Name______________________________ **Date**__________________

PRE-LAB PREPARATION SHEET FOR LAB 6: IMPULSE AND MOMENTUM

(Due at the beginning of Lab 6)

Directions:

Read over Lab 5 and then answer the following questions about the procedures.

1. What is your Prediction 1-2? Which would be more effective at closing the door—the bouncy ball or the clay ball of the same mass?

2. What is the final momentum of the clay ball in Activity 1-3?

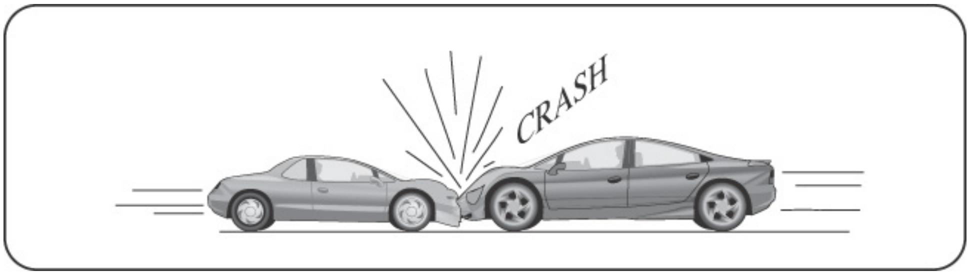
3. How do you find the impulse of a force from the force vs. time graph?

4. Why is the collision in Activity 2-2 made with a spring?

5. How will you measure the impulse in Activity 2-2?

Name__________________ Date__________ Partners________________________

LAB 6: IMPULSE AND MOMENTUM



In any system of bodies which act on each other, action and reaction, estimated by momentum gained and lost, balance each other according to the laws of equilibrium.

—Jean de la Rond D'Alembert

OBJECTIVES

- To understand the definition of momentum and its vector nature as it applies to one-dimensional collisions.
- To develop the concept of impulse to explain how forces act over time when an object undergoes a collision.
- To study the interaction forces between objects that undergo collisions.
- To examine the relationship between impulse and momentum experimentally in both *elastic* (bouncy) and *inelastic* (sticky) collisions.

OVERVIEW

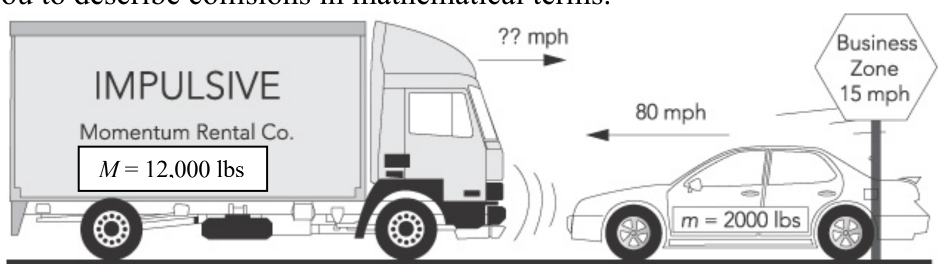
In this lab we explore the forces of interaction between two objects and study the changes in motion that result from these interactions. We are especially interested in studying collisions and explosions in which interactions take place in fractions of a second. Early investigators spent a considerable amount of time trying to observe collisions and explosions, but they encountered difficulties. This is not surprising, since the observation of the details of such phenomena requires the use of instruments—such as high-speed cameras—that were not yet invented.

However, the principles describing the outcomes of collisions were well understood by the late seventeenth century when several leading European scientists, including Isaac Newton, developed the concept of *quantity-of-motion* to describe both *elastic* collisions in which objects bounce off each other and *inelastic* collisions in which objects stick together. These days we use the word *momentum* rather than *quantity-of- motion* to help us understand the nature of collisions and explosions.

We will begin our study of collisions by exploring the relationship between the forces experienced by an object and its momentum change. It can be shown mathematically from Newton's laws and experimentally from our own observations that the change in momentum of an object is equal to a quantity called *impulse.* Impulse takes into account both the magnitude of the applied force at each instant in time and the time interval over which this force acts. The statement of equality between impulse and momentum change is known as the *impulse–momentum theorem.*

INVESTIGATION 1: MOMENTUM AND MOMENTUM CHANGE

In this investigation we are going to develop the concept of momentum to predict the outcome of collisions. But you don't officially know what momentum is because we haven't defined it yet. Let's start by predicting what will happen as a result of a simple one-dimensional collision. This should help you figure out how to define momentum to enable you to describe collisions in mathematical terms.



