Physics 200B Lab 9
Impulse, momentum, and collisions

OBJECTIVES

- To examine the relationship between impulse and momentum change.
- To understand the definition of momentum and its vector nature.
- To study the interaction forces between objects that undergo collisions.
- To investigate the behavior of linear momentum and kinetic energy for different types of 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 in which interactions take place in fractions of a second.

A particularly important quantity in collisions is called the momentum and it is equal to the product of the mass of an object and its velocity ($\mathbf{p} = m\mathbf{v}$). One of the reasons it is so important is that the total momentum (vector sum) of an isolated system is is conserved (remember: that means that it is constant during a physical process).

We will begin by exploring the relationship between the forces experienced by an object and its momentum change. It can be shown that the change in momentum of an object is equal to a quantity called impulse. Impulse is the integral of the applied force over time interval over which this force acts (area under the F vs. t curve during the time force acts). The statement of equality between impulse and momentum change is known as the *impulse-momentum principle.*

Since interactions like collisions and explosions never involve just one object, we also examine the mutual forces of interaction between two or more objects. This will lead us to revisit Newton's *third law,* which relates the forces of interaction exerted by two objects on each other.
Finally, you will investigate how linear momentum ($\mathbf{p} = m\mathbf{v}$) and kinetic energy ($K = (1/2)mv^2$) change (or don't change) throughout various interactions.

INVESTIGATION 1: COLLISIONS, IMPULSE, AND CHANGE IN MOMENTUM

Activity 1-1: Which Packs the Bigger Wallop-A Dart or a Superball?

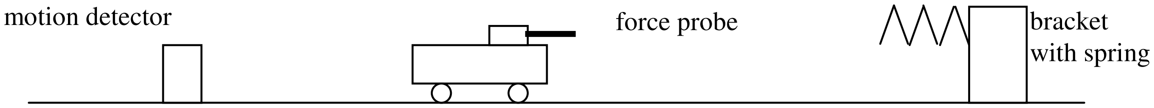
Let's test your intuition about momentum and forces. You are sleeping in your sister's room while she's away at college. Your house is on fire and smoke is pouring into the partially open bedroom door. To keep the smoke from coming in, you must close the door. The room is so messy that you can't get to the door. The only way to close the door is to throw either a dart or a superball at the door-there isn't time to throw both!

Prediction 1-1: Assuming the dart and the superball have the same mass, and that you throw them with the same velocity, which would you throw to close the door: the dart, which will stick to the door, or the superball, 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 making a low-friction cart hit a solid object (a bracket mounted on the track) and either bounce off or stick to the bracket. In order to measure the force the object exerts on the cart, fasten a force probe securely to the cart. Measure the mass of the cart and force probe combination.

Mass of cart plus force probe: _________________ kg

Attach a fairly weak spring to the end of the bracket mounted on the track. Set up the motion detector as shown. Be sure that the track is level, and that the wire from the force probe is out of the way, so that it won't be seen by the motion detector.



Open the experiment file called **Impulse and Momentum test**. This experiment has been set up to record force and motion data at 50 data points per second. We'll take the positive direction to be away from the bracket, so the software has been set up to record a *push* on the force probe as a *positive* force, and velocity *toward the motion detector as positive.*

Zero the force probe while no force is acting on it.

Begin graphing, and then give the cart a quick push toward the bracket, letting it bounce off (be sure to keep the force probe cable from dragging). Repeat until you get a good set of graphs, i.e., a set in which the motion detector saw the relatively constant velocity of the cart as it moved toward the bracket and as it moved away, and also the maximum force was no more than 10 N.

Store (Data/Store Latest Run) the data from your last good run so that the graphs are persistently displayed on the screen for later comparison and analysis.

Now attach a pin to the force probe, and replace the spring with a holder containing a large cone of clay so that the cart will stick to the bracket when it hits. Be sure to **zero** the force probe before beginning to graph.

Push the cart toward the bracket in the same way as before. **Try to make the speed just before the collision approximately the same as it was with the rubber stopper**. When you have a good run, store the data.

