Section 3 Energy and Work: Why Air Bags?

What Do You See?

Learning Outcomes

In this section, you will

- **Model** an automobile air bag.
- **Relate** the energy of a moving object to the work required to stop the object.
- **Demonstrate** an understanding about the relationship between the force of an impact and the stopping distance.

What Do You Think?

Automotive engineers often think in terms of energy management when they design safety systems. A good example of energy management is the use of an air bag to protect passengers during an accident.

- **How does an air bag protect you during an accident?**

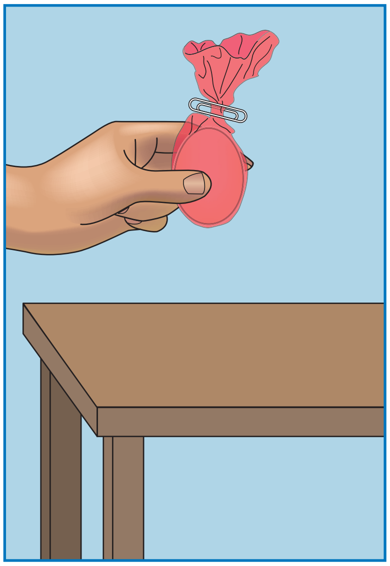
Record your ideas about this question in your *Active Physics* log. Be prepared to discuss your responses with your small group and the class.

Investigate

In this section, you will use an egg to simulate the head of a passenger traveling in an automobile. An egg is a fairly good model of a human head. It has a fairly thin outer shell with a fragile interior.

1. Wrap an egg in plastic wrap or bag to minimize cleanup, as shown in the diagram on the next page.
2. Drop egg # 1 onto a hard surface (such as a counter) from a very low height. Start with a drop of 2 cm. Check the egg for any cracks. Try to drop the egg so that it always lands the same way, for example, on its side.

For best results, hold the egg with your thumb and index finger as shown in the diagram below.



3. Gradually increase the height of the drop in increments of 2 cm until you get a crack in the shell.

a) Record this as crack height in your log.

4. Continue dropping from greater heights until you get a full break in the shell and the yolk spills out.

a) Record this as smash height # 1.

5. Now create a softer surface for a second egg to fall on. Try a bed of flour, sand, or rice about 2 cm thick. Drop egg # 2 from smash height # 1. Try to drop the egg so that it lands in the same way as your first egg.

a) Record your observations.

6. Measure the depth of the indentation left in the landing material for the drop at smash height # 1. This can be challenging. Try measuring how much of the egg is still sticking out above the original level of the landing material. Then take the difference between the amount above the surface and the total height of the egg. This should be what remains below the surface, or the indentation depth.

a) Record your measurement.

7. Compare the damage of egg # 1 and egg # 2 when dropped from the smash height # 1. When dropped from the same height, egg # 1 and egg # 2 have the same speed just before hitting the landing material. The material must supply a force over a distance (that is, the indentation of the material) for the energy to be dissipated.

a) Compare the force (damage) and distance (indentation) of egg # 1 and egg # 2 when dropped from smash height # 1.

8. The next part of the *Investigate* is best done as a class demonstration. Take a large bed sheet to an area with a clear throwing area. Choose a volunteer that has a good throwing arm, such as a pitcher from the softball or baseball team. Have two other students be the "catchers." They should design a target for the egg-thrower by stretching the sheet out, holding the top two corners of the bed sheet over their heads and the lower two corners a little lower than their waists. The goal for the catchers is to catch the egg in the sheet by creating a cup or scoop at the bottom, which will prevent the egg from rolling off the sheet. Have the pitcher throw the egg as hard as she or he can at the center of the sheet. The pitcher should try to break the egg when it hits the sheet. Everyone else should observe the motion of the sheet when the egg hits it. Have the egg in a plastic bag. It will be a bit harder to throw, but much easier to clean up.

a) Explain why the sheet cannot exert a force large enough to break the egg.

Physics Talk

ENERGY AND WORK

In this section, you observed the damage to an egg from collisions. This is similar to the damage to a person's skull during collisions.

