Conservation of Momentum: Marble Collisions
Teacher Version

In this lab you will roll a marble down a ramp, and at the bottom of the ramp the marble will collide with another marble. You will measure the speed of each marble before and after the collision to determine whether momentum is conserved in this system for collisions between marbles of varying relative masses.

Preparation and Lab Notes:
- Download and get familiar with Audacity before using it in the lab.

Prerequisites:
- There is a great deal of computation in the lab. Most students should be able to manage it with a calculator. For the advanced lab students should be comfortable with Algebra

California Science Content Standards:
- **2. Conservation of Energy and Momentum: The laws of conservation of energy and momentum provide a way to predict and describe the movement of objects.**
- 2d. Students know how to calculate momentum as the product mv.
- 2e. Students know momentum is a separately conserved quantity different from energy.
- 2f. Students know an unbalanced force on an object produces a change in its momentum.
- 2g. Students know how to solve problems involving elastic and inelastic collisions in one dimension by using the principles of conservation of momentum and energy.

Complete List of Materials:
For each group (2-4 students per group) you will need the following:
- A smooth, flat surface
- Wall
- 2 grooved rulers OR 2 paper towel tubes (these will be the ramps)
- 1 meter stick
- 2 marbles of the same size (same mass)
- 1 marble with a larger mass than the first two marbles
- Textbooks or other prop to give ramp height of 5 cm
- 1 laptop with microphone (either built-in or separately attached) and the program Audacity installed (see instructions on downloading and installing Audacity below)
- Electronic Scale
- or Rudimentary scale:
    - o 3-hole punched ruler with 1 piece of string 10 cm long attached to each hole, and one plastic sandwich bag attached to a string at each end of the ruler
    - o One pack of jelly beans

Key Concepts:

- ***Velocity*** is the rate of change of an object's position over time.
- ***Momentum*** is the quantity of motion an object has, given by the product of an object's mass and velocity. The momentum of a system is conserved in a collision.
- ***Kinetic energy*** is the energy an object in motion has.
- An ***elastic collision*** is a collision between at least two objects in which the total kinetic energy is conserved.
- In an ***inelastic collision***, on the other hand, some kinetic energy is lost to other forms of energy or processes but the total momentum is still conserved.

Introductory Mini-Lecture:

A ***vector*** is a quantity that has both size and direction. The most common example of a vector quantity is velocity. ***Velocity*** is the rate of change of an object's position over time. The size of the velocity vector is the speed of the object (for example, 15 miles per hour), while the direction of the vector indicates which way the object is traveling. Mathematically, velocity = distance / time, or symbolically, $v = \Delta x/\Delta t$. The typical units of velocity are meters per second (m/s).

Momentum is the "quantity of motion" an object has, given by the product of an object's mass and its velocity. Mathematically, momentum = mass x velocity, or symbolically, $p = m \cdot v$. The typical units of momentum are kilogram-meters per second (kg·m/s). Because velocity is a directional quantity, momentum also has a direction associated with it and is thus a vector. If an object is in motion, it has momentum because all objects have mass and momentum equals mass times velocity. For this reason, momentum is often referred to as "mass in motion."

More intuitively, we can think of the amount of momentum an object has as expressing how hard it is to stop that object. We know from personal experience that the heavier something is or the faster something is moving, the harder it is to stop – in other words, the more momentum that object has. For example, even a car moving very slowly is extremely difficult to stop in its tracks; even though the car's velocity is small, its mass is very large, so moving cars have a lot of momentum even at slow speeds. The most important thing to remember about momentum is that ***momentum is conserved***. This means that the total momentum of a system never changes; it is always the same. So, for example if one object collides with another, the momentum of that object doesn't just disappear – its momentum is transferred to the object it collides with.

