5.2 Energy in Mechanical and Fluid Systems II

Objectives

- Explain the relationship between gravitational potential energy and an object's position in a gravitational field.
- Explain the relationship between elastic potential energy and an object's position.
- Describe the relationship between work done on a system and its potential energy.
- Explain the law of conservation of energy.
- Solve problems using the law of conservation of energy.
- Explain Bernoulli's principle.
- Use Bernoulli's equation to solve problems in fluid flow.

INTERNET *connection*

To find out more about energy in mechanical and fluid systems, follow the links at **www.learningincontext.com.**

In the last section, you learned that objects and fluids in motion have energy because they have the ability to do work. Energy of motion is called kinetic energy and is calculated by KE = $\frac{1}{2}mv^2$ for translational motion and KE = $\frac{1}{2}I\omega^2$ for rotational motion. You also learned that, when work is done on an object, the object's kinetic energy changes by an amount equal to the work done. This is the work-energy theorem.

Gravitational Potential Energy

What happens when you toss a ball straight up into the air (with no rotation)? You give the ball an initial speed and kinetic energy. But the Earth's gravity exerts a force on the ball, which slows it down. (Drag also slows the ball, but we will neglect this force for now.) At some height *h* above the point at which you released the ball, it stops moving upward and begins moving downward. At this height the speed of the ball, and therefore its kinetic energy, is zero.

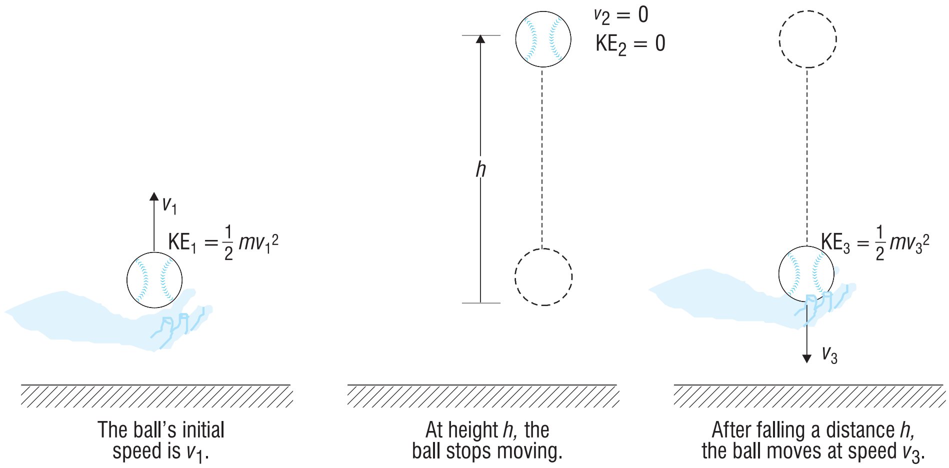


Figure 5.9
The round trip of a tossed ball

You can write a relationship between *h* and the ball's initial speed v_1 using the work-energy theorem:

$$W = \Delta KE$$

For the upward motion, work is done in slowing the ball by the force of gravity (or weight) *mg*, where *m* is the mass of the ball and *g* is the acceleration of gravity. This force is directed downward, while the ball's displacement is upward. Since force and displacement are in opposite directions, work is negative.

$$-mgh = KE_2 - KE_1$$

When the ball reaches height *h*, it stops moving, so $KE_2 = 0$.

$$-mgh = 0 - KE_1$$

$$mgh = KE_1$$

Since $KE_1 = \frac{1}{2}mv_1^2$, we can write the following equality: (What property of mathematics do we use?)

$$mgh = \frac{1}{2}mv_1^2$$

From height h, the ball accelerates downward under the force of gravity. This time gravity acts in the same direction as displacement, and work is positive. Let v_3 represent the speed of the ball when it returns to your hand. You can write the following equation from the work-energy theorem:

$$mgh = \mathrm{KE}_3 - \mathrm{KE}_2$$

$$mgh = \mathrm{KE}_3 - 0$$

$$mgh = \mathrm{KE}_3 = \tfrac{1}{2} m{v_3}^2$$

Notice that $mgh = \mathrm{KE}_1$ and $mgh = \mathrm{KE}_3$. Therefore, $\mathrm{KE}_1 = \mathrm{KE}_3$. (What property of mathematics allows you to make this conclusion?) In other words, by the time the ball returns to your hand, it has recovered all its original kinetic energy. The ball loses kinetic energy on the way up, until it is zero, and then gains kinetic energy on the way down, until all the original kinetic energy is back. What happens to the kinetic energy during this process—where does it go?

As the ball rises, it gains the *potential* for doing work. This potential is realized when the ball drops from height h and does work on your hand as you catch the ball. The amount of work the ball can do because of its height above your hand is called its **gravitational potential energy**. As the ball rises, it loses kinetic energy and gains potential energy.

