ENERGY, FORCE, AND MOTION

This section is based on the understanding that energy is conserved. In a system, energy can be transferred and transformed. In doing so, energy affects, and is affected by, matter. This section ties together energy at the nuclear level, the atomic/molecular level, and the macroscopic level of everyday experience. Content topics include energy transformations in systems, and the relationships among force, mass, and motion. The principles of force and motion influence our daily lives whether we walk, throw a ball, rake leaves, or launch missiles. At the atomic level, the relative motion of tiny particles such as atoms and molecules is used to explain the phases of matter. The relative proximity of one particle to another in a system describes the denseness of that matter. In this section, students will have opportunities to observe, measure, and discuss how matter and the forces that act upon it combine to create regularities and patterns that explain scientific phenomena.

CORE IDEAS

- Transformations of energy usually release some energy, typically in the form of heat. (SPS7a)
- Heat, or thermal energy, only moves from warmer places to cooler places, and does so by conduction, convection, or radiation. (SPS7b)
- Different substances absorb different amounts of heat before their temperature changes. (SPS7c)
- Temperature can change as heat is being transferred. (SPS7a, b, c)
- If a substance's temperature or pressure is altered, a phase change may result. (SPS7d)
- While the total amount of work remains constant, when using a simple machine, a mechanical advantage can be calculated. (SPS8d)
- Work is defined as applied force acting through a distance. (SPS8d)
- A simple machine changes the applied force and distance while maintaining the total amount of work. (SPS8d)
- Mechanical advantage is a comparison of the applied force required in using a simple machine versus using no machine. (SPS8d)
- Objects change their motion only when a net force is applied. (SPS8b)
- Force, mass, and acceleration are interdependent. A change in any one of these affects the others. (SPS8a)
- Knowledge of the conditions of an object's motion allows us to predict how its motion will change. (SPS8b)
- Friction is an ever-present force that opposes motion. (SPS8b)
- Whenever one object exerts a force on another, an equal amount of force is exerted in return. (SPS8b)
- A change in the energy of a system affects the attraction between the particles or molecules, and a phase change may occur. (SPS7d)

KEY CONCEPTS

Just as matter is conserved, so is energy. The **law of conservation of energy** states that energy, like matter, cannot be created or destroyed; it can only be changed from one form of energy to another. Energy takes many forms in the world around us. Each form of energy can be converted to and from other forms of energy. The box to the right shows some energy types. **Electrical energy** is used in our homes to produce stereo sound through speakers, light from a fluorescent lamp, and **thermal energy** for cooking and heating. **Nuclear energy**, which is stored in the nucleus of atoms, is harnessed to produce electrical energy in modern power plants. **Chemical energy** is stored in the bonds that hold atoms together in molecules. When fuels or foods are broken down, chemical energy is converted to heat energy or to kinetic energy. **Kinetic energy** is the energy contained by moving objects due to their motion. Even objects at rest have energy, based on their position. **Potential energy**, also known as stored energy, is the energy of position. When a boulder sits on top of a cliff, it has gravitational potential energy as a result of its height above the ground. When the boulder tumbles off the cliff, its gravitational potential energy is converted to kinetic energy. When a ball is thrown up into the air, the kinetic energy of the ball is converted into gravitational potential energy as the ball approaches its highest point. As the ball falls back to the ground, the potential energy it gained during its upward flight turns back into kinetic energy. Kinetic and potential energy are types of mechanical energy.

Energy Types

- Chemical
- Electrical
- Electromagnetic
- Mechanical
- Nuclear
- Radiant or Light
- Sound
- Thermal

We obtain energy from a variety of sources. The most common source of energy for electrical generation worldwide is coal. The chemical energy contained in coal is converted to electrical energy through the following series of energy transformations:

Chemical —*burning*→ **Heat** —*turbine*→ **Mechanical** —*generator*→ **Electrical**

Petroleum and natural gas represent other fuels that, along with coal, are known collectively as **fossil fuels.** The box to the right shows some energy sources.