Kinetic energy is the energy an object in motion has. Mathematically, kinetic energy = (one-half) mass x velocity (squared), or symbolically, $KE = (½)mv^2$. An **elastic collision** is a collision between at least two objects in which the total kinetic energy is conserved; it remains the same before and after the collision, because the objects' velocities relative to each other are switched after the collision. For example, if an object in motion collides with an object at rest, it comes to a complete stop and transfers all of its velocity to the object at rest, causing the latter to move at the same velocity with which it was hit. Meanwhile, an **inelastic collision** is a collision between at least two objects in which some kinetic energy is lost to other forms of energy or processes (heat, friction, etc.), but the total momentum is still conserved.

Instructions for downloading and installing Audacity:

1. Go to the website <http://audacity.sourceforge.net/>

2. Click on "Download Audacity 1.2.6a," unless you run Windows Vista or Windows 7, in which case you should click on "Download Audacity 1.2.13 (Beta)."

3. Download the appropriate version for your type of computer (PC, Mac, or Linux/Unix).

4. Once you click on the appropriate link, click "Save to Disk." Follow the "Installation Instructions" on that website. Click on the Audacity icon to launch the application.

5. Make sure the microphone is working by clicking the record button and tapping the table next to the computer a few times. To delete the recording, go to Edit → Undo.

Instructions for measuring the mass of the marbles if you don't have an electronic scale using an improvised scale:

1. If you uses the jelly bean scale hold your balance by the middle string. The weights in both bags are equal when the ruler is straight.

2. Insert one small marble into one of the sandwich bags.

3. Insert a couple of jelly beans into the second bag.

4. **Add or remove jelly beans to/from the second bag until the ruler is straight.** You are finding the marble's mass in terms of jelly beans. Record the mass of the marbles.

Note: For this situation of the lab, we'll be working with the marbles that are the same size, so in the table below, the mass of top marble should equal the mass of bottom marble.

** 1 jelly bean = 1 gram **

Marble	# of Jelly Beans	Mass (g)
Top		
Bottom		

Part 1 – Equal Masses

In this first part, you will determine whether momentum is conserved for a collision between two marbles of equal masses.

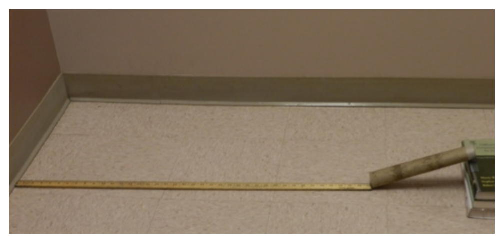
1. Measure the mass of one marble using an electronic scale.

Note: For this situation of the lab, we'll be working with the marbles that are the same size, so in the table below, the mass of the top marble should equal the mass of the bottom marble.

Marble	Mass (g)
Top	
Bottom	

2. Place textbooks (or other props) on a smooth, flat surface, such as a floor or table, approximately 1 m away from wall. With a meter stick, **give them a height of 5 cm.**

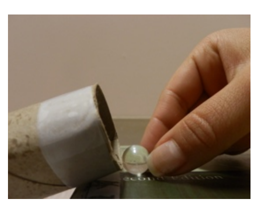
3. **Lean a grooved ruler or paper towel tube against the textbooks (or other props) so that the top end is at the 5 cm height while the other end is touching the floor.** The ramp should be positioned so that the marble rolled down the ramp will roll across the floor and collide with the wall.

4. Tape down the top of the ramp onto the textbooks/props (if needed).

5. Place the Top Marble at the top of the paper towel tube ramp.

6. Place the Bottom Marble at the bottom of the ramp, directly in the path of where the first marble will roll.

7. **Measure the distance (in meters) from Bottom Marble to the wall** that it will eventually hit.
   Distance to wall: ____________________ (m)

STUDENT ADVANCED VERSION ONLY

8. **Calculate and record the initial velocity of each marble** in the table below using the laws of conservation of energy (the velocity of the stationary Bottom Marble is 0 m/s).

    a. Due to gravitational potential energy (GPE), all unsupported objects fall downward with a "gravitational acceleration" of 9.8 m/s^2. The total GPE is a product of mass m, gravitational acceleration g, and height h:

    $$GPE = mgh$$

    b. Conservation of energy states that the marble's kinetic energy at the bottom of the ramp is equal to its GPE at the top of the ramp.

    c. To find the velocity v of the rolling marble, set the two equations equal to each other and solve for the unknown variable v.