We use the symbol PE to represent potential energy. We have shown that an object of mass m raised to a height h near the surface of the Earth can do an amount of work mgh, where g is the acceleration of gravity. Therefore, gravitational potential energy $\mathrm{PE_g}$ is defined as follows:

$$\begin{array}{c} \text{Gravitational} \\ \text{potential energy} \end{array} = (\text{mass})\begin{pmatrix} \text{gravitational} \\ \text{acceleration} \end{pmatrix}(\text{height})$$

$$\mathrm{PE_g} = mgh$$

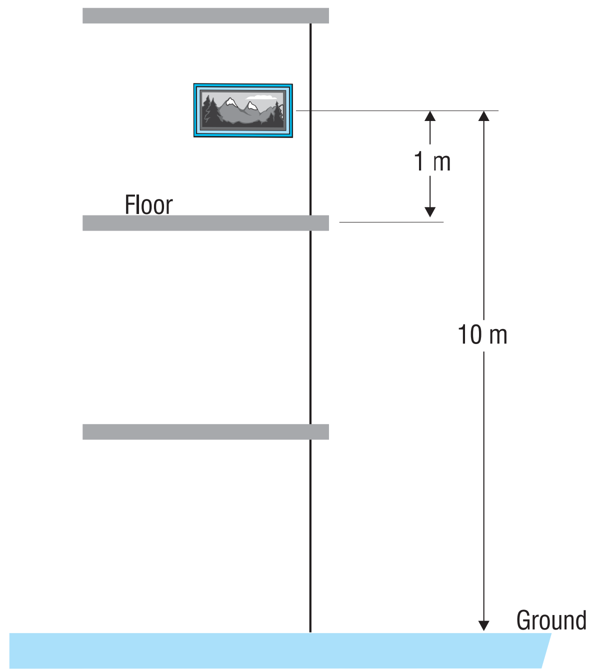
The units of potential energy are the same as kinetic energy and work—joules (J) in the SI system and ft-lb in the English system.

In calculation of gravitational potential energy, the height h is measured from a reference level that you select. The reference level is where you decide $h = 0$ and $\mathrm{PE_g} = 0$. Example 5.6 demonstrates the importance of the reference level.

Example 5.6 More Than One Potential Energy

(a) A 1-kg picture hangs one meter above a floor. What is the gravitational potential energy of the picture with respect to the floor?

(b) The floor is nine meters above the ground. What is the gravitational potential energy of the picture with respect to the ground?



Solution:

(a) Measured "with respect to the floor" means the floor is the reference level. Therefore, *h* is 1 m:

$$PE_g = mgh = (1\ \text{kg})(9.80\ \text{m/s}^2)(1\ \text{m}) = 9.8\ \text{kg}\cdot\text{m}^2/\text{s}^2 \quad \text{or} \quad 9.8\ \text{J}$$

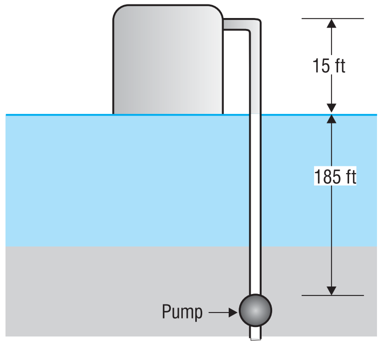
(b) Measured with respect to the ground, *h* is 10 m:

$$PE_g = mgh = (1\ \text{kg})(9.80\ \text{m/s}^2)(10\ \text{m}) = 98\ \text{kg}\cdot\text{m}^2/\text{s}^2 \quad \text{or} \quad 98\ \text{J}$$

Notice that, when you specify a reference level, you are defining the potential energy to be zero at that level. In Example 5.6(a), the height is measured above the floor. The floor is the reference level, and if the picture is moved to the floor $PE_g = mg(0) = 0$. In Example 5.6(b), where does $PE_g = 0$?

Example 5.7 Potential Energy and Work of a Pump

A submersible pump is in a 185-ft-deep well. It pumps water at a rate of 1 ft^3 per second from the well into a tank's inlet 15 ft above the ground. What is the potential energy of 1 ft^3 of water at the tank's inlet, using the pump's location as the reference level? How much work is done by the pump each second? The weight density of water is 62.4 lb/ft^3.



Solution: Each second, the pump moves 1 ft^3 of water. Calculate the weight of this water:

$$\text{Weight} = \rho_w V = (62.4\ \text{lb/ft}^3)(1\ \text{ft}^3) = 62.4\ \text{lb}$$

For calculation of the water's potential energy using the pump's location as the reference level, the height h is 185 ft + 15 ft = 200 ft. The weight of the water is mg.

$$\text{PE}_g = mgh = \text{weight} \cdot h = 62.4\ \text{lb} \cdot 200\ \text{ft}$$

$$\text{PE}_g = 12{,}480\ \text{ft} \cdot \text{lb}$$

The potential energy of the water at height h is the same as the work done by the pump in lifting the water a height h.

Each second the pump does the following amount of work:

$$W_{\text{pump}} = \text{PE}_g = 12{,}480\ \text{ft} \cdot \text{lb}$$

So far, you have seen how an object or fluid has potential energy because of its position in the Earth's gravitational field. Actually, it is more accurate to say the *system* has potential energy. In these cases the system consists of the object (or fluid) and the Earth. The object has potential energy because it is in the gravitational field of the Earth. The Earth also has potential energy, since it is in the gravitational field of the object. The Earth exerts a force on the object, and the object exerts an equal but opposite force on the Earth. The forces can do work on the system, accelerating the object toward the Earth and the Earth toward the object. But we can usually ignore the acceleration of the Earth since it is usually so small that it cannot be measured. (Can you describe a situation where a force does have a noticeable effect on the Earth?)

Elastic Potential Energy

A system can also have potential energy because of an object's position when other types of forces act on it. As with gravity, these forces have magnitudes that depend on the object's position. For example, when you stretch a rubber band it exerts a *restoring force* that increases in magnitude as you increase the distance stretched. When you release the rubber band, it returns to its original shape (assuming you did not stretch it too far).

A rubber band is *elastic*. Elasticity is an object's or material's tendency to return to its original shape after being stretched. On the other hand, a piece of chewing gum is *inelastic*. If you stretch the gum, it does not exert a restoring force and it does not tend to return to its original shape.