When egg # 1 was dropped from smash height # 1, the shell broke. In contrast, egg # 2 dropped from the same height probably did not experience the same damage because the new surface was softer. How can you describe "softer" in terms of physics concepts?

Kinetic Energy

An automobile traveling down a highway at 100 km/h (about 60 mi/h) represents a considerable amount of energy. This kind of energy is called **kinetic energy**. Kinetic energy is the energy an object has because of its motion. The adjective "kinetic" comes from the Greek word for motion, "*kinesis*."

Kinetic energy depends on the mass and the velocity of the object. The following equation shows this relationship.

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

where KE stands for kinetic energy,
m represents the mass of the vehicle and its occupants, and
v represent the velocity of the vehicle.

In your investigation, the falling eggs had kinetic energy and approximately the same mass. Both eggs also had the same velocity at the moment before hitting the surface because they were both dropped from the same height (smash height # 1). Both eggs, therefore, had the same kinetic energy (KE).

Physics Words

kinetic energy: the energy possessed by a moving body is called kinetic energy. $KE = \frac{1}{2}mv^2$

To stop the egg, a surface had to apply a force over some distance. This distance can be seen as the indentation of the surface. For a hard surface, you cannot see the indentation. For the soft surface, you were able to measure the indentation.

Work and Change in Kinetic Energy

In order to stop an automobile safely, the braking system must decrease the speed of the vehicle and effectively eliminate the kinetic energy by applying a great deal of force over a large distance. When force is applied over a distance, *work* is being done. **Work** is calculated using the following equation:

$$\text{Work} = \text{force} \times \text{distance}$$

$$W = F \cdot d$$

Work is equal to the change in kinetic energy. Work can either increase the kinetic energy or decrease the kinetic energy depending on the direction of the applied force and the distance (displacement) that the object moves.

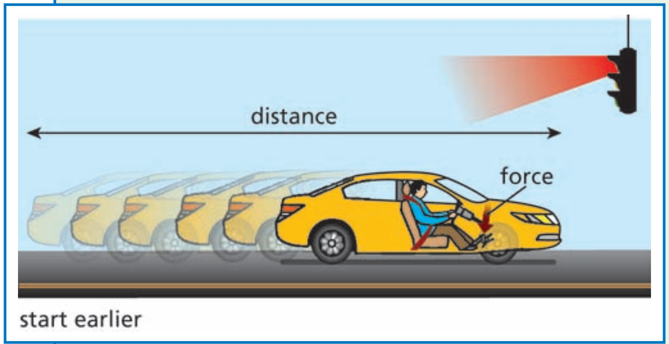
You can write this as a new equation using the symbol Δ to represent "change in."

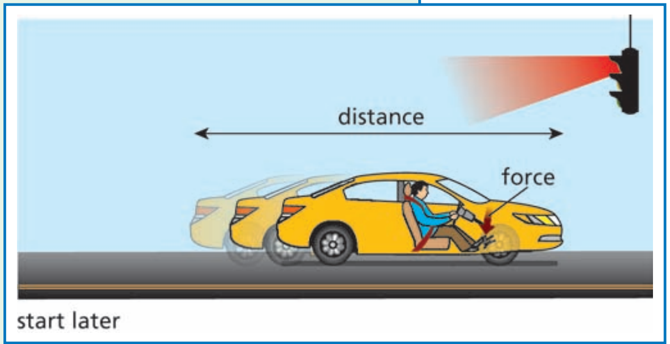
$$W = \Delta KE$$

Getting rid of the kinetic energy that an automobile and its occupants have before a collision can be done in different ways. It can be done either safely, or dangerously (causing injury to the passengers). This is what automotive safety engineers call energy management. They need to create a system that transfers the energy of the automobile safely. The work that is needed to stop the automobile traveling at a given speed is a fixed quantity, so it could be done with a small force and a large distance, or a large force and a small distance.

Physics Words

work: the amount of force applied on an object over a certain distance; $W = F \bullet d$





Work = force • **distance** (safely)   Work = **force** • distance (dangerously)

If the change in kinetic energy (*KE*) equals 5000 J (joules), different forces and distances can all provide this change.