It's early fall and you are driving along a two-lane highway in a rented moving van. It's full of all of your possessions, so you and the loaded truck weigh 12,000 lbs. You have just slowed down to 15 mph because you're in a business zone. Just as you pass through an intersection, you see a 2000-lb sports car in the other lane heading straight for the intersection at about 80 mph. It will never be able to stop for the stop sign!

A desperate thought crosses your mind. You just have time to swing into the other lane and speed up a bit before making a head-on collision with the sports car. *You want your truck and the sports car to crumple into a heap that sticks together and doesn't move.* Can you keep the sports car from entering the intersection or is this just a suicidal act?

To simulate this situation you can observe two carts of different mass set up to stick together in trial collisions. You will need:

- 2 IOLabs (work with a partner)
- 2 thumb screws with velcro
- 1 wood or metal block of mass more or less equal to IOLab
- Scotch tape

Screw the thumb screws into the IOLab force sensors. Place the IOLabs so that the wheels are on a flat and horizontal surface. Use tape to attach the wood block to the top of one of the IOLabs. Note that the wood block is about the same mass at the IOLab.

Activity 1-1: Can You Stop the Car?

Prediction 1-1: How fast would you have to be going to completely stop the sports car? Explain the reasons for your prediction.

1. Try some head-on collisions with the IOLabs of different mass to simulate the event on a small scale. Be sure that the IOLabs stick together after the collision.

2. Observe *qualitatively* what combinations of velocities cause the two IOLabs to be at rest after the collision.

Question 1-1: What happens when the less massive IOLab is moving faster than the more massive IOLab? Slower? At roughly the same speed?

Question 1-2: Based on your prediction and your observations, what mathematical definition might you use to describe the momentum you would need to stop an oncoming vehicle traveling with a known mass and velocity? Should it depend on the mass, the velocity, or both? Explain your choice.

Comment: Just to double-check your reasoning, you should have come to the conclusion that momentum is defined by the vector equation

$\vec{p} \equiv m\,\vec{v}$ where the symbol ≡ is used to designate "defined as."

Originally, Newton did not use the concept of acceleration or velocity in his laws. Instead, he used the term "motion," which he defined as the product of mass and velocity (the quantity we now call momentum). Let's examine a translation from Latin of Newton's first two laws with some parenthetical changes for clarity.

NEWTON'S FIRST TWO LAWS OF MOTION

1. Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed on it.

2. The (rate of) change of motion is proportional to the motive force impressed: and is made in the direction of the right line in which that force is impressed.

The more familiar contemporary statement of the second law is that the net force on an object can be calculated as the product of its mass and its acceleration where the direction of the force and of the resulting acceleration are the same. Newton's statement of the second law and the more modern statement are mathematically equivalent.

Now let's test your intuition about momentum and forces. You are sleeping in your room, and your younger brother is making too much noise outside. To keep the noise out, you want to close the door. The room is so messy that you cannot get to the door. The only way to close the door is to throw either a blob of clay or a bouncy ball at the door.

To complete the next activity you will need:

- IOLab
- Knurled head thumb screw with plate
- Thumbtack
- Clay
- Bouncy ball

Activity 1-2: Which Packs the Bigger Wallop—A Clay Blob or a Bouncy Ball?

Prediction 1-2: Assuming the clay blob and the bouncy ball have the same mass, and that you throw them with the same velocity, which would you throw to close the door—the clay blob, which will stick to the door, or the bouncy ball, which will bounce back at almost the same speed as it had before it collided with the door? Give reasons for your choice using any notions you already have or any new concepts developed in physics, such as force, energy, momentum, or Newton's laws. If you think that there is no difference, justify your answer. Remember, your life depends on it!

You can test your prediction by dropping a clay blob and a bouncy ball from equal heights onto the force sensor of the IOLab. First, set up your IOLab to gather force data:

1. Calibrate the force sensor of your IOLab
2. Insert the knurled head thumb screw into the force probe of the IOLab.
3. Run the IOLab software, select "Force"
4. Place the IOLab so that the force sensor is on top as pictured
5. Zero the force sensor, then weigh the bouncy ball.
6. Break off a piece of clay and obtain a piece of equal weight as the bouncy ball.
7. Weigh the rest of the clay.

Complete the first two rows in the table below using a height of approximately 10 cm above the surface of the thumb screw plate. For dropping the clay balls, put a small piece of clay on the platform and stick the thumb tack onto the plate pointing upward. Now if you drop the clay on the thumbtack it will stick. This will make this experiment go much easier. Of course, you will have to Rezero the force sensor once you put the thumbtack and clay on the platform.