Energy Sources

- Fossil Fuels
- Geothermal
- Hydroelectric
- Nuclear
- Solar
- Wind

The movement of thermal energy from hot to cold materials is called **heat transfer.** There are three basic types of heat transfer: conduction, convection, and radiation.

- **Conduction** is the transfer of heat energy between materials that are in direct contact with each other. Heat transfer by conduction occurs as hot molecules and free electrons become agitated and collide with less energetic neighbors. These neighbors then become agitated and pass along thermal energy in a process similar to a "fire-bucket brigade." The process of conduction can be felt in the handle of a metal spoon that has been placed in a bowl of hot soup. The hot soup transfers heat to the end of the spoon; the heat is then transferred through the spoon to the handle. The rate of heat transfer depends on the type of material. Good conductors, such as metals, conduct heat rapidly. **Insulators**, such as wood or plastic, conduct heat very slowly.
- **Convection** is the transfer of heat energy by the mass movement of fluids containing heated particles. Fluids are materials that can flow. Liquids and gases are examples of fluids. When particles of a fluid are heated, the particles move farther apart, causing the fluid to expand. This movement of heated particles creates convection currents. Home heating systems force heated air into rooms by way of convection currents. These currents heat the colder air in the room.

- **Radiation** is the transfer of heat energy through electromagnetic waves. These waves originate from accelerated charged particles. Electromagnetic waves travel through matter or through empty space. Heat transfer through empty space is unique to radiation. Both conduction and convection require a medium or matter to transfer heat energy. Since the space between the sun and Earth is essentially a vacuum, the heat energy from the sun is transferred to Earth only by radiation.

Different substances have varying capacities for storing energy within their molecules. Heat energy can cause molecules to move about faster, increasing their random kinetic energy. An increase in this energy raises the temperature of the substance. Heat energy can also increase the vibrational or rotational energy of molecules, but this does not result in a temperature increase. Each substance has a unique **specific heat capacity**, meaning different substances have the ability to absorb only a certain amount of heat in given conditions. Specific heat values for some common substances are shown in the table below. The specific heat capacity is generally defined as the amount of heat energy required to raise the temperature of 1 kilogram of a substance by 1°C. It is a measure of how much heat energy a particular substance can hold. The units most commonly used are joules per kilogram per degree Celsius. The amount of heat energy that a substance gains or loses (Q) depends on the mass (m), the specific heat (c), and the change in the temperature (ΔT) of the substance. The formula for finding the heat energy is simply the product of the three factors, $Q = mc\Delta T$.

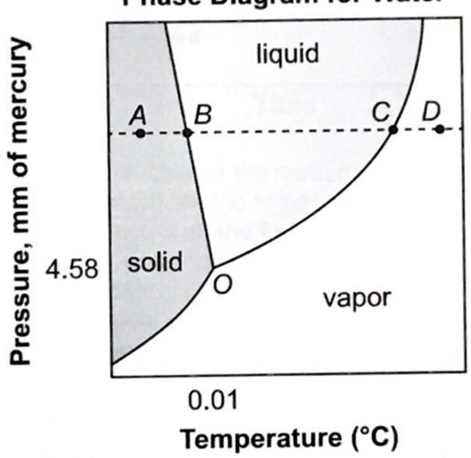
Specific Heat for Some Common Substances

Substance	Specific Heat, c $\left(\frac{\text{J}}{\text{kg} \cdot {}^\circ\text{C}}\right)$
air (dry)	1,010
aluminum	900
copper	390
ethanol	2,450
glass	840
ice (at −15°C)	2,000
mercury	140
steel	450
water (at 15°C)	4,190