Now we want to compare the forces in the two runs. Since the force-time graphs probably have different shapes and different peak forces, how should we compare them? We have defined a quantity called *impulse*. It combines the applied force and the time interval over which it acts. In one dimension, the impulse can be calculated as the *area under the force vs. time graph.* (The area under the curve is the same as the *integral* of force vs. time.)

Use the **integration routine** in the software to find the area under the force-time graph (the impulse) for each of your runs.

bouncing: I = _____________ N*s

sticking: I = _____________ N*s

Question 1-1: Which resulted in a greater impulse: bouncing off the bracket, or sticking to the bracket? If you could make the speed of the cart just before the collision exactly the same in both cases, would bouncing or sticking give the greater impulse?

Now you will explore the mathematics of calculating momentum changes for these two types of collisions.

Activity 1-2: Momentum Changes

Prediction 1-2: Which object undergoes the greater *momentum change* during the collision with a door-the dart (that sticks) or the superball (that bounces back)? Explain your reasoning carefully. Recall that momentum is defined as a vector quantity; i.e., it has both *magnitude* and *direction.*

Now check your prediction by calculating the momentum changes for each of the collisions.
For the run with the cart bouncing off the spring, use the **Analyze|Statistics** feature in the software to measure the average velocity of the cart for a short time period just before it hit, and the average velocity just after it hit. Don't forget to include a sign. Positive velocity should be *away from* the end.

Average velocity just before collision: ______________________ ± ________________ m/s

Average velocity just after collision: ______________________ ± ________________ m/s

Calculate the change in momentum of the cart. Show your calculations and include uncertainties.
bouncing cart: Δ**p** =

Now repeat the determination of the change in momentum for the sticking cart from just before it hits until just after it hits. Show your data and calculation below. Be very careful of signs!

Average velocity just before collision: ______________________ ± ________________ m/s

Average velocity just after collision: ______________________ ± ________________ m/s
sticking cart: Δ**p** =

Question 1-2: Which cart had the larger change in momentum? If you had been able to make the initial speeds exactly the same, which cart would have had the larger change in momentum? Explain briefly.

Question 1-3: In both cases (bouncing and sticking), does the calculated change in momentum of the cart agree with the impulse applied to it during this collision, as the impulse-momentum principle states? Justify your answer.

Question 1-4: Based on the experiments you have done in this activity, which would you choose to close the door: the dart or the superball? Explain your reasoning.

! Checkpoint 1

INVESTIGATION 2: FORCES BETWEEN INTERACTING OBJECTS

All individual forces on an object can be traced to an interaction between it and another object. For example, we believe that while a falling ball is experiencing a gravitational force exerted by the Earth on it, the ball is exerting a force back on the Earth. In this investigation we want to compare the forces exerted by interacting objects on each other. There are many situations where objects interact with each other, for example, during collisions. What factors might determine the forces the objects exert on each other? Is there some general law that relates these forces?

Activity 2-1: Interaction Forces in a Tug-of-War

Prediction 2-l: Suppose that you have a tug-of-war with someone who is the same size and weight as you. You both pull as hard as you can, and it is a stand-off. One of you might move a little in one direction or the other, but mostly you are both at rest. Place a check next to your prediction of the relative magnitudes of the forces between person 1 and person 2.
______Person 1 exerts a larger force on person 2.
______The people exert the same size force on each other.
______Person 2 exerts a larger force on person 1.

Open the experiment file called **Tug-of-War (L07A2-1)**. The software will then be set up to measure the force applied to each probe with a data collection rate of 20 points per second. Make sure the force probes are set up on the 50 N scale. Note: Normally the force probes are set up to read a pull as a positive force. Since the force probes will be pulling in opposite directions in the tug-of-war, the software is set up to reverse the sign of one of them.

Check the calibration of both force probes with a force of 9.8 N applied using hanging 1.0 kg masses. If the probes don't read the same magnitude under these conditions, check with your instructor.

When you are ready to start, **zero** both of the force probes with no applied force. Then hook a short loop of string between them, **begin graphing,** and begin *a gentle* tug-of-war. Pull back and forth while watching the graphs. **Be sure to pull straight** on the force probes (not at an angle). *Do not pull too hard, since this might damage the force probes.*

Question 2-1: How did the two pulls compare to each other? Was one significantly different from the other? How did your observations compare to your prediction?