Springs are made of elastic materials, usually metal. Like all elastic materials, the elasticity of a spring is due to electric forces acting between atoms in the metal. Figure 5.10 shows an elastic system composed of a spring with a mass attached to one end and fixed at the other end. On the right end of the spring, the mass and spring can move freely (without friction) left-to-right. The left end of the spring is fixed in place and cannot move.

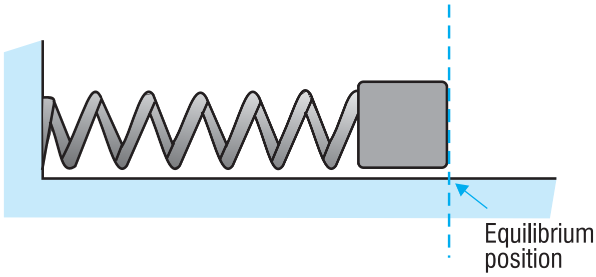


Figure 5.10
A spring-mass elastic system. At the equilibrium position, the spring exerts no force on the mass.

The **equilibrium position** of the spring is its unstretched position—where the spring does not exert a restoring force. If you push or pull the mass and displace the mass and spring from the equilibrium position, the spring exerts a restoring force in the opposite direction. If you push the mass to the left, the spring pushes to the right, toward the equilibrium position. Most springs exert restoring forces that are directly proportional to the displacement. (This is true as long as the displacement is less than the *elastic limit* of the spring. If you extend or compress a spring farther than the elastic limit, the spring will be permanently deformed, like the chewing gum.) Let F represent the restoring force exerted by the spring, and let x represent the displacement.

$$F = kx$$

The proportionality constant k is called the **spring constant**. It has units of force per unit distance—for example, N/cm or lb/in. A "stiff" spring has a high value of k; a "soft" spring has a low value.

When a spring is compressed (or extended) it exerts a force through a distance, and therefore does work. This work is stored in the spring as **elastic potential energy**. You can calculate the work and energy as follows.

Suppose the spring from Figure 5.10 is compressed, by pushing the mass from the equilibrium position to the left a distance *x*. Since it starts at equilibrium, the initial force of the spring is $F_i = 0$. The final force is $F_f = kx$. The average force exerted by the spring during the compression is

$$F_{average} = \frac{F_i + F_f}{2} = \frac{0 + kx}{2} = \tfrac{1}{2}kx$$

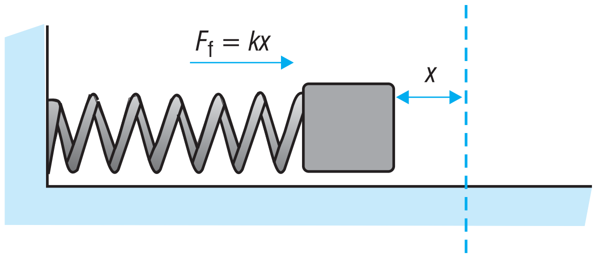


Figure 5.11
A compressed spring exerts a restoring force.
The work done by the spring is stored as elastic potential energy.

The work done by the spring is the product of the average force and the displacement. Since the spring force and displacement are in opposite directions, the work is negative.

$$W_{spring} = -F_{average}x = -\tfrac{1}{2}kx^2$$

If there is no friction in the system, the work done *by* the spring is the opposite of the work done *on* the spring (by whoever pushed the mass to the left). This work is stored in the spring as elastic potential energy $PE_{elastic}$. This is the amount of work the spring can do as a result of its change in shape.

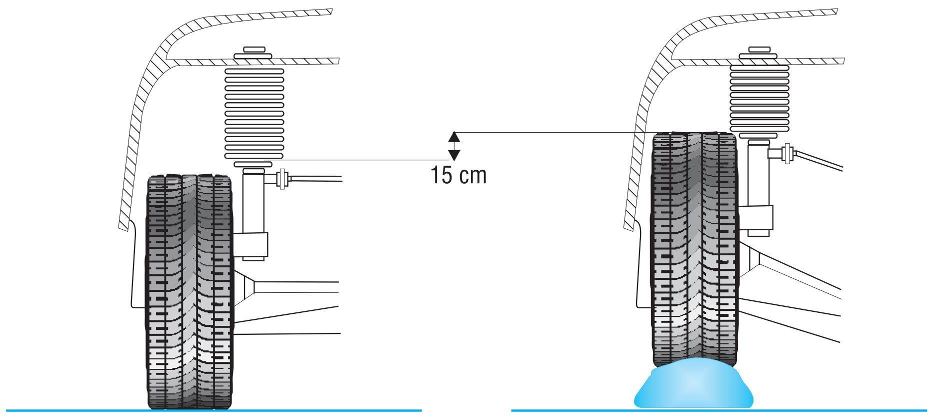
$$\text{Elastic potential energy} = \tfrac{1}{2}(\text{spring constant})\left(\text{spring displacement}\right)^2$$
$$PE_{elastic} = \tfrac{1}{2}kx^2$$

Suppose the mass and compressed spring in Figure 5.11 are released. The spring exerts a net force on the mass to the right and accelerates the mass in the direction of the net force. As the mass accelerates, the spring's stored potential energy is converted to kinetic energy. When the mass reaches the equilibrium position (where $x = 0$) PE = 0 but the mass has maximum KE. Its inertia causes it to continue moving to the right, extending the spring. As the spring extends, kinetic energy is converted to potential energy. Now the spring exerts a force to the left, and the mass will slow down, eventually stop, and begin moving to the left. This process continues, with the mass vibrating right to left and back again, alternately converting potential and kinetic energies. This process is called **simple harmonic motion**.

