows menu 2. Select the Hyperbola tool (a curved line) from the tool palette 3. Select the Delete button 4. Click the event the hyperbola passes through
Delete lightcone	1. Choose Spacetime Diagram from Windows menu 2. Select the Lightcone tool (two crossed lines) from the tool palette 3. Select the Delete button 4. Click the event the lightcone originates from
Delete object	1. Choose Highway from Windows menu 2. Select the object 3. Press the [Backspace] or [Delete] key
Disconnect	See "Delete connection"
Display help screen	1. Choose Help from the ⌘ menu (a different help screen appears for each window) 2. Click anywhere to resume from where you were
Display information about object	1. Choose Highway from Windows menu 2. Select the object (Information appears on line below the highway)
Display Table	1. Choose Table from Windows menu

Erase	See "Delete"

File	See "Save," "Open"

Get	See "Display"

Go to	See "Jump to" and "Transform"

Help	See "Display Help Screen"

Jump to object	1. Choose Highway from Windows menu 2. Select the object 3. Choose Jump to Object from Transform menu

Magnify	1. Choose Zoom In from Options menu

Move object	To move object by changing the time, click +*t* or –*t* buttons To move object without changing the time, 1. Select the object 2. Choose Edit Object Details from Objects menu 3. Make changes 4. Click OK button

Move screen left or right	1. Click < or > button

Move screen up or down	In *Spacetime Diagram*, 1. Click +*t* or –*t* button In *Split Window*, 1. Use scroll bar arrows or slider to move the highway 2. Click +*t* or –*t* buttons to move *Spacetime Diagram* 3. Drag black dividing bar to change which window is more exposed

New scenario	1. Choose New from File menu

Open scenario file	1. Choose Open from File menu 2. Double-click title of desired scenario file

Print	1. Choose window you want to print using Windows menu 2. Choose Print from File menu
Program Shuttle	1. Choose Highway from Windows menu 2. Hold down the ⸢Shift⸥ key (pointer changes to a hand) 3. Drag shuttle to lane of new velocity (coordinates shown on screen at lower left)
Quit	1. Choose Quit from File menu (you are asked if you want to save any changes you have made)
Read scenario file	See "Open scenario file"
Round Coordinates	1. Choose Round Coordinates from Options menu (when checked, pointer coordinates are rounded to nearest 0.25 unit)
Save scenario file	1. Choose Save from File menu to save using same name, or 1. Choose Save As from File menu to save using a different name
Select	1. Click object or event you want selected (to have nothing be selected, click a blank area of the window)
Show	See "Display"
Split the window	1. Choose Split Window from Windows menu
Synchronize clock	1. Choose Highway from Windows menu 2. Select clock to be synchronized 3. Choose Synchronize clock from Objects menu
Transform frame	In *Highway*, 1. Select object to whose frame you want to jump 2. Choose Jump to Object from Transform menu In *Highway* or *Spacetime Diagram*, 1. Choose Transform up or Transform down from Transform menu (select size of change by choosing appropriate $\partial\beta$ = from Transform menu), or

1. Choose Enter *b*, Gamma from Transform menu
2. Select *b* or Gamma button
3. If entering *g*, click *b* <0 or *b* >0
4. Type in numerical value
5. Click OK button

Transform to last frame	1. Choose Last Frame from Transform menu (The last frame is the frame previous to the current frame)
Transform to original frame	1. Choose Original Frame from Transform menu (The original frame is the frame at the beginning of the scenario)
Turn on/off interval labels	1. Choose Spacetime Diagram from Windows menu 2. Choose Display Interval from Options menu (when a ✓ appears on the menu, the interval labels are being shown)
Turn on/off worldlines	1. Choose Spacetime Diagram from Windows menu 2. Choose Display Worldlines from Options menu (when a ✓ appears on the menu, the worldlines of all objects are being shown)
Unselect	1. Select something else, or 2. Click a blank area of the window
Unsynchronize clock	1. Choose Highway from Windows menu 2. Choose Edit Object Details from Objects menu 3. Click inside the Time on Clock box 4. Type numerical value of new time 5. Click OK button
Write notes	See "Annotate"
Zoom in	1. Choose Zoom In from Options menu
Zoom out	1. Choose Zoom Out from Options menu

Appendix B: Commands, by Menu

Here is a complete listing of all the menu commands for SPACETIME. Some commands in these menus show a keyboard equivalent. These keyboard equivalents do *not* require the simultaneous pressing of the command key, ⌘.
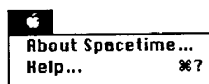
Apple (⌘) Menu

About Spacetime...
Help...   ⌘?