Kinetic energy	Force	Distance	Work = *F* • *d*
5000 J	50,000 N	0.10 m	5000 J
5000 J	10,000 N	0.50 m	5000 J
5000 J	5000 N	1.00 m	5000 J

You should see that the smaller the stopping distance, the larger the force. You noticed this in the *Investigate* in which egg # 1 hitting the hard surface had more damage than egg # 2 hitting the soft surface which has a larger indentation or distance. This is what happens in a collision, where the automobile and its passengers come to a stop in a very small distance. If a passenger strikes the interior of the automobile, such as an unpadded steering wheel or windshield, the stopping distance will be very small. That would require an extremely large force. Such a force would certainly cause serious injury. That is why air bags are used. An air bag increases the distance over which the stopping force is applied. The force is reduced considerably.

Speed and Kinetic Energy

You noticed that the work, W, equals the change in kinetic energy, KE. The fact that $W = \Delta KE$, also helps to explain why slowing down is always a good safety move.

To stop an automobile moving at 9 m/s (20 mi/h) requires the force of the brakes to be applied over a fairly large distance. An automobile traveling at 9 m/s requires about 6 m to stop safely. Imagine that an automobile going three times as fast would require three times the distance to stop, but this is not the case. If you carefully examine the formula for kinetic energy ($KE = \frac{1}{2}mv^2$), you will notice that the energy is proportional to the square of the velocity. That is, if you triple the speed, the KE is not three times greater, but it is nine times greater (3^2 or 3×3). It would take an automobile traveling at 27 m/s nine times the distance to stop than at 9 m/s, assuming that the brakes apply the same force. That means that it would require 54 m (9×6 m) to stop safely. The fact that kinetic energy is proportional to the square of the velocity also explains why high speed greatly increases the damage done during a collision. The automobile at three times the speed has nine times as much kinetic energy requiring nine times the distance to stop safely.

If you assume that the mass of a car is 1000 kg, you can see the effect of speed on kinetic energy and stopping distance for a given braking force. In the table below, you should notice the following:

- The speed has tripled from 9 m/s in the first row to 27 m/s in the second row.
- The kinetic energy has increased nine times as the speed tripled.
- The work required to stop the car is equal to the kinetic energy at all speeds.
- The braking force of the car is constant irrespective of the speed.
- The stopping distance increased by a factor of nine when the speed tripled.

Speed (meters per second)	$KE = \frac{1}{2} mv^2$ (joules)	Work to stop car $W = \Delta KE$ (joules)	Braking force (newtons)	Stopping distance (meters)
9	40,500	40,500	6740	6
27	364,500	364,500	6740	54

On dry roads, you can safely stop a car traveling at 9 m/s in 6 m. Drivers are used to this speed-to-distance relationship after many years of driving. When the road is wet or icy, there is less force between the tires and the road. With less force you need a larger distance to stop, since the work is still the same for a given amount of kinetic energy. Alternatively, you can decrease the speed of your car so that the kinetic energy decreases and the required work and stopping distance will be smaller. The key to safety when road conditions change is to slow down. Slowing down will permit a safer stop and will also significantly decrease the kinetic energy (and damage) if there is an accident.

For example, imagine a 70.0-kg passenger traveling at a speed of 13 m/s. That person's kinetic energy is

$$\begin{aligned} KE &= \frac{1}{2}mv^2 \\ &= \frac{(70.0\ \text{kg}) \times (13\ \text{m/s})^2}{2} \\ &= 5915\ \text{J or } 5900\ \text{J (rounded off to two significant figures)} \end{aligned}$$

Dimensional Analysis

Notice how the numbers and units were handled in the solution. The numbers were multiplied together to get the numerical answer:

$$\begin{aligned} \frac{1}{2} \times 70 \times 13^2 &= \frac{70 \times 13 \times 13}{2} \\ &= 5915 \end{aligned}$$

The units were also multiplied together in the same way:

$$\text{kg} \times \left(\frac{\text{m}}{\text{s}}\right)^2 = \text{kg} \times \left(\frac{\text{m}}{\text{s}}\right) \times \left(\frac{\text{m}}{\text{s}}\right)$$
$$= \text{kg} \cdot \frac{\text{m}^2}{\text{s}^2}$$

This derived SI unit is given a special name. The unit for energy is called a joule (J).

$$1\ \text{J} = \text{kg} \cdot \frac{\text{m}^2}{\text{s}^2} \text{ or kg} \cdot \text{m}^2/\text{s}^2$$

Paying attention to units is an important problem-solving skill and tool. It is called dimensional analysis.