Activity 2-2: Interaction Forces Pulling Someone Along

Prediction 2-2: Suppose now that you have a tug-of-war with someone who is much smaller and lighter than you. This time the lighter person is on a skateboard, and with some effort you are able to pull him or her along the floor. Place a check next to your prediction of the relative magnitudes of the forces between person 1 and person 2.

_____Person 1 exerts a larger force on person 2.
_____The people exert the same size force on each other.
_____Person 2 exerts a larger force on person 1.

Use the same force probes and experiment file-Tug-of-War (L7A2-l)-as in the last activity. The person holding force probe 2 (person 2) should be on a skateboard. **Zero** both force probes with nothing pulling on them just before taking measurements. Then hook them together, begin graphing, and have person 1 begin pulling, softly at first, then slowly increase the force until person 2 begins to move along the floor.

Question 2-2: How did the two pulls compare to each other? Was one significantly different from the other? How did your observations compare to your prediction?

Question 2-3: In this activity and the last activity, you should have found that the force person 1 exerted on person 2 was equal and opposite to the force person 2 exerted on person 1. Explain carefully how person 1 was able to pull person 2 in this activity, if the forces they exert on each other are equal and opposite.

Activity 2-3 : Collision interaction forces

Prediction 2-3: Suppose two objects have the same mass and are moving toward each other at the same speed so that $m_1 = m_2$ and $v_1 = -v_2$ (same speed, opposite direction).
Predict the relative magnitudes of the forces between object 1 and object 2 during the collision. Place a check next to your prediction.

_____Object 1 exerts a larger force on object 2.
_____The objects exert the same size force on each other.
_____Object 2 exerts a larger force on object 1.

Prediction 2-4: Suppose the masses of two objects are the same and that object 1 is moving toward object 2, but object 2 is at rest: $m_1 = m_2$ and $v_1 \neq 0$, $v_2=0$.
Predict the relative magnitudes of the forces between object 1 and object 2 during the collision.

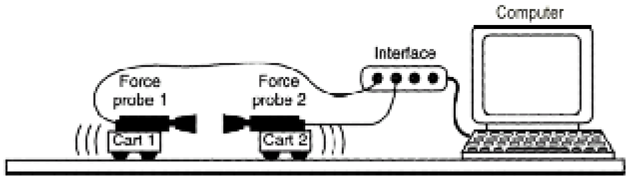
_____Object 1 exerts a larger force on object 2.
_____The objects exert the same size force on each other.
_____Object 2 exerts a larger force on object 1.

Prediction 2-5: Suppose the mass of object 1 is greater than that of object 2 and that it is moving toward object 2, which is at rest: $m_1>m_2$ and $v_1\neq0$, $v_2=0$.
Predict the relative magnitudes of the forces between object 1 and object 2 during the collision.

_____Object 1 exerts a larger force on object 2.
_____The objects exert the same size force on each other.
_____Object 2 exerts a larger force on object 1.

To test the predictions you made you can study gentle collisions between two force probes attached to carts. You can add masses to one of the carts so it has significantly more mass than the other.

Set up the apparatus as shown in the following diagram. The force probes should be securely fastened to the carts. One force probe should have a rubber stopper, and the probes should be carefully aligned so that they will collide head-on with each other. If the carts have friction pads, these should be raised so that they don't rub on the ramp. Set the force probes to the 50 N range.



Open the experiment file called **Collisions test**. The software will be set up to measure the forces applied to each probe with a very fast data collection rate of 4000 points per second. (This allows you to see all of the details of the collision, which takes place in a very short time interval.) The software will also be set up to be **triggered,** so that data collection will not start until the carts actually collide.

Use the two carts to explore various situations that correspond to the predictions you made about interaction forces. Your goal is to find out under what circumstances (if any) one cart exerts more force on the other. Try collisions (a)-(c) listed below.

Be sure to **zero** the force probes before each collision. The collisions should be rather gentle, so the peak force does not exceed 50 N.

For each collision, use the **integration routine** to find the values of the impulses exerted by each cart on the other (i.e., the areas under the force-time graphs). Record these values and the peak values of the forces in the spaces below.