Kinetic Energy = Gravitational Potential Energy

$$(\tfrac{1}{2})mv^2 = mgh$$

** By rearranging the above equation, v(initial) = $\sqrt{[2gh]}$ **

** To convert height in cm to height in m, multiply the height in cm by 0.01 **

Marble	g (acceleration)	Height (m)	Initial Velocity (m/s)
Top	9.8 m/s^2	*5 cm x 0.01 = 0.05 m*	~ 1 m/s
Bottom	9.8 m/s^2	*0 cm*	0 m/s

QS1. Which marble do you predict will have a larger momentum right before they collide at the bottom of the ramp? Explain. Remember momentum

The Top Marble will have a greater initial momentum. Momentum is a product of mass and velocity, so if both marbles have equal masses, whichever has a greater velocity will have a greater momentum. The Bottom Marble is stationary until the Top Marble hits it.

QS2, QSA1. If momentum is conserved, what do you think will happen when the two marbles make contact with each other?

The Bottom Marble has no momentum whatsoever, which means all the momentum comes from the rolling Top Marble. In order for the moving marble's momentum to be conserved, some of the momentum of the Top Marble should transfer to the unmoving Bottom Marble upon contact, putting the "immobile" marble in motion.

QSA2. Assume this will be an elastic collision, meaning that the velocity of the Top Marble is transferred to the Bottom Marble. Calculate the time it will take the Bottom Marble to cross the 1 m distance to the wall.

If the collision is elastic, the objects' velocities relative to one another are switched:
v_1 *(initial)* = v_2 *(final)*

Use the equation [velocity = distance / time → v = d / t]:
v_1 *(initial)* = d / t

Solve for the time t:
$t = d / v_1$ *(initial)*

Finally, plug in d = 1 m and the initial velocity of Marble 1 (in m/s).

9. **Calculate and record the initial momentum of each marble** using the formula: p = mv, where p is momentum, m is mass and v is velocity Add the two individual momentums to get the total initial momentum.

** p = mv **

Marble	Mass (g)	Velocity (m/s)	Initial Momentum (g·m/s)
Top		~ 1 m/s	
Bottom		0 m/s	0 g·m/s

Total initial momentum (g·m/s) =

10. Have one student prepare to start recording on Audacity as soon as Top Marble is rolled down the paper towel ramp.

11. **Start Audacity, wait a few seconds, then roll the Top Marble** by simply releasing it at the top of the ramp without pushing it down at all.

12. **Observe the collision and make sure that the collision sound recorded on Audacity.** If not, redo the procedure or adjust the microphone until a peak in the sound recording appears at the moment of the collision.

13. **Redo steps 17 and 18, this time having one student focusing on the Top Marble and stopping its motion as soon as the Bottom Marble hits the wall.**

14. Stop recording on Audacity after the Bottom Marble hits the wall (there should also be a sound peak at the moment of collision with the wall).

15. **Measure and record the distance traveled by the Top Marble after the collision.**

16. **Measure the time difference between the two collision sound peaks on Audacity.** This corresponds to the time spent rolling after the collision by both the Top Marble and the Bottom Marble. Record this time below and use it to **calculate the velocity of each marble.**

** v = distance / time **

Marble	Distance (m)	Time (s)	Final Velocity (m/s)
Top			
Bottom			

17. **Calculate the final momentum of each marble** and add the two individual momentums to get the total final momentum.

** p = mv **

Marble	Mass (g)	Velocity (m/s)	Final Momentum (g·m/s)
Top			
Bottom			

Total final momentum (g·m/s) =

Q3. Do the marbles' final momentums add up to the total initial momentum? If not, what are some sources of error in your procedure?