Table 5-1

	Weight (N)	Mass (kg)	Height (m)	Maximum force (N)
Bouncy ball				
Small clay ball (same height and weight)				
More massive clay ball (same height)				
Small clay ball, larger height				

Question 1-3: Did your observations agree with your prediction? Which resulted in a bigger maximum force—the bouncy ball or clay?

Question 1-4: Based on your observations, which should you throw at the door—the bouncy ball or the clay? Explain.

Prediction 1-3: What will happen to the maximum force if you increase the mass of the ball of clay but allow it to collide with the same velocity (drop it from the same height)?

Prediction 1-4: What will happen to the maximum force if the velocity just before impact is increased by dropping the ball from a greater height?

10. Test your Prediction 1-3 by using a more massive clay ball dropped from the same height, so that the mass of the clay ball is about doubled. Measure the maximum force and record it in Table 5-1.

11. Test your Prediction 1-4 by dropping the smaller clay ball from about twice the height. Record the height and maximum force in Table 5-1.

Question 1-5: Did your observations agree with your predictions? What factors seem to determine the maximum force exerted on the force sensor?

It would be nice to be able to use Newton's formulation of the *second law* of motion to find collision forces, but it is difficult to measure the rate of change of momentum during a rapid collision without special instruments. However, measuring the momenta of objects just before and just after a collision is not usually too difficult. This led scientists in the seventeenth and eighteenth centuries to concentrate on the overall changes in momentum that resulted from collisions. They then tried to relate changes in momentum to the forces experienced by an object during a collision.

In the next activity you are going to explore the mathematics of calculating momentum changes for the two types of collisions—the *elastic* collision, where the ball bounces off the door, and the *inelastic* collision, where the clay blob sticks to the door.

Activity 1-3: Momentum Changes

Prediction 1-5: Which object undergoes the greater *momentum change* during the collision with a door—the clay blob or the bouncy ball? Explain your reasoning carefully.

> **Comment:** Recall that momentum is defined as a *vector* quantity; i.e., it has both *magnitude* and *direction.* Mathematically, momentum change is given by the equation
> $$\Delta\vec{p} = \vec{p}_{final} - \vec{p}_{initial}$$
> where $\vec{p}_{initial}$ is the initial momentum of the object just before a collision and $\vec{p}_{final}$ is its final momentum just after. Remember, in one dimension, the *direction* of a vector is indicated by its *sign.*

Check your prediction with some calculations of the momentum changes for both collisions that you carried out. This is a good review of the properties of one-dimensional vectors. Carry out the following calculations for the *original height* and *original mass* of both the clay blob and bouncy ball.

1. Calculate the initial momentum of the clay blob just before it hits the IOLab plate. (**Hint:** You will need to recall from kinematics with constant acceleration that, $v = \left(2a_g h\right)^{1/2}$, where a_g = 9.8 m/s^2 is the gravitational acceleration, and h is the distance the ball falls before hitting the table.) Take the positive y direction as *upward.* Show your calculation.

$$\vec{p}_{initial} =$$

2. What is the final momentum of the clay blob after it collides with the IOLab? Explain.

$$\vec{p}_{final} =$$

3. What is the change in momentum of the clay blob? Be careful of the sign.

$\Delta\vec{p} =$

4. Now calculate the change in momentum of the bouncy ball from just before it hits the IOLab until just after it bounces up. Assume that the ball bounces in such a way that the *magnitude* of its velocity doesn't change. Show your calculation below. Be very careful of signs!

$\Delta\vec{p} =$

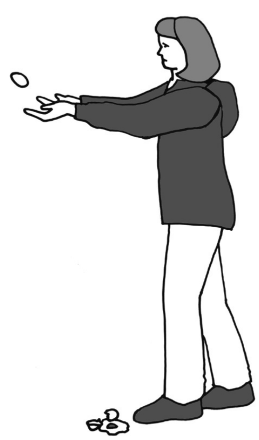
Question 1-6: Compare your calculated changes in momentum to your predictions. Do they agree? Which object had the larger change in momentum?

Question 1-7: How does change in momentum seem to be related to the maximum force applied to the ball? **Note:** Assume that the time intervals the clay ball and bouncy ball are in contact with the IOLab are the same.

You have observed that the ball that bounces off the door will exert a larger maximum force on the door than the clay blob, which sticks to it. The ball that bounces off the door has the larger change in momentum because it reverses direction, while the clay blob merely comes to rest stuck to the door.