To stop the person, something has to do the 5900 J of work to get rid of that energy. In an accident, it could be the windshield. What would happen if the person strikes the windshield? Since the windshield is fairly rigid, it might only give 3.0 cm (0.030 m) in stopping the person. So the work done by the windshield is

$$\text{Work} = \text{force} \times \text{distance}$$
$$5900\ \text{J} = \text{force} \times 0.030\ \text{m}$$
$$\text{Force} = \frac{5900\ \text{J}}{0.030\ \text{m}}$$
$$= 196{,}667\ \text{N or } 197{,}000\ \text{N when rounded off}$$

That is a lot of force exerted on the skull. What happens if the passenger strikes a fully inflated air bag instead of the windshield? Suppose that the air bag creates a stopping distance of 30.0 cm (10x greater stopping distance). The amount of work to be done is still the same, 5900 J. But this time, it is applied over a greater distance than the 3 cm of the windshield.

$$\text{Work} = \text{force} \times \text{distance}$$
$$5900\ \text{J} = \text{force} \times 0.300\ \text{m}$$
$$\text{Force} = \frac{5900\ \text{J}}{0.300\ \text{m}}$$
$$= 19{,}667\ \text{N or } 19{,}700\ \text{N}$$

This is still a lot of force, but it is much less than before (10x smaller force). Air bags are not the only system in the automobile that is designed to absorb energy. Seat belts and crumple zones in the frame of the automobile also help a lot. You will learn more about crumple zones in a later section.

The work done by the air bag decreases the kinetic energy of the person. However, energy in the entire system must remain the same. In this case, the kinetic energy of the person decreases while the energy of the air bag increases. An air bag with increased energy may become a bit hotter as all the molecules in the air bag gain some kinetic energy. Some of the energy during the collision may have produced some sound energy as well.

SI Units of Force, Work, and Energy

Notice that dimensional analysis was used, once again, in calculating the force and the work.

Newton's second law states that force is equal to mass multiplied by acceleration.

$$F = ma$$

The units of mass (kg) multiplied by the units of acceleration (m/s^2) provide the units for force ($\frac{kg \cdot m}{s^2}$ or $kg \cdot m/s^2$).

Since force is such an important concept in physics, this unit is given a special name, the newton (N).

$$1\ N = 1 \frac{kg \cdot m}{s^2} \text{ or } 1\ kg \cdot m/s^2$$

Work is equal to force multiplied by distance. $W = F \cdot d$

Referring only to the units

$$\begin{aligned} W &= N \cdot m \\ &= \frac{kg \cdot m}{s^2} \cdot m \\ &= \frac{kg \cdot m^2}{s^2} \text{ or } kg \cdot m^2 \cdot s^{-2} \\ &= J \end{aligned}$$

Work and kinetic energy are equivalent, and therefore both are expressed in joules.

Also, notice the unit in the following calculation:

$$
\begin{aligned}
F &= \frac{W}{d} \\
&= \frac{\text{J}}{\text{m}} \\
&= \frac{\text{kg} \bullet \text{m}^2 \bullet \text{s}^{-2}}{\text{m}} \\
&= \frac{\text{kg} \bullet \text{m}}{\text{s}^2} \text{ or } \text{kg} \bullet \text{m/s}^2 \\
&= \text{N}
\end{aligned}
$$

Sample Problem

A total of 12,000 J of work is required to stop a 45-kg cart.

a) What speed would the cart be traveling before it was brought to a stop?