When adding up the momenta of the two marbles after the collision, some margin of error is to be expected, but the total initial and total final momentum should be fairly close. ***It can be very difficult to get good data from this lab****. Some sources of error include: (1) ability to stop the second marble at the same time the first marble hits the wall, (2) ability to accurately identify both the collision and the first marble hitting the wall on Audacity, (3) slight incline in the table changing the marbles path*

Q4. Was this experiment an example of an elastic collision or an inelastic collision? How do you know?

Students should be able to relate this situation to an elastic collision, since the second marble does pick up a considerable amount of speed and velocity even though it had been sitting still until the collision, though the answer will actually depend on the results, since *this situation could prove to be inelastic if the Top Marble does not come to a complete stop or it keeps rolling with considerable speed.*

Part 2 – Different Masses

In this part, you will determine whether momentum is conserved if the mass of the marble at the top of the ramp is less than that of the marble at the bottom of the ramp.

1. Exchange one of the marbles for a marble with a different mass.

2. **Measure the mass of the marbles** using an electronic scale.

Marble	Mass (g)
Top (small)	
Bottom (large)	

QS5. Now that the marble hitting it has less mass, will the marble at the bottom of the ramp have a higher or lower speed compared to the previous situation?

The large marble's speed will be lower in this situation.

QSA5. How do you think the Top Marble's lower mass will affect the momentum and velocity of the larger Bottom Marble after the collision? Explain.

Momentum is a product of mass and velocity. We know that the marble at the bottom of the ramp has zero initial momentum because it has zero velocity, just as in the previous trial. But the marble at the top of the ramp now has both a smaller mass and the same initial velocity. This smaller mass means that the Top Marble will have a smaller momentum. Because momentum is conserved, the marble at the bottom of the ramp will end up with a similar momentum, and therefore will move with a smaller velocity.

3. Place the smaller marble at the top of the ramp; place the larger marble at the bottom of the ramp, directly in the path of where the first marble will roll.

STUDENT ADVANCED VERSION ONLY

4. **Calculate and record each marble's initial velocity**, referring to step 11 of part 1.

Marble	g (acceleration)	Height (m)	Initial Velocity (m/s)
Top (small)	9.8 m/s^2	*5 cm x 0.01 = 0.05 m*	~ 1 m/s
Bottom (large)	9.8 m/s^2	*0 cm*	0 m/s

QSA6. Assume this will be an elastic collision, meaning that the velocity of top marble is transferred to bottom marble. Calculate the time it will take the bottom marble to cross the 1 m distance to the wall.

See question QSA2.

5. **Calculate the initial momentum of each marble.** Add the two individual momentums to get the total initial momentum, referring to step 9 (step 8 for Student version) of part 1.

Marble	Mass (g)	Velocity (m/s)	Initial Momentum (g·m/s)
Top (small)		~ 1 m/s	
Bottom (large)		0 m/s	

Total initial momentum (g·m/s) =

6. Have one student prepare to start recording on Audacity just before the Top Marble is rolled down the paper towel ramp.

7. **Start Audacity, wait a few seconds, then roll Top Marble** by simply releasing it at the top of the ramp without pushing it down at all.

8. **Observe the collision and make sure that the collision sound recorded on Audacity.** If not, redo the procedure or adjust the microphone until a peak in the sound recording appears at the moment of the collision.

9. **Redo steps 7 and 8 this time having one student focusing on Top Marble and stopping its motion as soon as Bottom Marble hits the wall.**

10. Stop recording on Audacity after Bottom Marble hits the wall (there should also be a sound peak at the moment of collision with the wall).

11. **Measure and record the distance traveled by the Top Marble after the collision.**

12. **Measure the time difference between the two collision sound peaks on Audacity.** This corresponds to the time spent rolling after the collision by both marbles. Record this time below and use it to **calculate the velocity of each marble**, referring to step 16 (step 15 for Student version) of part 1.