However, just looking at the *maximum* force exerted on the ball does not tell the whole story. You can see this from a simple experiment tossing raw eggs. We will do it as a thought experiment to avoid the mess! Suppose somebody tosses you a raw egg and you catch it. (In physics jargon, one would say in a very official tone of voice, "The egg and the hand have undergone an *inelastic collision.*") What is the relationship between the force you have to exert on the egg to stop it, the time it takes you to stop it, and the momentum change that the egg experiences? You ought to have some intuition about this matter. In more ordinary language, would you want to catch the egg slowly (by relaxing your hands and pulling them back) or quickly (by holding your hands rigidly)?

Activity 1-4: Momentum Change and Force on an Egg



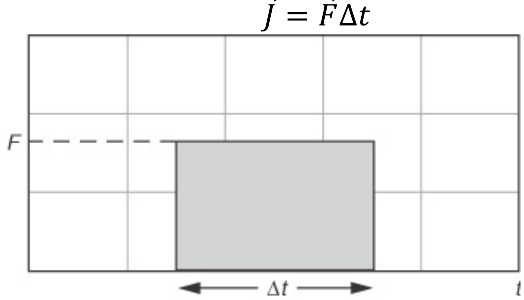
Question 1-10: Suppose the time you take to bring the egg to a stop is Δt. Would you rather catch the egg in such a way that Δt is small or large? Why?

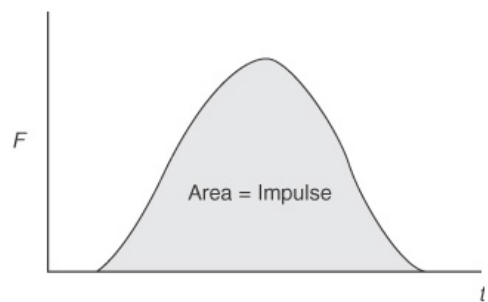
Question 1-11: What do you suspect might happen to the average force you exert on the egg while catching it when Δt is small?

In bringing an egg to rest, the change in momentum is the same whether you use a large force during a short time interval or a small force during a long time interval. *Of course, which one you choose makes a lot of difference in whether the egg breaks or not!*

A quantity called *impulse* may have been defined for you in lecture and/or in your textbook. It combines the applied force and the time interval over which it acts. *In one dimension,* for a *constant* force $\vec{F}$ acting over a time interval Δt, as shown in the graph below, the impulse $\vec{J}$ is

$$\vec{J} = \vec{F}\Delta t$$



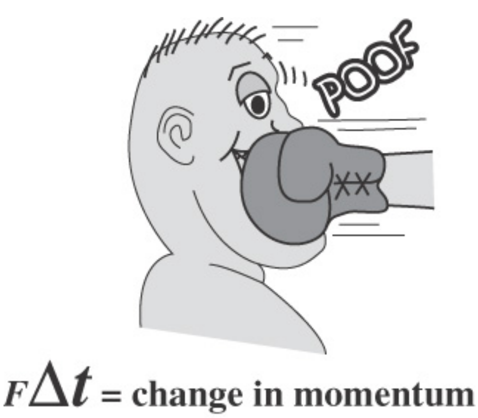


As you can see, a large force acting over a short time and a small force acting over a long time can have the same impulse.

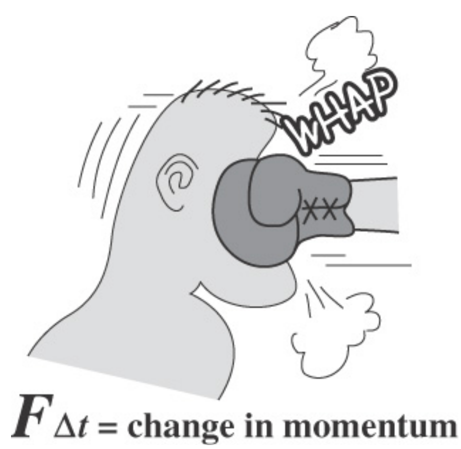
Note that $F\Delta t$ is the area of the rectangle, i.e., the area under the force vs. time curve. If the applied force is not constant, then the impulse can still be calculated as the *area under the force vs. time graph.*

It is the impulse that equals the change in momentum. *In one dimension,*

$$\vec{J} = \Delta\vec{p}$$



Small force, longer impact time (like catching the egg)



