



**Tom Hsu, Ph.D.**

**cpo**  
science

**First Edition**  
CPO Science  
Peabody, Massachusetts 01960

## *About the Author*

Dr. Thomas C. Hsu is a nationally recognized innovator in science and math education and the founder of CPO Science (formerly Cambridge Physics Outlet). He holds a Ph.D. in Applied Plasma Physics from the Massachusetts Institute of Technology (MIT), and has taught students from elementary, secondary and college levels across the nation. He was nominated for MIT's Goodwin medal for excellence in teaching and has received numerous awards from various state agencies for his work to improve science education. Tom has personally worked with more than 12,000 K-12 teachers and administrators and is well known as a consultant, workshop leader and developer of curriculum and equipment for inquiry-based learning in science and math. With CPO Science, Tom has published text books in physical science, integrated science, and also written fifteen curriculum investigation guides that accompany CPO Science equipment. Along with the CPO Science team, Tom is always active, developing innovative new tools for teaching and learning science, including an inquiry-based chemistry text.

Physics A First Course  
Teacher's Guide  
Copyright © 2005 CPO Science  
ISBN 1-58892-143-3

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CPO Science  
26 Howley Street  
Peabody, MA 01960  
(978) 532-7070  
<http://www.cposcience.com>

Printed and Bound in the United States of America

## Chapter 3: Conservation Laws

Newton's third law states that for every action there is an equal and opposite reaction. In other words, forces always come in pairs. There can never be a single force without its action-reaction partner. The momentum of an object is its mass multiplied times its velocity. When two objects exert forces on each other in an action-reaction pair, their motions are affected as a pair. The law of conservation of momentum states that the total momentum in a system of two interacting objects stays constant. If one gains momentum, the other loses the same amount, leaving the total unchanged.

Potential energy is energy due to position - like height. Kinetic energy is the energy of motion. When you throw a ball up in the air, kinetic energy is stored as potential energy as the ball moves up in the air against gravity.

When the ball falls back to Earth, potential energy is converted back to kinetic energy, and the ball's total energy stays the same. The idea that energy converts from one form to another without a change in the total amount is called the law of conservation of energy.


### Investigation Vocabulary

Newton's third law, momentum, law of conservation of momentum, potential energy, kinetic energy, law of conservation of energy

### Investigation 3A: Momentum and the Third Law

- Activities**
- Perform collision experiments
  - Measure time intervals
  - Calculate speed using measured time intervals
  - Calculate momentum
  - Describe activity using the law of conservation of momentum.

**Key Question** What makes moving objects keep going at the same speed in the same direction?


 **Time** One class period

**Comments** This investigation involves the car and track in an interesting collision experiment. Through their data, students come to understand the law of conservation of momentum.

### Investigation 3B: Conservation of Energy

- Activities**
- Measure time intervals
  - Calculate speed using measured time intervals
  - Measure height
  - Graph the speed vs. height of the car
  - Calculate potential energy
  - Use energy conservation to derive a formula for the speed of the car in terms of energy

**Key Question** What limits how much a system may change?

 **Time** One class period

**Comments** This investigation again uses the car and track. Students use their data to calculate potential energy and derive a new way to determine the speed of the car.

## Setup Information

### Setup and Materials A

Students work in groups of three to five.

Each group should have:

- Car and track (2 cars needed)
- Timer and 2 photogates
- Mass balance
- Two magnets
- Rubber bands
- Clay

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### Setup and Materials B

Students work in groups of three to five.

Each group should have:

- Car and track
- Mass balance
- Meter stick
- Physics stand
- Clay

## Chapter 3 Student Text Objectives

- Use Newton's third law to explain various situations.
- Explain the relationship between the third law and conservation of momentum.
- Solve momentum and impulse problems.
- Describe work and energy.
- Calculate potential and kinetic energy.
- Apply the law of conservation of energy to explain the motion of an object acted on by gravity.
- Distinguish between elastic and inelastic collisions.
- Use momentum conservation to solve collision problems.
- Explain how momentum, impulse, force, and time are related.

## Skill and Practice Sheets

- 3.1 Applying Newton's Laws of Motion
- 3.1 Momentum
- 3.1 Impulse
- 3.1 Momentum Conservation
- 3.2 Work
- 3.2 Potential and Kinetic Energy
- 3.3 Collisions and Conservation of Momentum

## Other Resources

- *Math Sheets*: Order of Operations Part 1, Order of Operations Part 2, Evaluating Algebraic Expressions, Inverse, Inverse Operations
- *Color Teaching Tools*: Newton's Third Law of Motion, Momentum and Impulse, Work, Kinetic and Potential Energy

## 1 Introduction: Making a collision

Forces always come in pairs.