A car's coil spring is an application of elastic potential energy. When you drive over a bump or depression and your car's wheel suddenly moves upward or downward, work is done on the coil spring. The spring stores an amount of potential energy equal to this work. Stored energy is returned to the wheel by lowering or raising it to its original position while keeping the rest of the car nearly level. (Not all the stored energy is returned to the wheel. Do you know what device in the car eliminates the simple harmonic motion that compressing the coil spring would otherwise cause?)

Example 5.8 Elastic Potential Energy in an Auto Spring

The spring constant of a car's front coil spring is 1800 N/cm. When a front tire of the car rolls over a rock, the spring is compressed 15 cm from its equilibrium position. How much potential energy is stored in the spring at the point of maximum compression?



Solution:

$$PE_{elastic} = \tfrac{1}{2}kx^2$$

$$= \tfrac{1}{2}(1800 \text{ N/cm})(15 \text{ cm})^2$$

$$= 202{,}500 \text{ N}\cdot\text{cm}$$

The units in this result are not SI energy units. Convert cm to m:

$$PE_{elastic} = (202{,}500 \text{ N}\cdot\text{cm})\left(\frac{1 \text{ m}}{100 \text{ cm}}\right) = 2025 \text{ N}\cdot\text{m} \quad \text{or} \quad 2025 \text{ J}$$

The coil spring stores 2025 joules of potential energy.

Several other applications of elastic potential energy are illustrated in Figure 5.12. When a golfer strikes a golf ball, the club compresses one side of the ball. The work done by the club is stored as elastic potential energy in the ball. The elastic potential energy is converted to kinetic energy as the golfer keeps the club in contact with the ball during the follow-through of the swing. The ball accelerates off the club as it returns to its original shape.

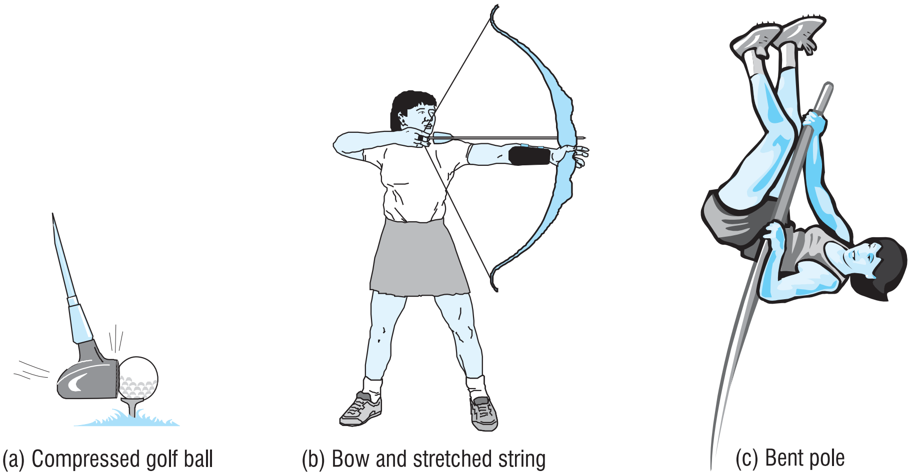


Figure 5.12
Applications of elastic potential energy

When an archer pulls the string on a bow, she does work, which is stored in the bow as elastic potential energy. This energy is converted to kinetic energy when the archer releases the string and it accelerates the arrow.

A pole-vaulter begins a vault by sprinting forward to gain kinetic energy. Some of this energy is converted to work when she plants one end of the pole in the box and bends the pole. This work is stored in the pole as elastic potential energy. The potential energy is converted back to work and kinetic energy as the pole straightens and lifts the vaulter upward. The work of the pole and the vaulter's kinetic energy are converted to gravitational potential energy as she clears the crossbar. Her gravitational potential energy is converted back again to kinetic energy as she falls into the pit.

Conservation of Energy

The examples above demonstrate how potential energy can be converted to kinetic energy, and vice versa. There are also other forms of energy that take part in energy conversion. Internal energy, for example, must be included when drag or friction is important. A soccer ball rolling across a grass field eventually stops due to friction. As it slows down, its potential energy is constant but it loses kinetic energy. Total energy is not *lost*, it is transformed from one type to another. The ball's initial kinetic energy is transformed to thermal energy in the grass and the ball. (What happens to the temperature of the grass and ball?)

Scientists have studied various forms of energy, and its transformation from one form to another, for over 150 years. Their conclusion is one of the most important generalizations in science: the law of **conservation of energy**.

> *In an isolated system, energy is conserved—it cannot be created or destroyed. Energy can change form, but the total amount of energy in the system does not change.*

We can demonstrate the law of conservation of energy using the example from the beginning of the section. Suppose the mass of the ball is 1 kg and you toss it straight upward with an initial speed of 10 m/s. We define potential energy to be zero at the point of release of the ball. So the total energy of the ball is the following sum:

$$\begin{aligned}\text{Total energy} &= PE_g + KE = 0 + \tfrac{1}{2}mv^2 \\ &= \tfrac{1}{2}(1\text{ kg})(10\text{ m/s})^2 \\ &= 50\text{ J}\end{aligned}$$

If we neglect energy transfer to the air through drag forces, the total energy of the ball does not change; it remains 50 J throughout its rise. Just as the ball is released, all its energy is kinetic. Energy is converted from kinetic to potential as the ball rises, but the total energy is constant. Table 5.1 lists the potential, kinetic, and total energies at six heights. Will the ball ever reach a height of 5.2 m? Why?