Just the opposite

INVESTIGATION 2: IMPULSE, MOMENTUM, AND COLLISIONS

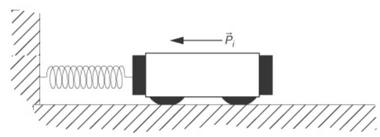
Let's first see qualitatively what an impulse curve might look like in a real collision in which the forces change over time during the collision. To explore this idea you will need:

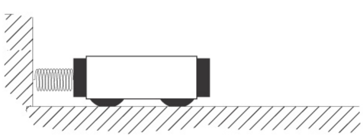
- IOLab
- Spring and screw
- Wall

Activity 2-1: Observing Collision Forces That Change with Time

Attach the spring and screw to the IOLab. Place the IOLab so that the wheels are on a horizontal surface. Collide the IOLab with the wall several times and observe what happens to the spring.

Question 2-1: If friction is negligible, what is the net force exerted on the cart *just before* it starts to collide?

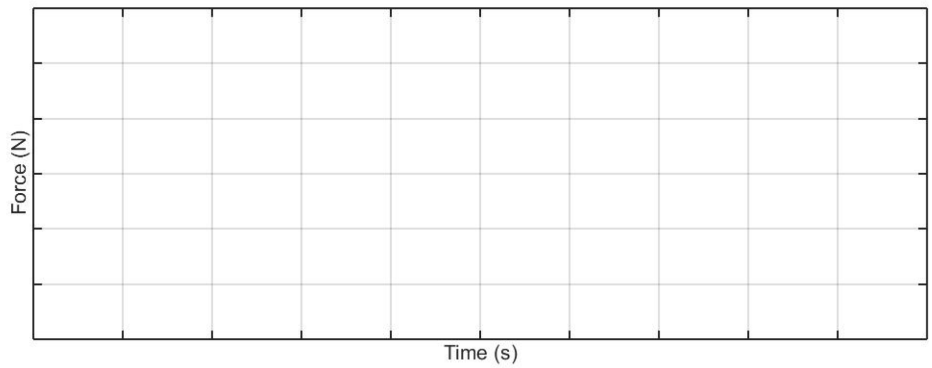




Question 2-2: When is the magnitude of the force on the cart maximum?

Question 2-3: Roughly how long does the collision process take? Half a second? Less time? Several seconds?

Prediction 2-1: Remembering what you observed, attempt a rough sketch of the shape of the force the wall exerts on the IOLab as a function of time during the collision.



During the collision the force is not constant. To measure the impulse and compare it to the change in momentum of the IOLab, you must (1) plot a force–time graph and find the area under it, and (2) measure the velocity of the cart before and after the collision with the wall. Fortunately, the IOLab will allow you to do this. You will need:

- IOLab
- Knurled head thumb screw
- Spring and screw

Activity 2-2: Examining the Impulse–Momentum Theorem in a *Nearly Elastic* Collision

In a perfectly elastic collision between a cart and a wall, the cart would recoil with exactly the same magnitude of momentum that it had before the collision. Because your cart's spring bumper is not perfect, you can only produce a *nearly* elastic collision.

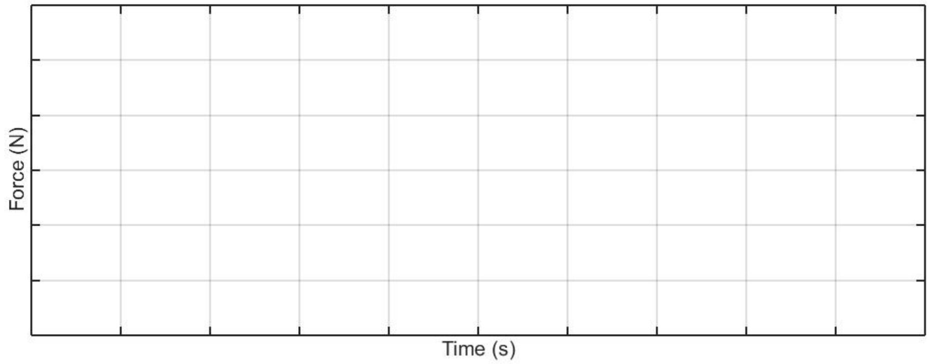
1. Attach the knurled head thumb screw to the IOLab force sensor. Make sure your force sensor is calibrated and is zeroed. Balance the IOLab on the thumb screw. In the IOLab software, click on force. Click on record and measure the weight of the IOLab:

   Weight = ____________(N)

2. Use the formula weight = mass*g to determine the mass of the IOLab:

   Mass = ______________(kg)

3. Remove the knurled head thumb screw and attach the spring and screw to the IOLab.
4. Click on "reset" in the IOLab software. Click on the "**Force**" and "**Wheel**". Deselect position (R_y) and acceleration (A_y) so that you are only graphing velocity (V_y). Aim the IOLab at a wall or other strong vertical surface (the spring should be pointing towards the wall). Click on "Record". Gently push and let go of the IOLab. Click "Stop" after the IOLab leaves the wall.
5. Save your graph and sketch them below.