Marble	Distance (m)	Time (s)	Final Velocity (m/s)
Top (small)			
Bottom (large)			

13. **Calculate the final momentum of each marble** and add the two individual momentums to get the total final momentum, referring to step 17 (step 16 for Student version) of part 1.

Marble	Mass (g)	Velocity (m/s)	Final Momentum (g·m/s)
Top (small)			
Bottom (large)			

Total final momentum (g·m/s) =

QS6, QSA7. Did the fact that the Bottom Marble had a larger mass have an effect on the velocity of either marble after the collision

The initial velocity of the Top Marble remains the same because that velocity depends only on the height of the ramp. However, the increased mass of the Bottom Marble will result in it having a lower velocity after the collision compared to a Bottom Marble with the same mass as the Top Marble. The momentum of the Bottom Marble may remain the same due to the relationship between mass and velocity.

QS7, QSA8. Do the marbles' final momentums add up to the total initial momentum?

There should be some margin of error here, but the momentums should still be roughly the same before and after the collision. The same sources of error from Part 1 are still in play and can make obtaining good data difficult.

Part 3 – Switch!

In this part, you will determine whether momentum is conserved if the mass of the marble at the top of the ramp is greater than that of the marble at the bottom of the ramp.

1. This time, **place the larger marble at the top of the ramp; place the small marble at the bottom of the ramp, directly in the path of where the first marble will roll.**

STUDENT ADVANCED VERSION ONLY

2. **Calculate and record the initial velocity of each marble**, referring to step 11 of part 1.

Marble	g (acceleration)	Height (m)	Initial Velocity (m/s)
Top (large)	9.8 m/s^2	*5 cm x 0.01 = 0.05 m*	~ 1 m/s
Bottom (small)	9.8 m/s^2	*0 cm*	0 m/s

QSA9. Assume this will be an elastic collision, meaning that the velocity of the Top Marble is transferred to the Bottom Marble. Calculate the time it will take the Bottom Marble to cross the 1 m distance to the wall.

See question QSA2.

3. **Calculate the initial momentum of each marble.** Add the two individual momentums to get the total initial momentum, referring to step 9 (step 8 for Student version) of part 1.

Marble	Mass (g)	Velocity (m/s)	Initial Momentum (g·m/s)
Top (large)		~ 1 m/s	
Bottom (small)		0 m/s	

Total initial momentum (g·m/s) =

4. Repeat steps 6-10 from part 2.

5. **Measure and record the distance traveled by Top Marble after the collision.**

6. Record the time each marble spent rolling after the collision and use this time to **calculate the velocity of each marble,** referring to step 16 (step 15 for Student version) of part 1.

Marble	Distance (m)	Time (s)	Final Velocity (m/s)
Top (large)			
Bottom (small)			

7. **Calculate the final momentum of each marble** and add the two individual momentums to get the total final momentum, referring to step 17 (step 16 for Student version) of part 1.

Marble	Mass (g)	Velocity (m/s)	Final Momentum (g·m/s)
Top (large)			
Bottom (small)			

Total final momentum (g·m/s) =

Concept Questions

QS8, QSA9. What do your observations from part 2 and the results of this section tell you about the relationship between mass and momentum?

If you change the mass of an object, you change its momentum as well. This means that the momentum transferred from the marble at the top of the ramp to the marble at the bottom of the ramp changes depending on the Top Marble's mass.

QS9, QSA10. Based on your response to the previous question, what are some ways an object can increase its momentum?

An object can increase its momentum by increasing either its velocity or its mass, since those are the two factors involved in calculating momentum.

QS10, QSA11. Who do you think would have a greater momentum, a 25 kg person running at 10 mph, or a 40 kg person running at 5 mph?

The 25 kg person will have a greater momentum. If you calculate each person's momentum, disregarding who may seem to be faster or "bigger," you come to find that the 40 kg person has a momentum of 200 kg·mph whereas the 25 kg person has a momentum of 250 kg·mph.