Strategy: This problem involves work required to stop a moving object. Work and kinetic energy are equivalent. That is, 12,000 J of work are necessary to change 12,000 J of *KE* of the cart to 0 J. You are given the mass of the cart. You can use the equation that relates kinetic energy and mass to calculate the speed of the cart.

Given:

$KE = 12{,}000 \text{ J}$

$m = 45 \text{ kg}$

Solution:

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

$$v^2 = \frac{2KE}{\text{m}}$$

$$v^2 = \frac{2(12{,}000)\text{J}}{45 \text{ kg}}$$

$$v^2 = 533.3 \frac{\text{J}}{\text{kg}}$$

$$
\begin{aligned}
v &= \sqrt{533.3 \frac{\cancel{\text{kg}} \bullet \text{m}^2 \bullet \text{s}^{-2}}{\cancel{\text{kg}}}} \\
&= 23 \text{ m/s}
\end{aligned}
$$

The speed of the cart was 23 m/s.

b) If the cart stopped in a distance of 3 m, what force was needed to stop the cart?

Strategy: This problem involves the kinetic energy and distance it takes to stop. You can use the equation that relates work and distance to calculate the force.

Given:

$W = 12{,}000 \text{ J}$

$d = 3 \text{ m}$

Solution:

$$W = F \cdot d$$

$$F = \frac{W}{d}$$

$$F = \frac{12{,}000 \text{ J}}{3 \text{ m}}$$

$$F = 4000 \text{ J/m}$$

$$= 4000 \text{ N}$$

Checking Up

1. What factors determine a body's kinetic energy?
2. When work is done on an object, what is the effect on its kinetic energy?
3. How does the force needed to stop a moving object depend upon the distance the force acts?
4. What is the unit of kinetic energy? What is the unit for work?

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
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Deriving the Equation for the Relationship between Work and Change in Kinetic Energy

In the *Physics Talk*, the equation for work and the relationship that work equals the change in kinetic energy were stated. By using algebra, this relationship can be derived from the definitions of work, Newton's second law and a motion equation that emerges from the definition of velocity and acceleration. (The derivation of the motion equation also uses algebra that is not shown here.)

Derive the equation for

$$W = \text{change in } KE$$

$$W = Fd$$

Since $F = ma$

$$W = mad$$

Using the definitions of $a = \Delta v/\Delta t$ and average $v = \Delta d/\Delta t$, you can derive one of the motion equations:

$$v_f^2 = 2ad + v_i^2$$

$$W = \frac{m(v_f^2 - v_i^2)}{2}$$

$$= \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

Work is required to change the *KE* of an automobile so that it stops.

$W = \Delta\left(\tfrac{1}{2}mv^2\right)$, where Δ is a symbol for "change."

In order to demonstrate your understanding of this equation:

1. Sketch a graph of the work necessary to bring an automobile to a stop as a function of the automobile's kinetic energy.
2. Sketch a graph of the work required to bring an automobile to a stop as a function of the automobile's speed.
3. Sketch a graph of the work required to bring an automobile to a stop as a function of the automobile's mass.

What Do You Think Now?

At the beginning of the section, you were asked

- **How does an air bag protect you during an accident?**

Explain how an air bag can protect you. Be sure to include the ideas of work and change in kinetic energy in your explanation.

Physics

Essential Questions

What does it mean?

During a crash, you will eventually stop. It can occur when you hit the hard dashboard or the softer air bag. Physics can be used to determine how much force will be exerted on you. Explain how two different forces can cause the same change in the kinetic energy of an object. Include the definition of work in your explanation.

How do you know?

How did you test whether a material is good for cushioning an egg during a collision?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Forces and motion	* Conservation laws	Experimental evidence is consistent with models and theories

* Energy is an organizing principle of all science. It states that the total energy of a system remains the same. It also allows for a force to be applied by an external force to change the energy. Explain how you can change the energy of an egg or an automobile during a collision without violating the conservation of energy.

Why should you care?

How will you use the physics concept of $Work = F \cdot d = \Delta KE$ to help design your safety system?