Question 2-4: Does the shape of the force–time graph agree with your Prediction 2-1? Explain.

6. Click and drag across the large peak in the force graph. The area under the force–time graph is the impulse. It will be labelled “a” (for area) in the graph and have units of N*s.

   $J =$ ____ $\mathrm{N \cdot s}$

8. Move the cursor onto the velocity graph so that a vertical line appears and lines up at the left end of the large peak in the force graph. This is the velocity of the IOLab just before it collides with the wall, the initial velocity. Move the cursor onto the velocity graph so that a vertical line appears and lines up at the right end of the large peak in the force graph. This is the velocity of the IOLab just after it collides with the wall, the final velocity.

   Don’t forget to include a sign. Positive velocity should be *away from* the wall.

   Initial velocity toward the wall:______m/s

   Final velocity away from the wall:______m/s

9. Calculate the change in momentum of the cart. Show your calculations.

   $\Delta p =$ ________ kg m/s

Question 2-5: Did the calculated change in momentum of the IOLab equal the measured impulse applied to it by the wall during the nearly elastic collision? Explain.

What would the impulse be if the initial momentum of the IOLab were larger? What if the collision were inelastic rather than elastic, i.e., what if the cart stuck to the wall after the collision? If you have more time, do the following extensions to find answers to these questions.

Extension 2-3: A Larger Momentum Change

Equipment you will need:

- IOLab
- Wood or metal block of mass approximately equal to the IOLab
- Tape
- Spring and screw

Suppose a more massive IOLab collided nearly elastically with the wall. What would the impulse be? You can add mass to the IOLab and find out.

Prediction E2-2: If the IOLab had twice the mass and collided with the wall elastically moving at the same velocity as in Activity 2-2, how large do you think the impulse would be? The same as before? Larger? Smaller? Why?

Test your prediction. Tape the wood block to the IOLab to make the total mass roughly twice as large. Use the method from Activity 2-1 to determine the new mass of the IOLab.

New mass of IOLab: ______kg

Collide the IOLab with the wall again. Try several times until you get the initial velocity about the same as in Activity 2-2. Find the velocities, as in Activity 2-2, and calculate the change in momentum.

Velocity toward the wall: ______m/s

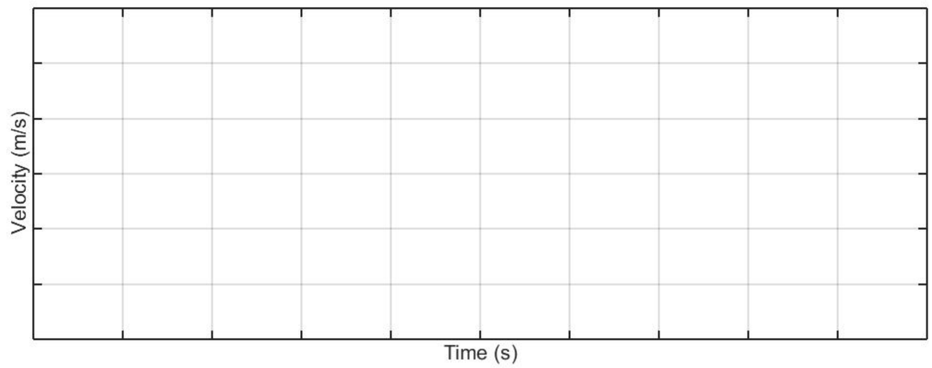
Velocity away from the wall: ______m/s

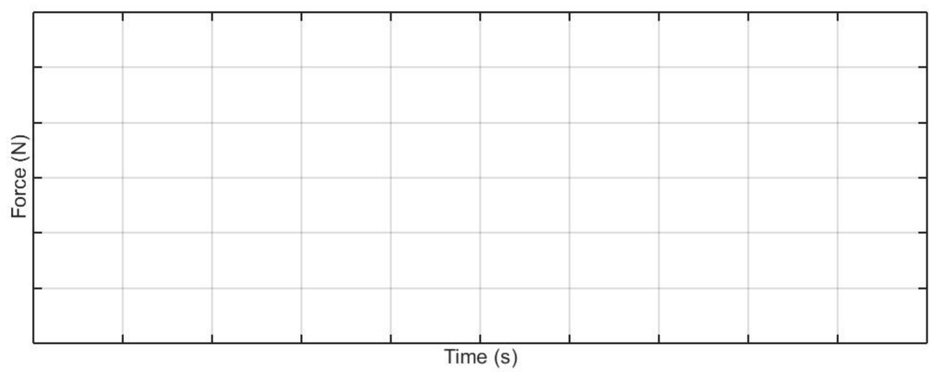
$\Delta p =$ _______ kg m/s

Find the impulse as in Activity 2-2.

