CHAPTER 11
Thermal Energy, Heat, and Work

Figure 11.1 The welder's gloves and helmet protect the welder from the electric arc, which transfers enough thermal energy to melt the rod, spray sparks, and emit high-energy electromagnetic radiation that can burn the retina of an unprotected eye. The thermal energy can be felt on exposed skin a few meters away, and its light can be seen for kilometers (Kevin S. O'Brien, U.S. Navy)

Chapter Outline

INTRODUCTION Heat is something familiar to all of us. We feel the warmth of the summer sun, the hot vapor rising up out of a cup of hot cocoa, and the cooling effect of our sweat. When we feel warmth, it means that heat is transferring energy *to* our bodies; when we feel cold, that means heat is transferring energy *away from* our bodies. Heat transfer is the movement of thermal energy from one place or material to another, and is caused by temperature differences. For example, much of our weather is caused by Earth evening out the temperature across the planet through wind and violent storms, which are driven by heat transferring energy away from the equator towards the cold poles. In this chapter, we'll explore the precise meaning of heat, how it relates to temperature as well as to other forms of energy, and its connection to work.

11.1 Temperature and Thermal Energy

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Explain that temperature is a measure of internal kinetic energy
- Interconvert temperatures between Celsius, Kelvin, and Fahrenheit scales

Section Key Terms

absolute zero	Celsius scale	degree Celsius ($^{\circ}\mathrm{C}$)	thermal energy
degree Fahrenheit ($^{\circ}\mathrm{F}$)	Fahrenheit scale	heat	
kelvin (K)	Kelvin scale	temperature	

Temperature

What is **temperature**? It's one of those concepts so ingrained in our everyday lives that, although we know what it means intuitively, it can be hard to define. It is tempting to say that temperature measures heat, but this is not strictly true. **Heat** is the transfer of energy due to a temperature difference. Temperature is defined in terms of the instrument we use to tell us how hot or cold an object is, based on a mechanism and scale invented by people. Temperature is literally defined as what we measure on a thermometer.

Heat is often confused with temperature. For example, we may say that the heat was unbearable, when we actually mean that the temperature was high. This is because we are sensitive to the flow of energy by heat, rather than the temperature. Since heat, like work, transfers energy, it has the SI unit of joule (J).

Atoms and molecules are constantly in motion, bouncing off one another in random directions. Recall that kinetic energy is the energy of motion, and that it increases in proportion to velocity squared. Without going into mathematical detail, we can say that **thermal energy**—the energy associated with heat—is the average kinetic energy of the particles (molecules or atoms) in a substance. Faster moving molecules have greater kinetic energies, and so the substance has greater thermal energy, and thus a higher temperature. The total internal energy of a system is the sum of the kinetic and potential energies of its atoms and molecules. Thermal energy is one of the subcategories of internal energy, as is chemical energy.

To measure temperature, some scale must be used as a standard of measurement. The three most commonly used temperature scales are the Fahrenheit, Celsius, and Kelvin scales. Both the **Fahrenheit scale** and **Celsius scale** are relative temperature scales, meaning that they are made around a reference point. For example, the Celsius scale uses the freezing point of water as its reference point; all measurements are either lower than the freezing point of water by a given number of degrees (and have a negative sign), or higher than the freezing point of water by a given number of degrees (and have a positive sign). The boiling point of water is 100 $^{\circ}\mathrm{C}$ for the Celsius scale, and its unit is the degree Celsius ($^{\circ}\mathrm{C}$).

On the Fahrenheit scale, the freezing point of water is at 32 $^{\circ}\mathrm{F}$, and the boiling point is at 212 $^{\circ}\mathrm{F}$. The unit of temperature on this scale is the degree Fahrenheit ($^{\circ}\mathrm{F}$). Note that the difference in degrees between the freezing and boiling points is greater for the Fahrenheit scale than for the Celsius scale. Therefore, a temperature difference of one degree Celsius is greater than a temperature difference of one degree Fahrenheit. Since 100 Celsius degrees span the same range as 180 Fahrenheit degrees, one degree on the Celsius scale is 1.8 times larger than one degree on the Fahrenheit scale (because $\frac{180}{100} = \frac{9}{5} = 1.8$). This relationship can be used to convert between temperatures in Fahrenheit and Celsius (see Figure 11.2).

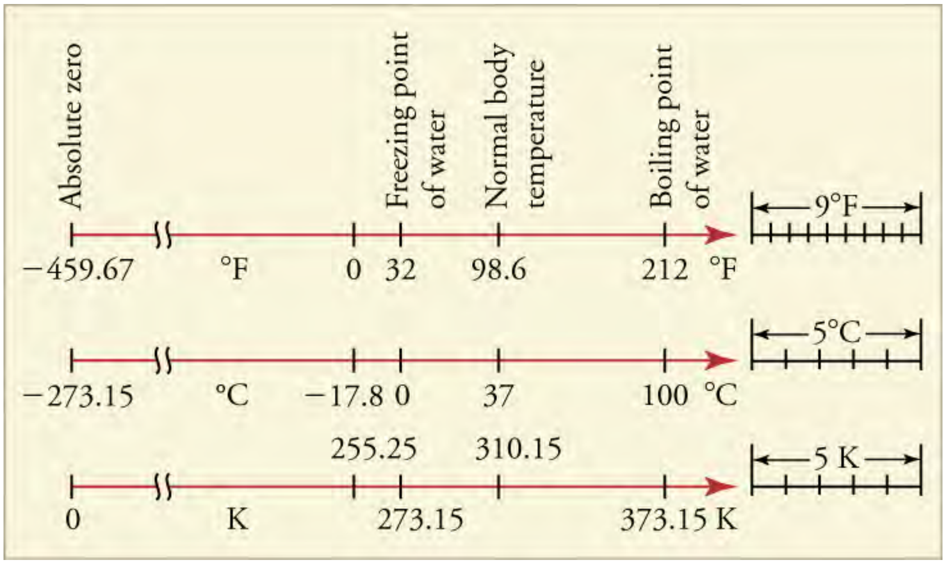

Figure 11.2 Relationships between the Fahrenheit, Celsius, and Kelvin temperature scales, rounded to the nearest degree. The relative sizes of the scales are also shown.