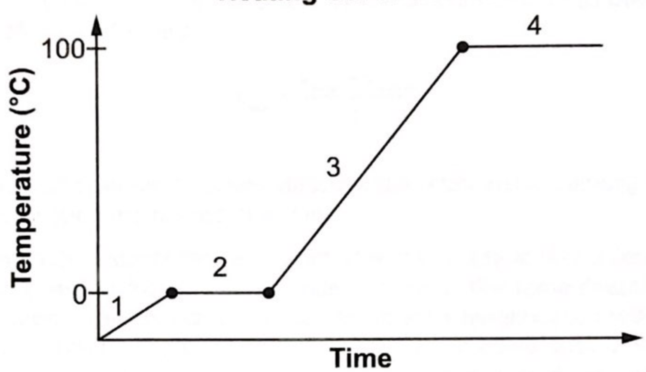
A **phase diagram** shows how a pure substance changes from one phase to another based on the temperature and the pressure. The phase diagram for water, below, shows how pressure and temperature changes are related to cause water to change phases. At point *O* on the diagram all three phases of water exist in equilibrium. On this point, the temperature is equal to 0.01°C and the pressure is equal to 4.58 mm of mercury, which is 0.6% of one atmosphere of pressure. One atmosphere (atm) is a unit of measurement equal to the average air pressure at sea level at a temperature of 15°C. One atmosphere is equal to 760 mm of mercury, or 1,013 millibars. Above point *O*, pathway *AD* has been marked on the diagram. If we trace along the dashed pathway on the phase diagram, we find at point *A*, water exists as a solid. As the temperature increases at a constant pressure, we reach point *B* on the diagram. At that point, solid ice melts and the temperature remains constant until all ice has melted.

From point *B* to point *C*, water exists as a liquid and the temperature increases. At point *C*, water boils, turning into a vapor (or gas). The temperature remains constant again during this phase change. After vaporization is complete, the temperature of the resulting vapor increases until we reach point *D*. There are no other phase changes after this point. Notice that if another pathway is marked out at a constant pressure of less than 4.58 mm of mercury (below point *O*), water will experience only one phase change, solid to vapor.

Phase Diagram for Water



A diagram called a **heating curve** shows how temperature changes as a substance is heated at a constant rate. The heating curve below shows how the state of matter changes as water is heated at a constant rate. In section 1, the water is solid ice, because not enough energy has been added to weaken the intermolecular forces enough. In section 2, enough energy has been added to make the ice start to melt, so now there is a mixture of solid ice and liquid water. In section 3, the water is all liquid, and the molecules of water are moving faster and faster as more energy is added. In section 4, the water has finally started to boil, so there is a mixture of liquid and gas until all of the liquid has changed into gas.



Simply stated, a **force** is an action that can change the motion of an object. A push or pull is an example of a force. The unit for force is the newton (N). All the forces acting on an object can be combined to determine the net force acting on the object. If all the forces acting on the object are balanced, the net force is zero and the motion of the object does not change. If an object is already at rest, it will remain at rest. If an object is moving, it will keep moving. **Balanced forces** do not change the motion of an object. If the combination of forces acting on an object is not balanced, then the net force is greater than zero and the motion of the object changes. **Unbalanced forces** change the motion of an object.

Displacement is the length and direction of a straight line between two locations, or positions. Since displacement considers only the length and direction of a straight line, it doesn't depend on the actual path of a moving object. If Town A is 10 miles east of Town B, the displacement of Town A is 10 miles east relative to Town B. For a moving object, displacement can be defined as the change between the initial and final position of the object.

Distance is a measure of the length of a path that a moving object travels. If the only road between the two towns has to wind through hills, the distance traveled between the two towns is longer than 10 miles, even though the displacement between the two towns is 10 miles east.

The distance an object moves per unit of time is known as the **speed (s) (often shown, as here, in *italics* to help distinguish it from the abbreviation s for seconds).** The average speed (s_{ave}) can be found by dividing the change in the distance (d) of an object by the amount of time (t) over which the change occurs.

$$s_{ave} = \frac{d_{final} - d_{initial}}{t}$$

Where time t can be found by subtracting the initial time from the final time of the period in which the object is moving:

$$t = t_{final} - t_{initial}$$

Velocity (*v*) is a quantity that indicates the rate at which on object changes its position. The velocity of an object includes a measurement of its speed and information about the direction in which the object is moving. Velocity can be calculated in the same way as speed but in this case the *d* in the equation stands for displacement instead of distance.

$$v_{ave} = \frac{d_{final} - d_{initial}}{t}$$

Acceleration, like velocity, has magnitude and direction. The average acceleration (*a*) of an object is found by dividing the change in the velocity (*v*) of the object by the amount of time (*t*) over which the change occurs, with the same definition of time *t*.