About Spacetime...

Help...

The Apple menu enables you to look at the SPACETIME title screen and the help screens.

Displays the SPACETIME title screen

Displays one of the four SPACETIME help screens. Which screen is displayed depends on which window is in the front when you choose Help.

File Menu

File
New   ⌘N
Open   ⌘O
Save   ⌘S
Save As...
Revert

Page Setup...
Print... ⌘P

Quit   ⌘Q
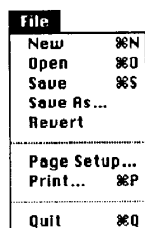
The File menu provides commands for the following functions:

* Starting a scenario
* Saving a scenario
* Reverting to a scenario as it was when last saved
* Printing the screen
* Quitting the SPACETIME program

You are asked to verify any operation that could result in losing information.

New   Creates a new, clean scenario on which to work. This command is executed by default when a program starts unless a specific file is being opened.

Open   Enables you to specify a disk file containing a saved scenario on which to work.

Save   Saves the current scenario to disk, using the existing name. If the scenario has not yet been saved, Save asks for a name (see Save As below).

Save as...	Asks for a name and a destination disk for a file before saving the scenario.
Revert	Returns a scenario to condition when it was last saved.
Print...	Prints the contents of the front-most window.
Quit	Exits the program, first asking if you want to save any changes made since the last time the current file was saved.

Windows Menu

Windows
✓Highway	⌘1
Space-Time Diagram	⌘2
Table	⌘3
Split Window	⌘4

The Windows menu controls which window is active and visible. All windows share the same data, so making a change on one affects the others. The windows are described in the corresponding sections of this manual.

Highway	Brings the *Highway* window to the front of the screen.
Spacetime Diagram	Brings the *Spacetime Diagram* window to the front of the screen.
Table	Brings the *Table* window to the front of the screen.
Split Window	Splits the screen between *Highway* and *Spacetime Diagram*.

Objects Menu

Objects
Clock String	
Beacon	
Object Event	
Synchronize clock	⌘Y
Align	
Delete Object	
Enter Object...	
Edit Object Details...	⌘E
Program Shuttle...	⌘G
Enter Event...	
Edit Event...	
Clear All	⌘A

The Objects menu provides commands for the following functions:

- Creating and deleting objects
- Editing (changing) objects
- Synchronizing the clock of an object
- Aligning objects (by changing the time)
- Creating events
- Editing (changing) events
- Clearing the scenario of all objects and events

Clock string	Attaches an infinite string of clocks to a selected rod, clock, or the shuttle. The clocks are spaced equal units of distance apart and are synchronized in the selected object's frame. If γ is close to 1, then the spacing between the clocks is one unit of distance, as measured in the clock rest frame. If γ is closer to 2, then the clocks are separated by two units of distance as measured in the clock rest frame, etc.
Beacon	Causes a selected rod or clock to emit flashes of light. Two flashes are emitted, one in each direction, at each unit of time in the selected object's frame, starting at $t = 0$. The shuttle cannot be made into a beacon. Neither can light flashes be made into beacons.

Object Event	Creates an event at the position of the currently selected object at the time specified by the current reference clock.
Synchronize Clock	Synchronizes the selected clock with other clocks in its rest frame.
Align	Select one object, choose this command, then click another object to change to the time at which the two objects are aligned. The align command does not work with two objects in the same velocity lane or with the shuttle.
Delete Object	Removes the selected object from the highway. Pressing the [Backspace] key or shift-clicking and dragging the object off of the highway also deletes the object.
Enter Object...	Enables you to create an object and numerically specify its position and speed.
Edit Object Details...	Enables you to change various parameters of the currently selected object. Use this command to add a description to an object. This description appears in the *Table*.
Program Shuttle...	Enables you to program the shuttle by changing its speed numerically. The shuttle remembers the speed change and jumps between frames at the appropriate time.
Enter Event...	Enables you to specify numerically the position and time of a new event.
Edit Event...	Enables you to edit the position and time of a selected event.
Clear All	Removes all events from the *Spacetime Diagram* and all objects from the highway.