A **collision** occurs whenever two or more objects interact, such as bouncing off one another.

Speed before - the speed before the collision occurs.

Speed after - the speed after the collision occurs.

Target car - the car that will be hit.

Moving car - the car that is launched and will hit the target.

Clean collision - a collision in which neither car falls off the track.

Today's investigation is about how things balance out in the universe. I would like to have two volunteers come up to the front of the class and push against each other. Describe what you are feeling on your hands as you push against each other. Suppose only one of you tries to push and the other one just tries to hold your ground. Does the person who is not trying to push still feel a force?

*That students should realize that they feel a force on their hands whether they are trying to push or not.*

It turns out that forces are never lonely. Forces only come in pairs. When one of you pushes against the other, that is a force we call the action force. However, the person pushing also feels a force pushing them back which is a reaction to the force they apply. Any time there is an action force, there is also an equal and oppositely directed reaction force. That is what I mean by forces always come in pairs. This effect is particularly important in collisions. In physics, a collision occurs whenever two or more objects interact, such as bouncing off one another. Today you are going to make small collisions between two cars on the track. By measuring the speeds of the cars before and after the collision, we will learn about a new law of nature, the law of conservation of momentum. We will also learn about Newton's third law, that third and last of Newton's three laws of motion.

*Set up a demonstration with the long straight track in front of the room and demonstrate how to launch cars and observe the collision. It is important to do a demonstration first so students know what they are expected to do with this investigation since there are some tricky techniques, such as launching the car without making it fall off the track. The demonstration also serves to clarify the meaning of "collision", "speed before", "speed after", "target car" and "moving car".*

Now I want each of you to set up your track the same way. The track should be level, which you can do by launching one car and getting equal time through the photogates. The target car has a rubber band wrapped around it that makes it bounce back when the moving car hits it. To make the bounce effective, the pointy end of the moving car must hit the indented end of the target car.

*Hold up the car and demonstrate the rubber band placement and how the cars must get each other to bounce correctly (pointy end hits indented end with rubber band). Allow the students to practice launching the moving car and getting clean collisions with the target car. A clean collision is one for which neither car falls off the track after the collision.*

We will use the photogates to measure the speeds of the car before and after the collision. This is a little tricky because one car might go through the same photogates twice once going in and once bouncing back. The trick is solved using the memory function of the timer. When you press and hold the memory button the timer displays the last value of the time indicated by the A and B lights. If only the A light is on, the display shows the most recent time for the car to pass through photogate A. Holding the memory button causes the timer to display that time from the second most recent pass through the photogate. If the moving car bounces off the target car it passes through photogate A twice. With just the A light on, the display shows the time from the car after it bounces, after the collision because that is the car's most recent pass through photogate A. Holding down the memory button allows you to see the time from the car before the collision since that is the second most recent pass through the photogate.

*Circulate and assist students to make and interpret time measurements that involve multiple passes through one photogate. Stress that careful observation and making good notes is the best way to interpret that data. It is easy to get confused about which time was before the collision and which time was after the collision.*



## 2 Thinking about what you observed

The target car exerts an action force on the rolling car, making it stop.

The reaction force is the rolling car pushing up against the target car.

It does not matter which force you call the action and which you call the reaction.

There can never be an action force without a reaction force.

## 3 Momentum

The **momentum** of an object is its mass multiplied times its velocity.

$$p = mv$$

## 4 Thinking about what you observed

The total momentum of the system (both cars) before and after the collision remains constant.

$$v_T = (m_R/m_T)(v_0 - v_R)$$

where  $m_R/m_T$  is the ratio of masses  
 $(v_0 - v_R)$  is the change in speed

For the first experiment both cars should have the same mass. Describe the speed and position of the cars before and after the collision. Use the photogates to measure the times and speeds before and after the collision.

Students should take data to complete table 1 with cars of equal mass. They should make several trials to ensure consistent results.

The target car must exert a force on the rolling cart to make it stop. What force makes the target cart move?

Use this example to explain action and reaction. The target car exerts an action force on the rolling car to make it stop. The reaction force is the rolling car pushing against the target car, which makes the target car move.

It does not matter which force you call the action and which is the reaction. The words action and reaction are just labels. If you choose to call one force the action, then the other force is the reaction. The important idea is that there can never be an action force without a reaction force. The action force and reaction force have exactly the same strength, always. The action force and reaction force point in exactly opposite directions, always. The action force and reaction force always act on different objects. If the action force is the target car acting on the moving car, then the reaction force is the moving car acting on the target car. The action force acts on the moving car and the reaction force acts on the target car.