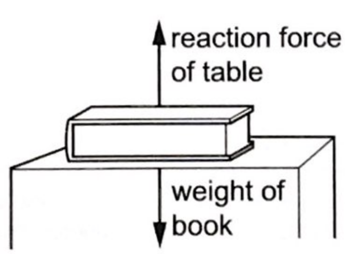
$$a_{ave} = \frac{v_{final} - v_{initial}}{t}$$

Sir Isaac Newton was the first scientist to clearly describe the relationships among force, mass, and motion. The three laws of motion are named after him.

- **Newton's first law** of motion states that an object *at rest* will stay at rest unless it is acted upon by an unbalanced force. An object *in motion* will continue to move in the same direction and with the same speed unless acted upon by an unbalanced force. An object's tendency to resist a change in motion is called **inertia.** Inertia is directly related to an object's mass. An object with a large mass has a large amount of inertia, while an object with a small mass has a small amount of inertia. Large forces are required to change the motion of objects with large masses, while small forces can change the motion of objects with small masses.
- **Newton's second law** of motion states that the acceleration, *a*, of an object is directly related to the net force, *F*, which is the result of unbalanced forces acting on an object, applied to the object and inversely related to the mass, *m*, of the object. The following equation represents Newton's second law of motion.

  $$a = \frac{F}{m} \quad \text{or} \quad F = ma$$

  According to the equation, the greater the net force acting on an object, the greater the acceleration of the object, for an object of a given mass. Also, the greater the mass of the object, the lower the acceleration of the object for a given force acting on the object. For example, a large truck has a much lower acceleration than a compact car when the same force is applied by each vehicle's engine. The larger mass (or inertia) of the truck resists acceleration.
- **Newton's third law** of motion states that forces occur as equal and opposite pairs. For every action force, there is an equal and opposite reaction force. For example, when a book is sitting on a table, the weight of the book produces a downward action force on the table. The tabletop in turn pushes on the book with an upward reaction force. These forces are equal in magnitude but opposite in direction.



Frictional forces tend to stop the motion of an object by dispersing its energy as heat. Friction must be overcome for an object to move.

There are four types of fundamental forces in nature, as shown in the box. However, in this course we will focus only on the gravitational and electromagnetic fundamental forces.

Some Types of Forces

- Gravitational
- Electromagnetic
- Strong nuclear
- Weak nuclear

Gravitational force is a force between any two objects. The strength of the force is related to the masses of the objects and the distance between them. The more mass an object has, the greater the gravitational force it exerts. As the distance between two objects increases, the force of gravity decreases by a factor equal to the square of the distance. For example, if the distance between two objects is doubled, the force of gravity will decrease by a factor of four. The moon has less mass than Earth. The resulting lower gravitational force made astronauts appear nearly "weightless" as they moved across the lunar surface.

One should note that mass and **weight** are not the same quantity. An object has mass regardless of whether gravity or any other force is acting upon it. Weight, on the other hand, changes depending on the influence of gravity. The relationship between weight, W, and mass, m, can be written as the following equation:

$$W = mg$$

In this equation, g represents the acceleration due to gravity. At the surface of Earth, the acceleration of gravity is approximately 10 m/s^2. The value of g decreases the farther away from the center of Earth an object gets. This means the weight of an object would decrease if it were placed on top of a mountain or put into space.

Other forces include **electromagnetic forces.** These forces include both electric forces and magnetic forces. The forces exerted within the nucleus of an atom are called **nuclear forces.** These forces hold the protons and neutrons together.