(a) Two carts of the same mass moving toward each other at about the same speed.

(b) Two carts of the same mass, one at rest and the other moving toward it.

(c) One cart twice as massive as the other, moving toward the other cart, which is at rest.

Question 2-3: Did your observations agree with your predictions? How do forces compare on a moment-by-moment basis during each collision? What can you conclude about forces of interaction during collisions?

Question 2-4: Are your observations in Activities 2-1, 2-2, and 2-3 consistent with *Newton's third law* of motion? Explain.

Question 2-5: In Activity 1 you saw that an object's change in momentum is equal to the impulse on it. In Activity 2, you saw that two objects interacting with each other experience equal and opposite forces, and therefore equal and opposite impulses. So, if two objects interact with each other (and don't interact with anything else), how is the change in momentum of one object related to the change in momentum of the other object?

Question 2-6: What does your answer to the previous question imply about the total momentum (sum) for the two objects?

! Checkpoint 2

INVESTIGATION 3: MOMENTUM AND ENERGY IN COLLISIONS

We will now investigate several different types of collisions, paying careful attention to how linear momentum (**p** = m**v**) and kinetic energy ($K = mv^2$) change (or don't change) throughout various interactions. Remember that momentum is a vector quantity and energy is a scalar.

In the first activity you will examine whether momentum is conserved in a perfectly inelastic collision between two carts of unequal mass.

Activity 3-1: Perfectly Inelastic Collision

Remove the force probes from the carts and set up two motion detectors (one for each cart) to take data on the motion of the carts. Open the experiment file **Collisions**.

Place the carts with the Velcro pads toward each other so that they will stick together after the collision. Add mass to cart 1 so that it is about twice as massive as cart 2. Measure the mass of the two carts. Then, from the top menu bar under **Data**, go to **Column Options** and select **Mass1**. In the equation for **Mass1**, enter the mass (in kg) of the cart closest to the motion detector plugged into dig/sonic port 1. Repeat for **Mass2**.

Before collecting data, play around with the system so you know what the "active" area of each motion sensor is. You'll need to make sure that the collision occurs in this area.

Prediction 3-1: You give the more massive cart 1 a push and collide it with cart 2, which is initially at rest. The carts stick together after the collision. Consider the system consisting of the two carts. How do you think the total momentum after the collision will compare to the total momentum before the collision? How will the total kinetic energy after the collision compare to the total kinetic energy before the collision? Explain.

Test your predictions. Begin with cart 1 at least 0.50 m from the motion detector. Begin graphing, and when you hear the clicks of the motion detector, give cart 1 a push toward cart 2 and release it. Be sure that the motion detector does not see your hand and that cart 2 is at rest until the collision. Repeat until you get a good run when the carts stick and move together after the collision.

Question 3-1: How did the change in momentum of cart 1 during the collision compare to the change in momentum of cart 2 during the collision? Is this consistent with what you expected?

Question 3-2: Was total momentum conserved in the collision? Explain how you determined this.

Question 3-3: How did the collision affect the total kinetic energy of the system? Explain how you determined this.

Activity 3-2: Elastic Collision

Consider an elastic collision of two carts.

Prediction 3-2: Consider the system consisting of the two carts. How will the total momentum after the collision compare to the total momentum before the collision? How will the total kinetic energy after the collision compare to the total kinetic energy before the collision? Explain the basis for your predictions.

You may choose the masses and decide how the carts will be moving before the collision. The magnetic bumpers on one end of each cart will produce pretty good elastic collisions. Practice the collision before you actually record the data. If you change masses, be sure to enter the correct masses into Logger Pro as you did in the previous activity. When you have recorded a good collision and are happy with your data, use your graphs and observations to answer the following questions about this collision.

Question 3-4: Was the total momentum of the system consisting of the two carts conserved in the collision? Is this consistent with your prediction? Explain any differences between your prediction and observation.

Question 3-5: How did the collision affect the total kinetic energy of the system? Is this consistent with your prediction? Explain any differences between your prediction and what you observed.

! Checkpoint 3

Activity 3-3: A more complicated interaction

Consider the following situation: A cart is at rest on the track. A more massive cart moves toward it. The two carts collide, stick together, travel to the end of the track, and bounce off a spring mounted at the end of the track.