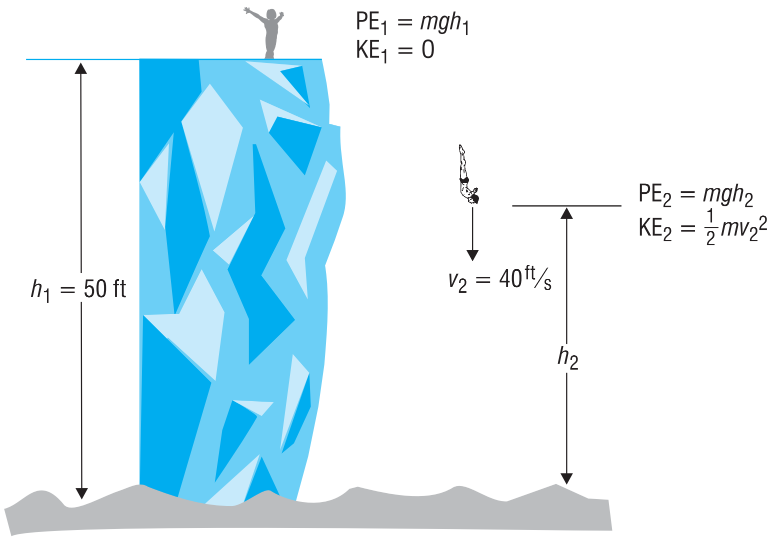
Table 5.1 Potential, kinetic, and total energies of a 1-kg ball tossed upward at 10 m/s

Height		PE = mgh	KE = $\frac{1}{2}mv^2$	PE + KE
5.1 m	$v = 0$ m/s	50 J	0 J	50 J
4.0		39.2	10.8	50
3.0		29.4	20.6	50
2.0		19.6	30.4	50
1.0		9.8	40.2	50
0	$v = 10$ m/s	0	50	50

Example 5.9 Total Energy of a Cliff Diver

A cliff diver dives from a height of 50 feet above the water surface. How far is he from the water when his speed is 40 ft/s? Neglect air drag.

Solution: Let PE_1 and KE_1 represent the diver's potential and kinetic energies before he jumps. Let PE_2 and KE_2 represent the energies at the point at which his speed is 40 ft/s.



Since total energy is conserved and the only forms of energy are potential and kinetic,

$$\text{Total energy} = PE_1 + KE_1 = PE_2 + KE_2$$

$$mgh_1 + \tfrac{1}{2}mv_1^2 = mgh_2 + \tfrac{1}{2}mv_2^2$$

$$m(32.2\ \mathrm{ft/s^2})(50\ \mathrm{ft}) + \tfrac{1}{2}m(0)^2 = m(32.2\ \mathrm{ft/s^2})(h_2) + \tfrac{1}{2}m(40\ \mathrm{ft/s})^2$$

Each term of this equation contains m, so divide both sides by m, and it cancels. The only unknown is h_2. It has units of feet.

$$(32.2)(50) + 0 = 32.2\,h_2 + \tfrac{1}{2}(1600)$$

$$1610 = 32.2\,h_2 + 800$$

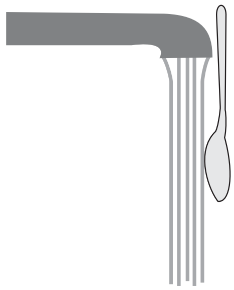
$$h_2 = \frac{1610 - 800}{32.2} = 25.2 \quad \text{or} \quad 25.2\ \text{ft}$$

The cliff diver is 25.2 feet above the water when his speed reaches 40 ft/s.

Bernoulli's Principle and Bernoulli's Equation

Do you think a fluid will have higher, lower, or the same pressure when it is moving compared to the pressure when the fluid is standing still? Compare your answer to the results of two simple experiments, illustrated in Figure 5.13. First, hold a piece of notebook paper just under your lower lip. Blow hard across the top surface. The paper moves upward. In the second experiment, turn on a water faucet until you establish a slow, steady stream of water. Hold a spoon from the end of the handle, with the back of the spoon just touching the stream. The spoon moves toward the stream.

The paper rises when you blow across the top surface.



The spoon moves to the left when water runs across the back surface.

Figure 5.13
Two demonstrations of Bernoulli's principle

The notebook paper and the spoon move because a net force is acting on them. The force is due to atmospheric pressure acting over a surface area. The pressure below the notebook paper is greater than the pressure in the moving air. The pressure to the right of the spoon is greater than the pressure in the moving water. These experiments demonstrate a relationship between the velocity and pressure of a moving fluid. The relationship was first recognized by a Swiss scientist named Daniel Bernoulli in the mid-1700s. **Bernoulli's principle** states:

As the velocity of a fluid increases, the pressure in the fluid decreases.

You may have seen how fluid velocity can increase. For example, water flowing in a stream speeds up when it passes through a narrow part of the stream. You could have predicted this increase in Section 3.2. You learned that the mass flow rate $\dot{m}$ of a fluid is the product of density ρ, cross-sectional area A of the flow, and fluid speed v: $\dot{m} = \rho A v$. If water flows continuously through a stream or pipe, mass flow rate into a narrow section must equal mass flow rate out. (There is no place in a pipe for fluid to be stored, removed, or inserted.) Therefore, $\dot{m}$ must be constant. If the density stays the same but A decreases, v must increase. This is illustrated in Figure 5.14 for a pipe with a gradual reduction in cross section.

