Your Name: ____

Your lab partner(s): ____________________________________

Lab 2: Special Theory of Relativity

A. Introduction to the Program

- Go to http://www.compadre.org/PQP/
- On the left-hand side of the screen, click on "*Special Relativity*".
- You will do several exercises using this program. Some program features:
  - **Animations** are controlled by these buttons: *play*, *pause*, *step*>>, <<*step* and *reset*.
  - **Units** are given in boldface in the statement of the problem
  - **Data input** can be in the form of numbers or formulas
  - **Data output** can be in the form of on-screen numerical values, data tables or graphs; you can usually right-click on the graph to clone it and resize it for a better view.
- **Light Clock:** Many simulations will use a light clock, represented by a box with a mirror on its top wall and a light pulse emitter and detector at its bottom wall. After light is emitted from the bottom, reflects from the mirror, and then returns to the bottom, the detector triggers a tick of the clock and another light pulse is emitted. The total vertical distance traveled by the light for the stationary clock is L_0, where $L_0/2$ is the distance between the bottom and top walls of the clock. The clock reads time in meters, which means that every click measures the time it takes for light to travel distance L_0.

B. Space and Time in Special Relativity

1. After clicking on "*Special Relativity*", select "*Ch. 2: Space and Time in Special Relativity*". If asked, give your permission to run Java.
2. **Simultaneity:** When we are dealing with moving reference frames, we must keep in mind that events that are simultaneous in one reference frame are not simultaneous in another. To study this, click on "*Section 2.3: Simultaneity*". Read the explanations and follow the instructions for this section.
3. **Time Dilation:** Select "*Section 2.4*". In this animation, the red light clock is stationary. We will refer to a stationary observer as an observer that is at rest with respect to the red clock. Set the speed of the green clock to β (= v/c) = 0.5 and press the "set value and play" button. When the red clock registers 5 ticks, the reading on the green (moving) clock is:

   ____

   Therefore, the moving clock runs _____________ when observed from stationary frames.
   (faster/slower)

   This happens because the distances traveled by the two light pulses must be the same as viewed in the frame of the stationary clock. However, the distance traveled by the moving clock, as seen from the point-of-view of an observer in the stationary clock's reference frame, involves both horizontal and vertical components, and it is only the vertical component of the light pulse's motion that contributes to the clock ticks (as seen from the reference frame of the clock at rest). Following the standard derivations (see the textbook), we get that:

$$\Delta t = \frac{\Delta t'}{\sqrt{1-\beta^2}} = \gamma \Delta t'$$

$\Delta t' = L_0/c$ = the time interval seen by an observer that is stationary with respect to the red clock; this is the same time that an observer moving together with the green clock would observe on the green clock.

Δt = the time interval observed on the green clock by someone in the stationary frame (frame of the red clock in this animation).

4. **Length Contraction:** Still in "*Section 2.4*", go to the second exercise at the bottom of the screen. Set the speed of the green clock to β (= v/*c*) = 0.5 and press the "set value and play" button. In this animation, the light clocks are rotated 90° (position is given in meters by dragging the cross-haired cursor around the animation). The results we saw for the time dilation still occurs for the rotated clocks. Therefore, given the fact that in the stationary frame the moving clock still ticks slower, the only way for this to happen is for the distance between the walls of the moving clock to be contracted. In fact, the clock must appear to be contracted to $L' = L_0/\gamma$ where L_0 is the length of the clock as seen in its own (stationary) reference frame and L' is the length of the moving clock as seen from the stationary frame. Notice that length contraction occurs only in the direction of motion of the object and not in the direction perpendicular to it.

Do *Physlet* Problems listed below and answer the questions:

5. Problem 2.1: Which of the four Animations is not an inertial reference frame?

   Answer: ____

6. Problem 2.3: calculate the time difference between these light flashes as seen from the beacon:

   ____

   Use the above time value and the speed of the spaceship to calculate the time difference between the light flashes as seen from inside the spaceship:

   ____

7. Problem 2.4: How much is the length of the pole in the reference frame of the barn?

   Answer: _____________________________________

How much is the speed of the pole with respect to the barn?

Answer: ____

How much is the length of the pole in its own reference frame?