It is worth ten or fifteen minutes discussion of action and reaction because this concept is elusive. Ask students to come up with other examples and point out the action and reaction forces. After a half dozen examples they realize that there are always action and reaction forces. Many times the reaction force is a normal force, such as the floor acting back up against the legs of a chair to keep the chair from falling through the floor.

Newtons third law leads to another interesting property: momentum. The momentum of an object is its mass multiplied by its velocity. Momentum is changed by force. Force causes acceleration which changes velocity, which changes momentum. If the action and reaction forces are always equal and opposite, then the change in momentum for two objects in a collision must also be equal and opposite. If this sounds like a complicated idea, let's do a few experiments to see how it works. Try bouncing cars off each other that have different mass. There are four combinations shown in part three of the investigation. Take data for all four combinations being sure to observe the direction of motion before and after the collision for both cars.

Students should repeat the experiment several times with different masses.

Describe the motion before and after the collision when the rolling car has a lower mass than the target car.

Describe the motion when the rolling car has a greater mass than the target car.

When the rolling car has lower mass, it bounces back in the direction it came. The target car moves forward at a speed that is less than the rolling car had before the collision. When the rolling car has greater mass then it rolls forward after the collision in the same direction it was going before the collision, although slower. The target car also moves forward, but at a greater speed than the rolling car after the collision.

We can understand the collision by thinking about momentum. Because the forces are always equal and opposite, when the action force transfers momentum to the target car the reaction force transfers the same amount of momentum away from the rolling car. The total momentum of the system (both cars) before and after the collision remains constant. We use this law to predict the speed of the target car after the collision from measurements of how the speed of the rolling car changed during the collision, and the masses of both cars.

Work through the conservation of momentum on the blackboard. Show that the target car (after the collision) has a speed given by  $v_T = (m_R/m_T)(v_0 - v_R)$ , where  $m_R/m_T$  is the ratio of masses and  $(v_0 - v_R)$  is the change in speed for the rolling car. (assuming + is the direction of the rolling car before the collision)



## 1 Introduction: energy exchange from potential to kinetic

Energy measures a system's ability to change or to cause change in other systems.

## 2 Thinking about what you observed

## 3 Analyzing the data

**Potential energy** is the energy stored in position (against gravity).

$E_p = mgh$   
 $m$  = mass  
 $g$  = gravity  
 $h$  = height

Let's review what we know about energy. Can anyone remember a definition for energy?

Energy measures a system's ability to change or to cause change in other systems. Change may take many forms. Change could include change in height, change in mass, change in pressure, change and speed temperature, or any other change which can be described by a variable.

Today we are going to make our definition of energy more exact. Our goal is to be able to predict exactly how fast the car is moving after rolling down a hill. Follow the instructions on page 14 to set up the track with a hill and a level section.

Circulate and assist students to put the apparatus together. It is important that the level section be level this time. Use a bubble level for this. Once the track is level, students should leave it in the same position so as not to change its adjustment. If you have multiple groups going, you may choose to have some groups set up the shallow ten degree hill and others set up the steeper twenty degree hill. This way you can compare data and show that the vertical height that the car drops is the most important factor.

We will use the upper stop to provide a repeatable starting point for the car. The clay ball on the lower stop will stop the car. The string provides a horizontal reference for measuring the height of the car at the start. It is important that the string be parallel to the level section of the track or you will not get an accurate measure of height.

Check the setup for each groups apparatus.

We are going to take a lot of measurements. We want to measure the speed of the car as we change the height from which it is released and also the mass of the car. Measure the height from the dot at the center of the car to the horizontal string. Record the height and mass measurements in table one along with the photogate time and your calculated speed.

This is the main body of the first activity, and should take twenty to twenty five minutes.

Make a graph showing the speed of the car versus the height from which it was released. Use different shape points for different masses but plot all of the data on the same graph. What does this graph show you?

The graphic should show an inverse relationship between height and speed and should also show that mass is almost irrelevant.

What are the two most important forms of energy that we should include when trying to understand the motion of the car?

Prompt students to answer potential energy and kinetic energy

Potential energy is energy that a system has because of its position relative to the center of the earth. The true name is gravitational potential energy, because there are other forms of potential energy. However, in this class when we say potential energy you can assume it is gravitational potential energy. The higher you go, the more potential energy you have. If an object moves down it is able to release potential energy by transferring that energy to other objects or by increasing its own speed. The amount of energy available is equal to the mass of the object ( $m$ ) multiplied by the strength of gravity ( $g$ ) multiplied by the vertical distance the object moves ( $h$ ). If an object moves down twice as far, then twice as much energy is available to be converted into other forms. That is why falling objects go faster the farther they are allowed to fall.