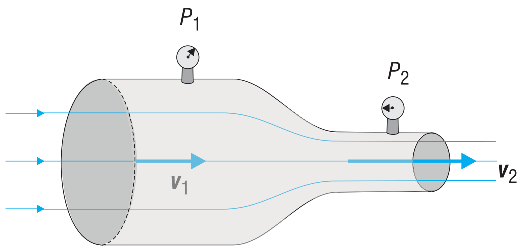
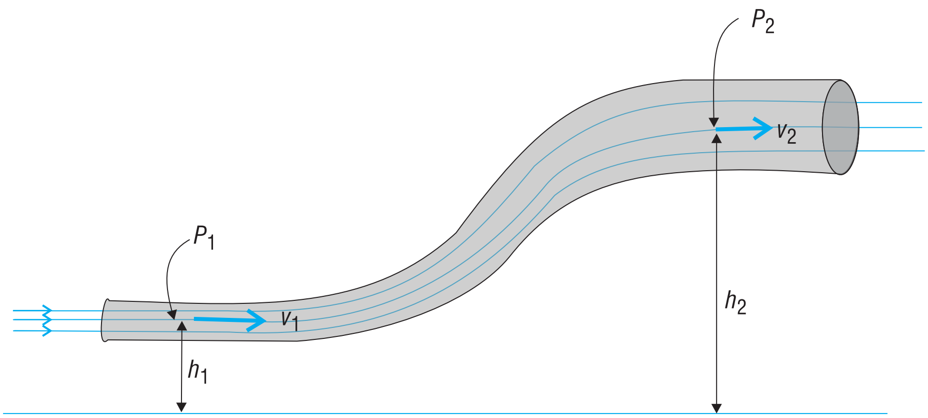


Figure 5.14
The velocity of water increases in the narrower section of a pipe. The pressure decreases.

Since the speed in the narrow section increases, so does kinetic energy. In Figure 5.14, $v_2 > v_1$. This means the fluid mass is accelerated from left to right. A net force is acting from left to right causing the acceleration and doing work on the fluid. In fluid systems, a net force per unit area means there is a pressure difference. Therefore, $P_1 > P_2$. *As the velocity of the fluid increases, the pressure in the fluid decreases.*

Bernoulli also applied energy conservation to fluid flow, as shown in Figure 5.15. Total energy is conserved in a fluid flowing between two points, through a curved pipe of nonuniform cross section. For simplicity, assume there is no viscosity in the fluid, so no energy is "lost" due to internal friction, drag, or turbulence ("lost" means converted to internal energy).



$$P_1 + \rho g h_1 + \tfrac{1}{2}\rho v_1^2 = P_2 + \rho g h_2 + \tfrac{1}{2}\rho v_2^2$$

Figure 5.15
Bernoulli's equation for two points in a fluid

In solving fluid-flow problems, it is usually simpler to use density instead of mass. The density of a fluid is constant in many processes. When we use density instead of mass, energy becomes energy per unit volume. For example, when you divide KE and gravitational PE by volume V, you get:

$$\mathrm{KE} = \tfrac{1}{2}mv^2 \qquad \mathrm{PE_g} = mgh$$

$$\frac{\mathrm{KE}}{V} = \frac{1}{2}\frac{m}{V}v^2 \qquad \frac{\mathrm{PE_g}}{V} = \frac{m}{V}gh \qquad \left[\rho = \frac{m}{V}\right]$$

$$\text{KE per unit volume} = \tfrac{1}{2}\rho v^2 \qquad \mathrm{PE_g}\text{ per unit volume} = \rho g h$$

The fluid pressure changes from point 1 to point 2. Since there are no other sources of work or energy, the pressure change must be caused by work done by the fluid. Remember from Section 2.2 that work done by a given volume of fluid is given by the equation $W = -\Delta P(V)$. Therefore, the work per unit volume done by the fluid is $W/V = -\Delta P$, or $P_1 - P_2$. Energy is conserved, so all this work goes into changing kinetic and potential energies.

$$P_1 - P_2 = \left(\tfrac{1}{2}\rho v_2^2 - \tfrac{1}{2}\rho v_1^2\right) + (\rho g h_2 - \rho g h_1)$$

If you rearrange this equation to get all the same subscripted variables on the same side, the result is **Bernoulli's equation**:

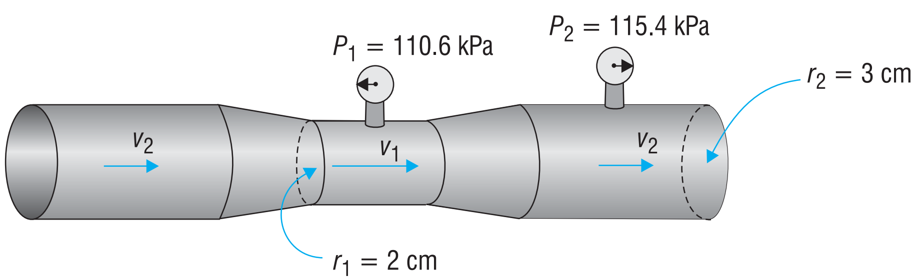
$$P_1 + \rho g h_1 + \tfrac{1}{2}\rho v_1^2 = P_2 + \rho g h_2 + \tfrac{1}{2}\rho v_2^2$$

The quantity $P + \rho g h + \frac{1}{2}\rho v^2$ represents total energy per unit volume. Bernoulli's equation states that this quantity is constant everywhere in the fluid.

Notice that, if fluid viscosity is not negligible, the quantity $P + \rho g h + \frac{1}{2}\rho v^2$ is not constant—it decreases in the direction of the flow.

Example 5.10 Flow Through a Constriction

A constriction is built into a 3-cm-radius pipe to measure the flow rate of water. The pipe has a 2-cm radius at the narrow part. When the water pressure in the narrow part of the pipe is 110.6 kPa, the pressure in the wide part is 115.4 kPa. What is the mass flow rate $\dot{m}$ of water through the pipe? The density of water is 1000 kg/m³.