Set this up (attach a spring to one of the end bumpers of the track). Practice it, observing what happens (but don't take data yet). Consider the system consisting of the two carts, and make predictions for the following.

1. Will the collision of the two carts change the total momentum of the system? If so, what will happen to the total momentum?

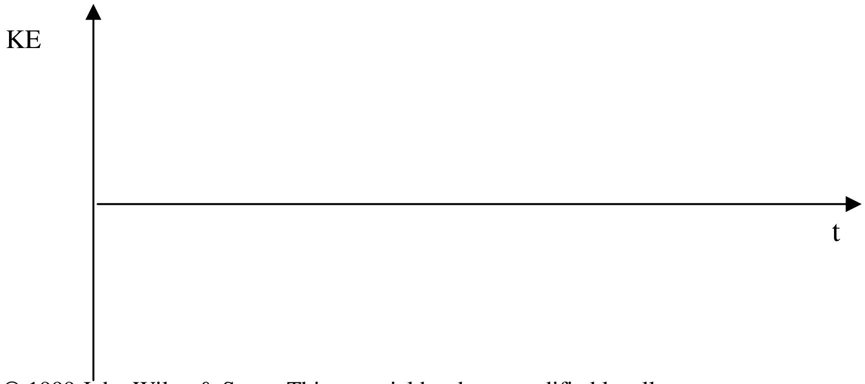
2. Will the collision of the two carts change the total kinetic energy of the system? If so, what will happen to the total kinetic energy?

3. Will the carts' collision with the spring change the total momentum of the system? If so, what will happen to the total momentum?

4. Will the carts' collision with the spring change the total kinetic energy of the system? If so, what will happen to the total kinetic energy?

On the axes provided below, sketch predictions for the following:

- velocity vs. time for each cart
- momentum vs. time for <u>each</u> cart, and also the <u>total</u> momentum
- kinetic energy vs. time for <u>each</u> cart, and also the <u>total</u> kinetic energy



Now do the experiment, taking data. Print the graphs, and mark on them the time interval during which the carts are colliding, and the time interval during which they're in contact with the spring.

Question 3-6: How well do your experimental results correspond to your predictions (your predicted graphs as well as your written predictions)? Comment on this for momentum and for kinetic energy. In particular, if there are aspects of your predictions that don't match your results, explain why the results are the way they are instead of the way you predicted.

Question 3-7: Consider the system consisting of the two carts. Based on your experimental results, over what time period(s) is the total momentum of this system conserved? Over what time period(s) is the total kinetic energy of this system conserved? Relate these observations to what you know about the system and the forces internal and external to the system.

Question 3-8: If the kinetic energy changed during any part of the motion, what happened to it?

! Checkpoint 4

INVESTIGATION 4: TWO-DIMENSIONAL COLLISIONS

The collision to be studied occurs between two pucks on an air table. The air table eliminates most of the sliding friction by providing a cushion of air under each puck. One puck, the "target," is originally at rest; the other, a "projectile," is given an initial velocity by pushing it. The ensuing collision is recorded on video.

Measure the initial velocity of the projectile and the final velocities of both projectile and target by using several overlapping intervals within each trajectory. Determine a mean velocity with uncertainty for each. (The precision of your results is improved greatly by choosing intervals which are relatively far apart, if that is possible.)

Consider the system consisting of the two pucks. Find the x and y components of the momentum of the system before and after the collision.

Also calculate the initial and final kinetic energy of the system, with units. Remember that kinetic energy is not a vector quantity.

Measure the angles of the trajectories of the pucks after the collision relative to the trajectory of the moving puck before the collision. In a good sized vector diagram, **graphically** find the vector sum of the momenta of the two pucks after the collision. Choose an appropriate scale. On the same diagram, with the same scale, construct a vector equal to the initial momentum. Compare these two vectors (both magnitude and direction) to see if momentum is conserved.

Question 4-1: Is momentum conserved in the collision? Is kinetic energy conserved in the collision? What type of collision (elastic, inelastic, perfectly inelastic) is the collision? Explain your reasoning.

! Checkpoint 5