Answer: ____

8. Problem 2.7: Which event (1 or 2) occurs sooner for the following relative velocities:

v/c	Green observer Event #	Red observer Event #
0.2		
0.4		
0.6		
0.8		
0.99		

Which of the following is true for all relative velocities (i.e from 0.2c to 0.99c)?
A) There is a unique speed when the events are simultaneous in both reference frames.
B) Event 1 always occurs before event 2.
C) At any speed, the red and green observers will always agree on which event occurred first.
______ D) None of the above.

C. Relativistic Mechanics

For momentum $\vec{p}$ to be conserved, it needs to be redefined as:

$$\vec{p} = \frac{m\vec{v}}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

where $\vec{v}$ is the velocity of the particle as measured in a given reference frame.

9. After clicking on "*Special Relativity*", select "*Ch. 3: Relativistic Mechanics*". If asked, give your permission to run *Java*.
10. Select "Section 3.2: Understanding Mass-Energy Equivalence". Play the animation and read the explanation of the mass-energy equivalence, $E = mc^2$.
11. Click on "Section 3.3: Understanding the Energy-Momentum Equation". The total energy, E,

of a particle is:

$$E = \sqrt{(pc)^2 + (m_o c^2)^2}$$

where p is the relativistic momentum, c is the speed of light, and m_0 is the rest mass of the particle (the mass of the particle measured in its own reference frame).

The total energy of the particle can also be expressed through its kinetic energy:

$$E = m_o c^2 + E_k$$

Set the values of m_o and E as given in the table below and record your observations.

m_o (MeV/c^2)	E (MeV)	Maximum β (= v/c)	For the max velocity, visually compare m_0c^2 with E_k (you don't need to calculate anything)	For the max velocity, visually compare *pc* with E (you don't need to calculate anything)
200	2000			
1000	2000			
1200	100 (not a typo!)			
1999	2000			

12. Using the animation in "Section 3.4: Exploring Particle Decays", choose a mass and an initial speed of a particle that will spontaneously decay into two other particles. Pick the masses of the two decay products that you want to create. How does the momentum before the decay compare to the momentum after?

____

Now run the animation in reverse. Notice that you see two particles colliding and creating a third particle that is more massive than the sum of the two initial particles. How is this possible? Where does the additional mass come from?

____

Do *Physlet* Problems listed below and answer the questions.

13. Problem 3.2: Which graph correctly shows the total energy of an electron? Explain.

Answer: ____

14. Problem 3.3: Set the initial momentum of the Sigma particle (Σ) to 5000 MeV/c. Run the simulation in which the Σ particle decays into a pion (π) and a neutron (n). Use the conservation of the total energy before and after the decay to find the rest mass of the Σ particle. Show your calculations.

Answer: $m_\Sigma =$ ____________

15. Problem 3.7:

How much is the frequency (in inverse years) of Pink's pulses in Pink's reference frame?

Answer: ____

How much is the frequency in Green's frame when Green is travelling away from Pink?

Answer: ____

How much is the frequency in Green's frame when Green is travelling toward Pink?

Answer: ____

16. Click on Section 3.5 (not Problem 3.5!) to study the relativistic Doppler effect - a phenomenon in which light from a moving source is shifted in wavelength. The Doppler shift is due to the relative motion of the two reference frames (the source and receiver) and is given by:

$$\frac{1}{\lambda} = \frac{1}{\lambda'} \cdot \sqrt{\frac{1 \mp \beta}{1 \pm \beta}}$$

We use the upper signs (−, +) for objects moving away from each other, and the lower signs

(+, −) for objects moving towards each other. Here $\beta = v/c$, λ' is the proper wavelength measured in the frame of the light source, and λ is the wavelength as seen from the reference frame moving with respect to the light source.

17. Problem 3.8: Observe the two pairs of spectral lines from the car at rest (your car) and from the moving car. Left click on each line to read the corresponding wavelength. Calculate the average wavelength for each pair of spectral lines and record below.

For the car at rest: λ_{avg} = ________________ (nm)

For the moving car: λ_{avg} = _______________ (nm)

Is the car moving toward or away from you? Explain how you know this.

Answer: ____

Calculate the speed of the moving car and record below. Show your calculations.

Answer: ____________________________________