Solution: The mass flow rate is $\dot{m} = \rho A v$ and is constant. Therefore $\rho A_1 v_1 = \rho A_2 v_2$. Solve this equation for v_1. The pipe is circular, so $A = \pi r^2$.

$$v_1 = \frac{\rho A_2 v_2}{\rho A_1} = \frac{A_2}{A_1} v_2 = \frac{\pi (0.03\text{ m})^2}{\pi (0.02\text{ m})^2} v_2 = 2.25 v_2$$

Substitute this result into Bernoulli's equation and solve for v_2. The height of the fluid does not change, so $h_1 = h_2$, and the PE_g terms cancel.

$$P_1 + \rho g h_1 + \tfrac{1}{2}\rho v_1^2 = P_2 + \rho g h_2 + \tfrac{1}{2}\rho v_2^2$$

$$P_1 + 0 + \tfrac{1}{2}\rho(2.25 v_2)^2 = P_2 + 0 + \tfrac{1}{2}\rho v_2^2$$

$$\tfrac{1}{2}\rho(2.25^2 v_2^2 - v_2^2) = P_2 - P_1$$

$$4.0625 v_2^2 = \frac{2(P_2 - P_1)}{\rho}$$

$$4.0625 v_2^2 = \frac{2(1.154\times 10^5\ \text{Pa} - 1.106\times 10^5\ \text{Pa})}{1000\ \text{kg/m}^3}$$

$$v_2 = \sqrt{\frac{9.6\ \text{m}^2/\text{s}^2}{4.0625}} = 1.54\ \text{m/s}$$

Now calculate the mass flow rate:

$$\dot{m} = \rho A_2 v_2 = (1000\ \text{kg/m}^3)\pi(0.03\ \text{m})^2(1.54\ \text{m/s})$$

$$\dot{m} = 4.35\ \text{kg/s}$$

The mass flow rate of water through the pipe is 4.35 kilograms per second.

The lifting force of a wing on an airplane is another application of Bernoulli's principle. Streamlines in the flow of air past a wing are shown in Figure 5.16. The wing divides air into two parts: One part flows over the top surface of the wing and the other flows along the bottom surface. Air flowing over the top of the wing travels farther than air flowing along the bottom, but in the same amount of time. This means the speed of air above the wing is greater than the speed below the wing. The difference in speed leads to a lower pressure over the top of the wing. The average pressure difference times the area of the wing is the lifting force produced by the wing.

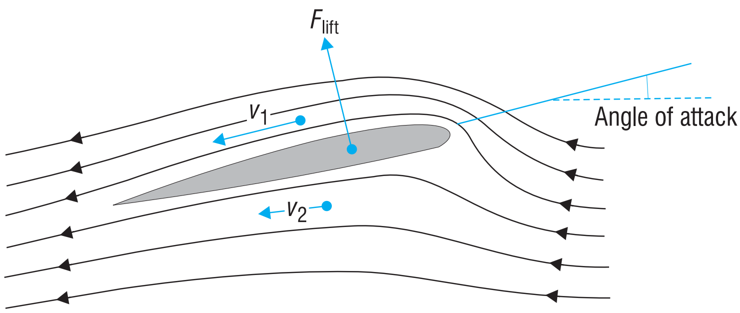


Figure 5.16
Streamlines show air flow around a wing. Air speed is higher where the streamlines are closer together.

At higher speeds, the pressure difference and the lift are higher. But, for any wing design, at some speed and angle of attack the air flow becomes turbulent. The lifting force of a wing is lowered by turbulent air flow.

Summary

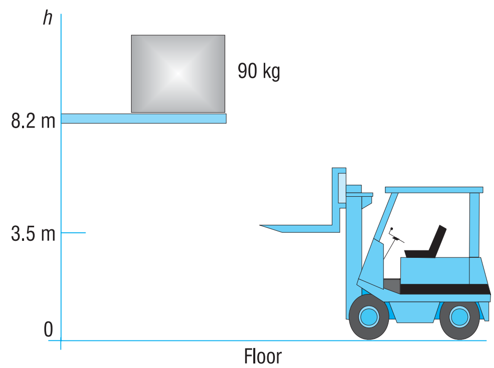
- Potential energy is energy that something has because of its position.
- In a gravitational field, $PE_g = mgh$.
- Elastic potential energy is energy stored in a spring or other material that exerts a restoring force when it is stretched or compressed.

$$PE_{elastic} = \frac{1}{2}kx^2$$

- Work done on a system can be stored as potential energy.
- The law of conservation of energy states that in an isolated system energy can change form, but the total energy does not change.
- Bernoulli's principle states that as the velocity of a fluid increases, the pressure in the fluid decreases.
- Bernoulli's equation states that, for a nonviscous, laminar fluid flow where the density does not change, $P + \rho gh + \frac{1}{2}\rho v^2$ is constant. This is a statement of conservation of energy for the fluid.

Exercises

1. Is energy the same as force? How are they related?
2. If you lift a 50-lb barbell 6 ft off the floor, how much work do you do? By how much do you change the barbell's potential energy? If you drop the barbell from 6 ft, what is its kinetic energy just before it hits the floor?
3. A 90-kg box is stored on a warehouse shelf 8.2 meters above the floor.



   (a) What is the box's gravitational potential energy relative to the floor?

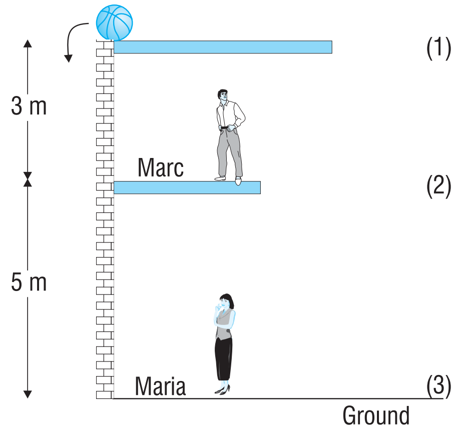
   (b) What is the box's gravitational potential energy relative to a forklift 3.5 m above the floor?