Reflecting on the Section and Challenge

In this section, you found that softer surfaces were better able to protect an egg during a collision. Similarly, softer surfaces such as air bags are able to protect you by extending the distance it takes to stop you in an automobile accident. Without the air bag, you will hit something else that will stop you in a shorter distance.

Work produces a change in the kinetic energy. A large force over a short distance or a small force over a large distance are two ways in which work can produce the same change in kinetic energy. The large force can injure you. With an air bag, the stopping distance is larger and therefore, the force required to stop you is smaller.

Energy and work must be considered in designing your safety system. Stopping an object over a large distance reduces the damage. The harder a surface is, the shorter the stopping distance, and the greater the damage. In part, this provides you with a clue to the use of padded dashboards and visors in newer vehicles. Understanding energy and work allows designers to reduce damage both to vehicles and passengers.

Physics to Go

1. There are many situations in which the force of an impact is reduced by increasing the stopping distance. Explain how each of the following actions reduces the force by increasing the stopping distance. Use the terms force, energy, and stopping distance in your answers.

   a) Catching a hard ball with a catcher's mitt

   b) Jumping to the ground from a large height and bending your knees

   c) Bungee jumping

   d) A wrestler's mat

2. If you triple the speed from 20 km/h to 60 km/h, by what factor does the kinetic energy increase?

3. Two eggs are thrown at a blanket. One egg is thrown at twice the speed of the other. If you assume that in both cases the force exerted by the blanket on the egg is the same, how far will the faster egg travel once it hits the blanket as compared to how far the slower egg travels when it hits the blanket?

4. If the work to stop an object is 60 J, list in your log three force and distance combinations that can stop the object.

5. Copy and complete the following table. The first row has been completed for you. In all the other rows, one of the values is missing.

Kinetic energy	Mass	Speed
500 J	1000 kg	1 m/s
	1000 kg	20 m/s
100,000 J		20 m/s
50,000 J	500 kg	
	1000 kg	30 m/s

6. A person with a mass of 60.0 kg is traveling at 18 m/s.

   a) How much kinetic energy does this person have?

   b) How much work is required to stop the person?

   c) Calculate the force required to stop the person if the stopping distance is 50.0 m.

For *Questions 7 and 8*, choose the best answer from those provided.

7. An egg dropped on a pillow is less likely to break than an egg dropped on concrete because:
   a) The pillow provides a larger force over a larger stopping distance.
   b) The pillow spreads the force out over a longer stopping distance.
   c) The egg loses less energy when it is stopped by the pillow as compared to when it is stopped by the concrete.
   d) The concrete contains sharp bits of sand and rock that break the shell.
8. A 60.0-kg runner has 1920 J of kinetic energy. At what speed is she running? Show your work.
   a) 5.66 m/s
   b) 32.0 m/s
   c) 8.00 m/s
   d) 64.0 m/s
9. Active Physics Plus In *Active Physics Plus*, you used the equation $v_f^2 = 2ad + v_i^2$. Demonstrate your algebra skills, and use the definitions of $a = \Delta v/\Delta t$ and average $v = \Delta d/\Delta t$, to derive the equation.
10. ***Preparing for the Chapter Challenge***

    What safety devices do you know that decrease the force experienced by passengers by increasing the distance over which the collision does work on the passenger? What are the characteristics of those devices that allow them to manage energy better? What can you put in your safety design to manage the energy of a collision?

Inquiring Further

1. **Are air bags always safe?**

   Conduct an Internet search on air bag safety. Do air bags sometimes cause injuries? What are the dangers? What is the physics behind those dangers? How can people reduce the chance of injury due to air bags?
2. **Design a landing pad**

   Design your own landing pad with whatever materials your teacher approves. A pillow might be a good landing pad, but it has one drawback that would make it unsuitable for an automobile. It takes up too much space. Automobile engineers are also limited by other constraints in the design of safety devices. For this problem, you are limited to a landing pad height of 5 cm.
   a) What is the maximum height that you can drop your egg onto your landing pad without getting a crack in the shell?
   b) Do a survey of what other students found and check out their landing pads.
   c) What are the characteristics or properties of a good landing pad?