$$J = \_\_\_\ \mathrm{N \cdot s}$$

Save your graphs and sketch them below:





Question E2-6: Did the impulse agree with your prediction? Explain.

Question E2-7: Were the impulse and change in momentum equal to each other? Explain why you think the results came out the way they did.

Extension 2-4: Impulse–Momentum Theorem in an Inelastic Collision

It is also possible to examine the impulse–momentum theorem in a collision where the cart sticks to the wall and comes to rest after the collision. This can be done by replacing the spring with the thumb screw and some clay.

In addition to the equipment you have used so far, you will need

- Thumb screw with plate
- Large blob of clay
- Thumbtack

Leave the wood block on your cart so that its mass is the same as in Extension 2-3. Remove the spring and replace it with a thumb screw. Attach a small piece of clay and attach the thumbtack with the sharp point pointing towards the large blob of clay which is attached to the wall.

Prediction E2-3: Now when the cart hits the wall, it will come to rest stuck to the clay. What do you predict about the impulse? Will it be the same, larger, or smaller than in the nearly elastic collision? What do you predict now about the impulse and momentum? Will they equal each other, or will one be larger than the other?

Collide the cart with the clay. Try several times until you get the initial velocity about the same as in Activity 2-2. Find the average velocity, as in Activity 2-2, and calculate the change in momentum.

Velocity toward the wall: ______m/s

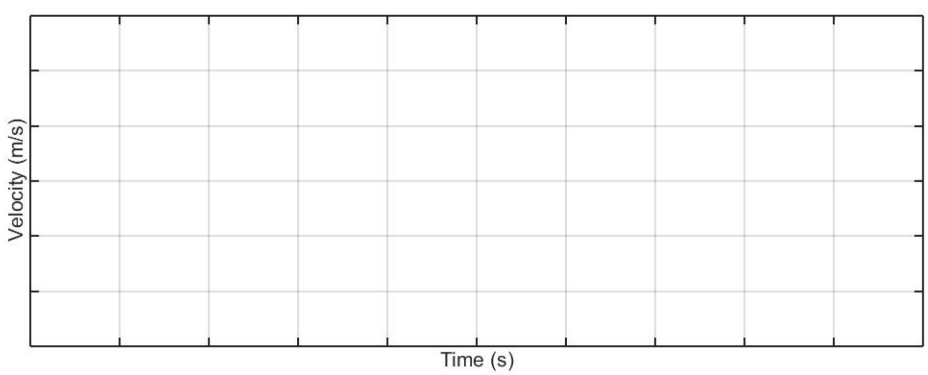
Velocity away from the wall: ______m/s

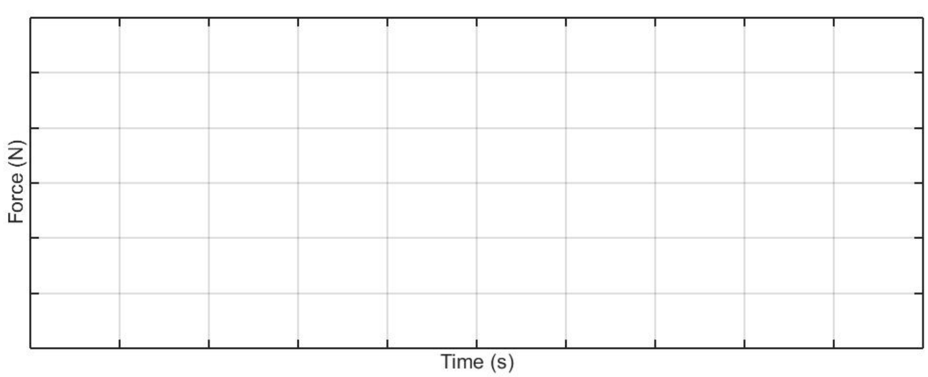
$\Delta p =$ ________ kg m/s

Find the impulse as in Activity 2-2.

