How does matter change when heated or cooled?

Adapted from *Conceptual Physical Science*, P. G. Hewitt, J. Suchocki, and L. A. Hewitt, Pearson Publishing (2004)

Think about the following phenomena: it is easier to open a glass jar with a metal lid after heating the metal lid with hot water than with just cold water. And, look at figure 1 and explain why the balloon does not explode even after several minutes of contact with the candle's flame. A balloon full of air will almost immediately explode when placed near the flame of a candle. Given these phenomena, what role does water play in helping the opening of the glass jar or preventing the rupture of the balloon?

Figure 0: A balloon filled with water is placed on top of a burning candle.

All matter—solid, liquid, and gas—is composed of tiny particles (atoms and molecules) that continually wiggle and jiggle, twist and turn, vibrate, or move back and forth.

When this random motion is slow, the particles form solids. When the motion is faster and they slide over one another, we have a liquid. When atoms and molecules move so fast that they are disconnected from each other and fly loose, we have a gas. Whether a substance is a solid, liquid or a gas depends on the motion of its particles.

The **total energy** in a substance is the total energy of all its atoms and molecules. Thermal energy consists of both the potential energy due to the forces between molecules and the kinetic energy of the particles due to movements of molecules within the substance and movements of atoms within molecules. The average kinetic energy of these individual particles causes an effect we can sense—warmth. Whenever something becomes warmer, the kinetic energy of its atoms or molecules has increased. When matter gets warmer, the atoms or molecules in the matter move faster.

It's easy to increase the kinetic energy in matter. You can warm a penny by striking it with a hammer—the blow causes the molecules in the penny to jostle faster. If you put a flame to a liquid, the liquid also becomes warmer. Rapidly compress air in a tire pump and the air becomes warmer.

What about the balloon? The air in the air-filled balloon absorbed thermal energy from the flame and started moving faster. The increased movement of the molecules of air expanded the balloon and plastic of the balloon quickly melted. The water in the water-filled balloon has a larger capacity than air to absorb a great deal of heat with little change in temperature. Thus, the temperature at the surface of the water-filled balloon does not increase sufficiently to rupture the balloon.

What is Temperature? How is temperature related to heat and energy?

The quantity that tells how hot or cold something is compared with a standard is **temperature**. We express temperature by a number that corresponds to a degree mark on some chosen scale.

Nearly all matter expands when its temperature increases and contracts when its temperature decreases. A common thermometer measures temperature by showing the expansion and contraction of a liquid—usually mercury or colored alcohol—in a glass tube using a scale. Temperature is generally measured on one of three different scales: Celsius, Fahrenheit, or Kelvin.

Temperature is related to the random motions of the molecules in a substance. In the simplest case, temperature is proportional to the average kinetic energy of molecules in matter. In gases, this motion is along a straight path (translational). In solids and liquids, where molecules are more constrained and have potential energy, temperature is more complicated. But it is still true that temperature is closely related to the average kinetic energy of translational motion of molecules.

The higher the temperature of a substance, the faster is the motion of its molecules. So the warmth you feel when you touch a hot surface is the kinetic energy transferred by molecules on the surface of the material you are touching to molecules in your fingers.

Note that temperature is not a measure of the total kinetic energy of all the molecules in a substance. There is twice as much kinetic energy in 2 liters of boiling water as in 1 liter. But the temperatures of both amounts of water are the same because the average kinetic energy of molecules in each is the same.

Figure two shows a bucket full of warm water and a cup full of very hot water. Which container has more total kinetic energy?

Figure 2: Which container has more total kinetic energy? There is more molecular kinetic energy in a bucket full of warm water than in a small cup full of higher-temperature water.

How is thermal energy transferred between systems? How does thermal energy transfer affect the properties of substances?

When you touch a hot stove, energy enters your hand from the stove because the stove is warmer than your hand. But if you touch ice, energy moves from your hand into the colder ice. The direction of this spontaneous energy transfer is always from a warmer to a cooler substance (Second Law of Thermodynamics).

The energy transfer from one object to another because of a temperature difference between them is called **heat**. Whenever heat flows into or out of a system, the gain or loss of **thermal energy** equals the amount of heat transferred (First Law of Thermodynamics). The amount of heat transferred can be determined by measuring the temperature change of the substances in contact with each other. Can you think about the change in motion of the molecules of the substance that takes in or gives off heat? How does its kinetic energy change?

When the temperature of a substance is increased, its molecules jiggle faster and normally tend to move farther apart. This results in a **thermal expansion** of the substance. Most forms of matter—solids, liquids, and gases—expand when they are heated and contract when they are cooled. For comparable pressures and comparable changes in temperature, gases generally expand or contract much more than liquids, and liquids expand or contract more than solids.
How does these properties of matter help explain the behavior of a thermometer?

Now, think back at the metal lid of the glass jar. It becomes easier to remove it because the hot water makes the metal lid expand more quickly than the glass does.
Different substances have different capacities for absorbing and storing thermal energy and it depends on their chemical composition.

For example, almost everyone has noticed that some foods remain hot much longer than others. Boiled onions and moist squash on a hot dish, for example, are often too hot to eat while mashed potatoes may be just right. The topping of a slice of pizza may be too hot to eat, even though the crust is not. The crust cools (gives off heat to the air) quicker that the cheese because it has a lower **heat capacity**.

If we heat a pot of water on a stove, we may find that it requires 15 minutes to raise it from room temperature to its boiling temperature. But if we were to put an equal mass of iron on the same flame, we would find that it would rise through the same temperature range in only about 2 minutes. Water has a much higher capacity for storing energy than most common materials. A relatively small amount of water absorbs a great deal of heat for a correspondingly small temperature rise. Because of this, water is a very useful cooling agent, and is used in cooling systems in automobiles and other engines.

Water also takes longer to cool. Water's capacity to store heat with respect to land also affects the climate in many places on Earth. For example, both Europe and the west coast of the United States both benefit from this property of water.