Review the potential energy formula on the blackboard.

The hill on the track is a form of falling too. The energy that speeds up the car comes from the car falling down the hill. That is why measuring the height in the vertical direction is important.



**Conservation of Energy**

**Question for this Investigation:**

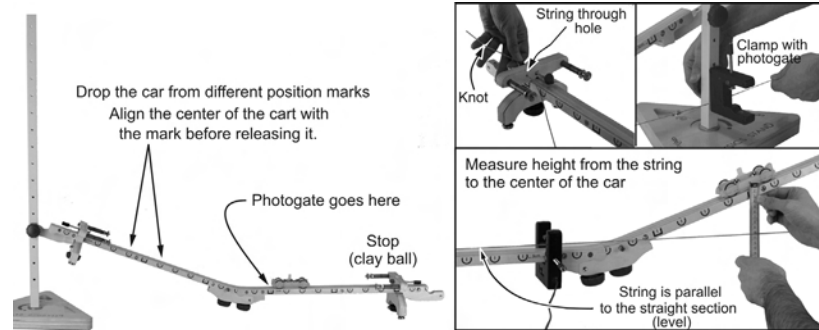
What limits how much a system may change?

A car launched up the hill at a given speed will never go higher than a certain point. A car rolling downhill will only reach a certain speed. Why? The answer is that nature keeps an exact balance of energy. Speed uses one form of energy and height uses another. This Investigation explores the exchange of energy.

**Materials**

- Car and track
- Mass balance
- Meter stick
- Physics stand
- Clay

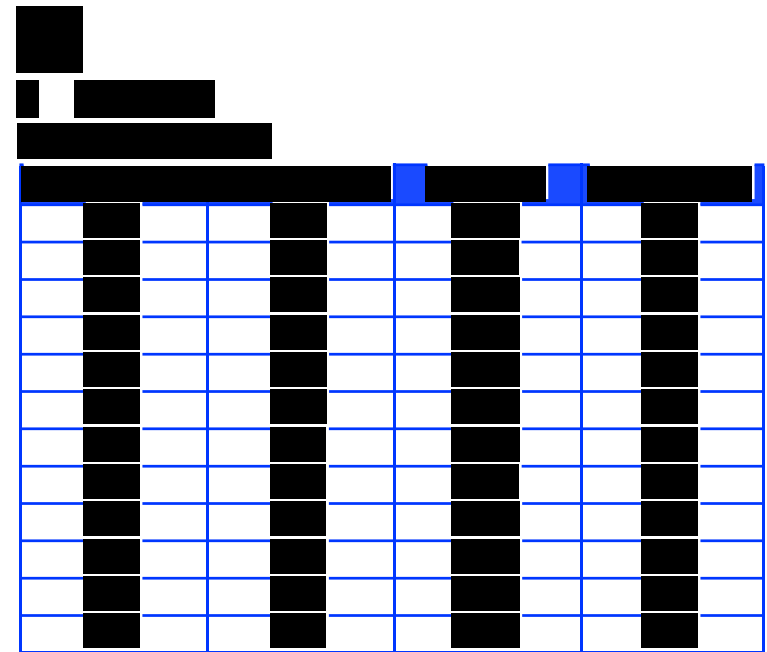
**1 Energy exchange from potential to kinetic**



1. Set up the track with the steeper hill and a level section. Make the level section as level as you can.
2. Thread a string through the hole in the lower stop and use a photogate to clamp the other end of the string to the stand. Adjust the string so it is parallel to the level section of the track.
3. Put a photogate at the bottom of the hill on the level section.
4. Drop the car from each 5-cm mark on the hill and measure the speed with the photogate. Measure the height of the car from the string to the center of the car.
5. Measure the mass of the car. Do the experiment for at least two different masses.

**Table 1: Downhill data**

Drop Height (m)	Mass of car (kg)	Photogate time (sec)	Speed (m/sec)



**Kinetic energy** is the energy of motion. It depends on an object's mass and speed.

$$E_k = \frac{1}{2} mv^2$$

$m$  = mass

$v$  = speed

$$mgh = \frac{1}{2}mv^2$$

$$gh = \frac{v^2}{2}$$

$$v = \sqrt{2gh}$$

#### 4 Thinking about what you observed

Energy can never be created or destroyed, just changed in form.