The idea of **work** is familiar to most people. For example, it takes more work to move heavier objects, such as a car at rest, than much-lighter objects, such as a bicycle. Work is the transfer of energy when an applied force moves an object over a distance. For work to be done, the force applied must be in the same direction as the movement of the object and the object must move a certain distance. If a person moves a box a distance of 10 meters, the applied force times the distance moved equals the work done, summarized with the equation:

$$W = Fd$$

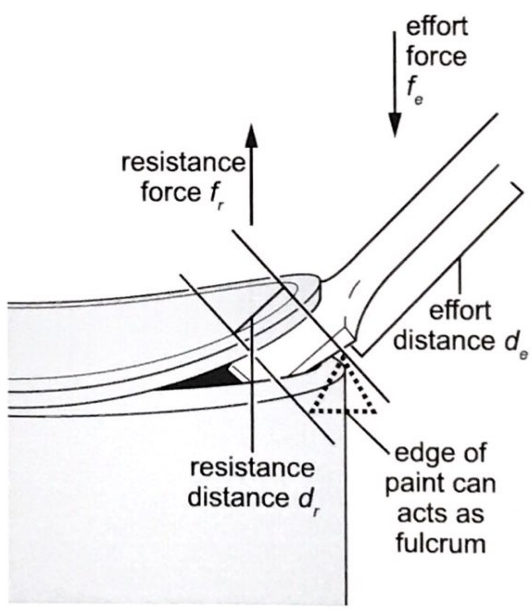
In the equation, W is equal to work, F is equal to the force applied, and d is equal to the distance that an object has moved. Remember, force is measured in newtons (N) and distance is measured in meters (m). A unit of work is the newton-meter (N-m) or the joule (J). So, if 10 newtons is applied to move the box a distance of 10 meters, 100 joules of work is done on the box. A person may push on a wall and get tired muscles as a result, but, unless the wall moves, the person has done zero work on the wall.

Work can be made easier or be done faster by using machines. Machines that work with one movement are called **simple machines**. There are six types of simple machines. These are listed in the box below.

Simple Machines

- Inclined Plane
- Lever
- Pulley
- Screw
- Wedge
- Wheel and Axle

Simple machines cannot decrease the amount of work done, but they can change the size and direction of the force used to do the work. The force applied to a simple machine is called the **effort force**, f_e. For a machine to do work, an effort force must be applied over a distance. The force exerted by the machine is called the **resistance force**, f_r. A lever rotates about a point called a fulcrum. The fulcrum is the reference point to find the resistance distance on one side of the fulcrum and the effort distance on the opposite side. For example, consider how a painter uses a screwdriver as a lever to pry open the lid on a can of paint. An illustration showing the bottom end of the screwdriver and the top of a paint can is shown below. When the painter pushes down on the screwdriver, an effort force is applied over a distance known as the **effort distance**, d_e. As a result, the tip of the screwdriver exerts a resistance force against the lid of the paint can. The screwdriver acts as a lever, with the fulcrum being the edge of the paint can where the screwdriver pivots. This force moves the lid of the can over the **resistance distance**, d_r.



Mechanical advantage is the ratio of the resistance force to the effort force or equivalently the ratio of the effort distance to the resistance distance. The mechanical advantage is determined using the following equations:

$$\text{Mechanical advantage} = \frac{\text{effort distance}}{\text{resistance distance}} = \frac{\text{resistance force}}{\text{effort force}} \left(MA = \frac{d_e}{d_r} = \frac{f_r}{f_e}\right)$$

Since these two ratios are equal, the mechanical advantage can be also be computed by using each ratio separately:

$$MA = \frac{f_r}{f_e} \quad \text{or} \quad MA = \frac{d_e}{d_r}$$

For the lever described on the previous page, pushing down on the effort side raises the load on the resistance side, and the mechanical advantage is the distance from the effort force to the fulcrum divided by the distance from the resistance force to the fulcrum. Applying the equations shows the ratio of the resistance force to the effort force.

For example, if 15 N of force is applied to the handle of the screwdriver against a resistance force of 150 N, the mechanical advantage of the screwdriver is 10. The tip of the screwdriver has multiplied the effort force 10 times. For an inclined plane, the mechanical advantage is the length of the sloped surface divided by the height of the ramp. For a simple pulley with one wheel, the mechanical advantage is 1, but the direction of the force to lift a weight has been changed from upward to downward. A compound pulley with multiple wheels has increasing mechanical advantage with additional wheels. Classroom resources can provide examples of the mechanical advantage of other simple machines.