Options Menu

The Options menu provides commands for the following functions:

- Program choices affecting time changes
- Changing the time to a particular time
- Automatic rounding of pointer coordinates
- Automatic display of intervals and worldlines on *Spacetime Diagram*
- Enlarging or reducing the area displayed on the screen

$\partial t = 0.01, 0.1, 1$	Sets the time increment used when stepping through time.
$t = 0$	Goes to the time $t = 0$ in the current reference frame.
Set Time...	Enables you to enter numerically the time to which you would like to go, as measured in the current reference frame.

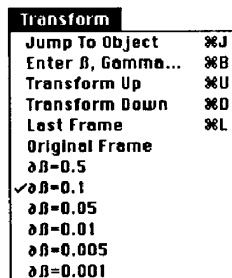|	
Stop At Events	This option has an effect only while you are changing time incrementally. When checked, every event is shown at the time it occurs, even if this requires changing the time less than one full step. This prevents you from time-stepping past an event.
Round Coordinates	When checked, rounds pointer x and t coordinates to the nearest multiple of 0.25.
Display Interval	When checked, causes the interval to be displayed on all connections in the *Spacetime Diagram*. (See "The *Spacetime Diagram*").
Display Wordlines	When checked, causes worldlines of objects on the highway to be displayed on the *Spacetime Diagram*. Dots at the intersections of the worldlines with the dashed line of simultaneity show the current position of each object.
Zoom In	Magnifies the scale of the window by a factor of two.
Zoom Out	Reduces the scale of the window by a factor of two.

Transform

Jump To Object	⌘J
Enter β, Gamma...	⌘B
Transform Up	⌘U
Transform Down	⌘D
Last Frame	⌘L
Original Frame	
$\partial\beta=0.5$	
✓$\partial\beta=0.1$	
$\partial\beta=0.05$	
$\partial\beta=0.01$	
$\partial\beta=0.005$	
$\partial\beta=0.001$	

Transform Menu

The Transform menu provides commands for the following functions:

- Jumping to the frame of an object
- Jumping to a specified frame
- Jumping to the original or last frame
- Changing the frame in incremental steps
- Choosing the size of the increment

Jump To Object	Jumps to the rest frame of the selected object.
Enter β, Gamma...	Enables you to specify a frame of reference, then jumps to that frame. You can specify numerically either β or γ for the desired frame with respect to the current frame.
Transform Up *Transform Down*	Jumps to frame moving with speed $\partial\beta$ in corresponding direction with respect to this frame.
Last Frame	Transforms to the most recent frame of reference before the current frame. Using this command repeatedly enables you to jump back and forth between the two most recent frames.
Original Frame	Transforms to the original frame of reference.
$\partial\beta= 0.1, 0.05...$	Sets the value of $\partial\beta$ used in Transform Up and Transform Down.

Introduction to Special Relativity

PHYS 1301
Prof. T.E. Coan
version: 4 Aug '99

Name _____ Section_____

Abstract

Calculations:

Data Table 1. γ vs. β

Object	β	γ
Clock A		
Rod B		
Rod C		
Rod D		
Rod E		

Data Table 2. Lorentz length contraction.

Object	X-position	β	Length	$\left(\dfrac{\text{Rod A lengt}}{\text{Rod length}}\right)$	γ
Rod A	0.00	0.00	1.00	1.00	1.00
Rod _____					
Rod _____					
Rod _____					
Rod _____					

Data Table 3. Time dilation

Object	X position	β	Clock time (sec)	$\left(\dfrac{\text{clock time}}{\text{clock B time}}\right)^{-1}$	γ
Clock B		0.00	10.0		1.00
Clock ____					
Clock ____					
Clock ____					
Clock ____					

Questions:

Question 1:

Question 2

Question 3

Question 4

Question 5

Question 6

Question 7

Question 8

Question 9

Conclusion: State clearly and concisely what you learned about how special relativity affects the measurements of time and length.