4. Shareka weighs 490 N. She rides an escalator in a mall to a level 6.7 m below her starting location. What is Shareka's change in gravitational potential energy?

5. (a) How much potential energy does a 55.2-kg rock-climber gain when she climbs a vertical distance of 35 m?

   (b) Does your answer to (a) change if the climber follows a zig-zag path instead of a straight-line path up the rock? Explain.

6. A 0.60-kg basketball drops from the top of a building, 8 meters above the ground. Marc is located 5 meters above the ground, and Maria is on the ground. They choose their own locations as the reference levels for the ball's gravitational potential energy.



Calculate the potential energy and kinetic energy of the ball, as seen by Marc and Maria at three locations: (1) on the top of the building, (2) at Marc's location, and (3) at Maria's location. Put your answers in a table like the one below.

	Marc	**Maria**
PE_1	?	?
PE_2	?	?
PE_3	?	?
KE_1	?	?
KE_2	?	?
KE_3	?	?

7. In Exercise 6, will Marc and Maria always agree on

   (a) The ball's potential energy?

   (b) The change in the ball's potential energy [from (1) to (2), (1) to (3), and (2) to (3)]?

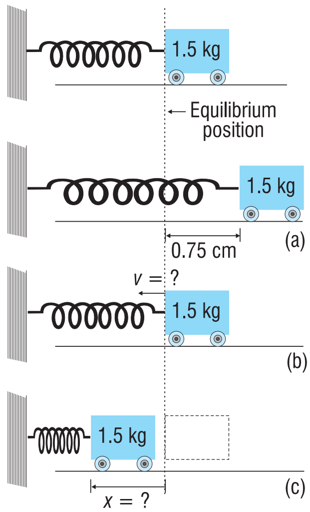
   (c) The ball's kinetic energy?

8. A spring compresses 1.25 in. from its equilibrium position when a force of 8.4 lb is applied.

   (a) Calculate the spring constant of this spring.

   (b) How much work can the spring do if it is extended 0.85 in. from equilibrium?

9. A spring with a spring constant of 1800 N/m is attached to a wall. A 1.5-kg mass is attached to the free end of the spring. The mass can move right and left without friction.



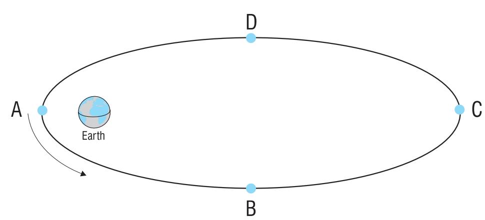
   (a) The mass is pulled to the right 0.75 cm from the equilibrium position. How much potential energy is stored in the spring relative to the equilibrium position?

   (b) The mass is released. When it reaches the equilibrium position, what is the kinetic energy of the mass? What is its speed?

   (c) How far to the left will the mass continue past the equilibrium position?

10. A tennis ball is dropped from a height of 1.6 m. The ball strikes the floor and rebounds to a height of 1.2 m. Has the collision with the floor changed the energy of the ball? Explain your answer.

11. Some satellites travel in elliptical orbits, like that shown here. As the satellite moves in the orbit, its PE and KE change but the total energy remains constant. At which point in the orbit, A, B, C, or D, does the satellite have the greatest PE? Greatest KE?



12. A hang-glider and his gear have a combined weight of 255 lb. With a running start, he leaves the edge of a cliff with an initial air speed of 14.6 ft/s.

    (a) What is the hang-glider's initial kinetic energy?

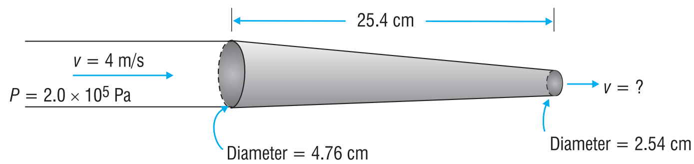
    (b) To gain air speed, the hang-glider immediately descends 250 ft. If you neglect air drag, what is the hang-glider's kinetic energy after the descent?

    (c) After descending 250 ft, the hang-glider's actual air speed is 105 ft/s. How much work is done on the hang-glider by drag forces during the descent?

13. An electric utility company uses electrical energy generated during the night (the low-demand hours) to pump water into a reservoir. During the day (the high-demand hours), the water is drained. As it runs out of the reservoir, the water turns hydroelectric turbines and generates additional peak-demand electricity for the company. The pump and piping system are 63% efficient. This means 63% of the energy supplied to the pump goes into increasing the water's gravitational potential energy.

    If the pump operates with a pressure difference of 250 psi and it pumps 366,000 ft^3 of water, how much work is done by the pump? By how many foot-pounds is the potential energy of the water increased? How much energy is supplied to the pump?

14. A fire hose *straight-stream nozzle* increases the speed of water leaving the hose. The nozzle is 4.76 cm in diameter where it connects to the hose and 2.54 cm in diameter at the open end. Water enters the nozzle at a speed of 4 m/s and a pressure of 2.0×10^5 Pa.



    (a) What is the speed of the water as it leaves the nozzle?

    (b) What is the pressure of the water as it leaves the nozzle?

15. Show that Bernoulli's equation includes the law of pressure change in a stationary fluid: In Figure 5.15, let $v_1 = v_2 = 0$. When the fluid is not moving, which should be greater, P_1 or P_2? Use Bernoulli's equation to complete the following for a stationary fluid.

$$P_1 = ?$$

    Explain why this equation makes sense. (Remember Pascal's law from Section 1.2.)