$J =$ ____ N·s

Save your graphs and sketch them on the axes below.





Question E2-8: Compare the force–time curve for the inelastic collision to that for the nearly elastic collision. How are they similar and how are they different?

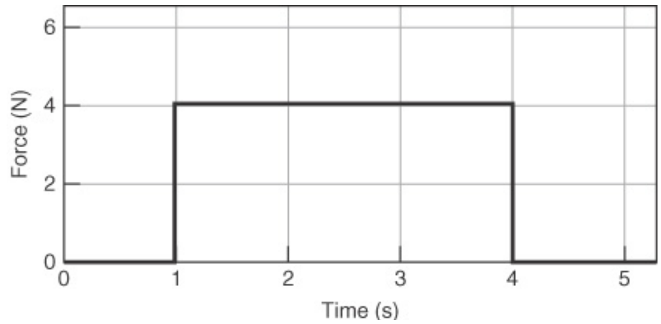
Question E2-9: Were the impulse and change in momentum equal to each other for the inelastic collision? Explain why you think the results came out the way they did.

Question E2-10: Do you think that the momentum change is equal to the impulse for all collisions? Justify your answer.

Question E2-11: Now think back at throwing a clay blob or a bouncy ball at the door. Do your answers to Questions 1-3 and 1-4 make sense? Justify your answer.

HOMEWORK FOR LAB 6:
IMPULSE AND MOMENTUM

1. Find the impulse of the force shown on the force–time graph below. Explain how you found your answer.



2. An object of mass 2.5 kg is moving in the negative *x* direction at a velocity of 2.0 m/s. It experiences the force shown above for 3 S. What is the final velocity after the object has experienced the impulse. Show your calculations.

3. A ball of mass 1.5 kg is thrown upward. It leaves the thrower's hand with a velocity of 10 m/s. The following questions refer to the motion *after the ball leaves the thrower's hand.* Assume that the upward direction is positive. Show all calculations.

a. How long does it take for the ball to return to the thrower's hand?

b. What is the final velocity of the ball just before it reaches the hand?

c. What is the change in momentum of the ball?

d. What is the impulse calculated from the change in momentum?

e. What is the average force acting on the ball? What is the origin of this force?

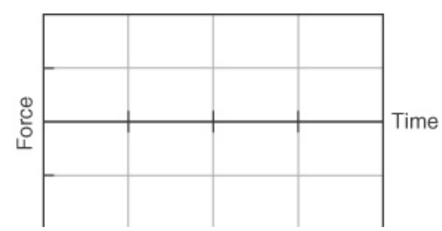
4. After the ball in Question 3 hits the thrower's hand, it comes to rest in a time of 0.25 s.

a. What is the net impulse exerted on the ball by the hand?

b. What is the average force exerted by the hand on the ball? (**Hint:** Don't forget the gravitational force.)

5. A bouncy ball of mass 0.05 kg is dropped from a height of 10 cm above a table top. It bounces off the table and rises to the same height.

Sketch the shape of the force exerted on the ball by the table as a function of time on the axes on the right.

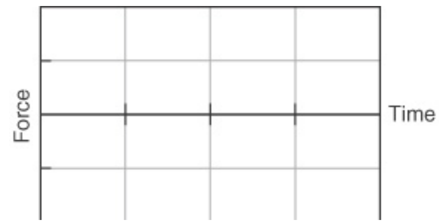


6. If the bouncy ball was in contact with the table for 30 ms, calculate the average force exerted *on the ball by the table.* Show your work. (**Hint:** First calculate the momentum before and after hitting the table. Don't forget the gravitational force.)

Average force: ______

7. The bouncy ball is now replaced by a clay ball the same size and mass. The ball is dropped from the same height and it sticks to the table.

Sketch the shape of the force exerted on the ball by the table as a function of time on the axes on the right.



8. Calculate the impulse exerted on the clay ball and compare it to that with the bouncy ball. Which is larger or are they both the same? Explain.

9. If the collision of the clay ball with the table takes the same 30 ms as the collision of the bouncy ball, calculate the average force exerted *by the table on the clay ball* and compare it to that exerted on the bouncy ball. Which is larger or are they the same? Explain.

10. Suppose that the clay has twice the mass and is dropped from the same height. Compare the impulse exerted on the ball by the table to that with the smaller clay ball. Explain your answer.

11. Suppose that the original clay ball is dropped from twice the height. Compare the impulse exerted on the ball by the table to that for the smaller height. Explain your answer.