The other important form of energy is kinetic energy. The kinetic energy of a moving object depends on its mass and speed. The fact that the speed is squared means an object which has twice the speed has four times as much kinetic energy because  $2^2$  is 4. Tripling the speed takes nine times as much energy because  $3^2 = 9$ .

Use in the blackboard to explain  $E_k = \frac{1}{2} mv^2$ .

Can anyone state the law of conservation of energy for me? First do it in words, and then in formulas. What does this law mean when applied to the car rolling down the track?

The law of conservation of energy says that energy can never be created or destroyed, just converted between one form and another. The total energy content of the universe is the same, forever. If energy cannot come in or out on a system, the total amount of energy in the system must be constant. That means the increase in kinetic energy as the car speeds up must exactly equal the decrease in potential energy as the car falls down.

To make it exact, let's apply the formulas. The energy before the car is released is the same as the energy at all other times along the track. Of course, this isn't exactly true since friction dissipates some energy. The energy taken by friction isn't really lost, it is just converted to heat, wearing away of the wood and rubber and other forms that diminish the amount that is available to become kinetic energy.

Derive the energy conservation condition on the board, potential energy at the start ( $mgh$ ) equals kinetic energy at the bottom of the hill ( $\frac{1}{2} mv^2$ ).

Notice that the mass cancels out on this equation from both sides. What does that mean? Is this conclusion supported by your experimental evidence?

The fact that mass cancels indicates that the speed of the car at the bottom of the hill is independent of mass, this should confirm an observation to students have already made.

We can use the formula we just derived from energy conservation to predict the speed of the car at any drop height. Fill in the predicted speed in table 2 using the energy conservation formula. How does this predicted speed compare with the speeds you actually measured? Plot both the predicted speed and the measured speed against the height on a single graph.

Circulate and assist students to do the data analysis and make the graph. They should find that the predicted speeds are just a little higher than the actual speeds. Frictional losses account for between five and ten percent of the initial potential energy.

What might explain the difference between the measured and predicted speeds? Does anyone think that energy conservation is not true?

Discuss the effect of friction. It is also worth discussing the difference between the term "energy conservation" as used in physics and "conserving energy" as used in common speech. Energy can never be created or destroyed, just changed in form. Conserving energy means using less energy in the form of electricity and fossil fuels. This energy is not used up in the sense that it is gone, it is just transformed into heat and other forms which are not as useful as electricity or gasoline. It is impractical to put the energy back into its useful form once the electricity has been used to do work or the gasoline has been burned in an engine.

When the car bounces off the rubber band, there is another transformation of energy. Can anyone describe the flow of energy as in the car bounces off the rubber band and goes back uphill?

Discuss the energy transformations that occur. The energy starts as potential energy, becomes kinetic energy as the car rolls along the level section, then becomes elastic potential energy as the rubber band stretches. The elastic potential energy becomes kinetic again as the car balances off the rubber band.



**2 Thinking about what you observed**

- a. Graph the speed of the car vs. the height. Use different symbols for different masses.
- b. What does the graph tell you about the relationship between speed and height?

**3 Analyzing the data**

- a. Use the formula for potential energy to fill in the first column of Table 2.
- b. Use energy conservation to derive a formula for the speed of the car in terms of the energy it has at the start. (Hint: your formula should include only two variables, energy and height.)
- c. Use the formula you just derived to fill in the column for the predicted speed of the car.
- d. Plot the curve for the predicted speed on the same graph as you made in part 2a above.

**Table 2: Energy data and predicted speeds**

Drop Height (m)	Potential energy (J)	Predicted speed (m/sec)	Measured speed from Table 1 (m/sec)

**4 Thinking about what you observed**

- a. Explain the relationship between speed and height using the idea of energy conservation.
- b. Explain any difference between the predicted and measured speeds. If there is a difference, what does it tell you about the energy of the car as it rolls along the track?
- c. Did changing the mass have a significant effect on the relationship between height and speed? How does your data support your answer?
- d. Let the car roll downhill, bounce off the rubber band and go back up hill again. Does it reach the same height as it was dropped from? Explain why or why not using the idea of energy conservation.
- e. Challenge experiment. Use a rubber band to launch the car uphill so it goes through the photogate with the same speed as it had going down. You won't be able to get it precisely the same, but come as close as you can. If the speeds are the same, the car's kinetic energy is also the same. Does the car reach the same height on the hill that it was dropped from to get the same speed in part 1? Explain any difference using the idea of energy lost to friction.