The **Kelvin scale** is the temperature scale that is commonly used in science because it is an absolute temperature scale. This means that the theoretically lowest-possible temperature is assigned the value of zero. Zero degrees on the Kelvin scale is known as **absolute zero**; it is theoretically the point at which there is no molecular motion to produce thermal energy. On the original Kelvin scale first created by Lord Kelvin, all temperatures have positive values, making it useful for scientific work. The official temperature unit on this scale is the kelvin, which is abbreviated as K. The freezing point of water is 273.15 K, and the boiling point of water is 373.15 K.

Although absolute zero is possible in theory, it cannot be reached in practice. The lowest temperature ever created and measured during a laboratory experiment was 1.0×10^{-10} K, at Helsinki University of Technology in Finland. In comparison, the coldest recorded temperature for a place on Earth's surface was 183 K (–89 °C), at Vostok, Antarctica, and the coldest known place (outside the lab) in the universe is the Boomerang Nebula, with a temperature of 1 K. Luckily, most of us humans will never have to experience such extremes.

The average normal body temperature is 98.6 $°\text{F}$ (37.0 $°\text{C}$), but people have been known to survive with body temperatures ranging from 75 $°\text{F}$ to 111 $°\text{F}$ (24 $°\text{C}$ to 44 $°\text{C}$).

WATCH PHYSICS

Comparing Celsius and Fahrenheit Temperature Scales

This video shows how the Fahrenheit and Celsius temperature scales compare to one another.

Click to view content (https://www.openstax.org/l/02celfahtemp)

GRASP CHECK

Even without the number labels on the thermometer, you could tell which side is marked Fahrenheit and which is Celsius by how the degree marks are spaced. Why?

a. The separation between two consecutive divisions on the Fahrenheit scale is greater than a similar separation on the Celsius scale, because each degree Fahrenheit is equal to 1.8 degrees Celsius.
b. The separation between two consecutive divisions on the Fahrenheit scale is smaller than the similar separation on the Celsius scale, because each degree Celsius is equal to 1.8 degrees Fahrenheit.
c. The separation between two consecutive divisions on the Fahrenheit scale is greater than a similar separation on the Celsius scale, because each degree Fahrenheit is equal to 3.6 degrees Celsius.
d. The separation between two consecutive divisions on the Fahrenheit scale is smaller than a similar separation on the Celsius scale, because each degree Celsius is equal to 3.6 degrees Fahrenheit.

Converting Between Celsius, Kelvin, and Fahrenheit Scales

While the Fahrenheit scale is still the most commonly used scale in the United States, the majority of the world uses Celsius, and scientists prefer Kelvin. It's often necessary to convert between these scales. For instance, if the TV meteorologist gave the local weather report in kelvins, there would likely be some confused viewers! Table 11.1 gives the equations for conversion between the three temperature scales.

To Convert From...	Use This Equation
Celsius to Fahrenheit	$T_{°F} = \frac{9}{5}T_{°C} + 32$
Fahrenheit to Celsius	$T_{°C} = \frac{5}{9}(T_{°F} - 32)$
Celsius to Kelvin	$T_K = T_{°C} + 273.15$
Kelvin to Celsius	$T_{°C} = T_K - 273.15$
Fahrenheit to Kelvin	$T_K = \frac{5}{9}(T_{°F} - 32) + 273.15$
Kelvin to Fahrenheit	$T_{°F} = \frac{9}{5}(T_K - 273.15) + 32$

Table 11.1 Temperature Conversions

WORKED EXAMPLE

Room temperature is generally defined to be 25 °C. (a) What is room temperature in °F? (b) What is it in K?

STRATEGY

To answer these questions, all we need to do is choose the correct conversion equations and plug in the known values.

Solution for (a)

1. Choose the right equation. To convert from °C to °F, use the equation

$$T_{°F} = \frac{9}{5}T_{°C} + 32. \tag{11.1}$$

2. Plug the known value into the equation and solve.

$$T_{°F} = \frac{9}{5}25\ °C + 32 = 77\ °F \tag{11.2}$$

Solution for (b)

1. Choose the right equation. To convert from °C to K, use the equation

$$T_K = T_{°C} + 273.15. \tag{11.3}$$

2. Plug the known value into the equation and solve.

$$T_K = 25\ °C + 273.15 = 298 K \tag{11.4}$$

Discussion

Living in the United States, you are likely to have more of a sense of what the temperature feels like if it's described as 77 °F than as 25 °C (or 298 K, for that matter).

WORKED EXAMPLE

Converting Between Temperature Scales: The Reaumur Scale

The Reaumur scale is a temperature scale that was used widely in Europe in the 18th and 19th centuries. On the Reaumur temperature scale, the freezing point of water is 0 $°\text{R}$ and the boiling temperature is 80 $°\text{R}$. If "room temperature" is 25 $°\text{C}$ on the Celsius scale, what is it on the Reaumur scale?

STRATEGY

To answer this question, we must compare the Reaumur scale to the Celsius scale. The difference between the freezing point and boiling point of water on the Reaumur scale is 80 $°\text{R}$. On the Celsius scale, it is 100 $°\text{C}$. Therefore, 100 $°\text{C} = 80\ °\text{R}$. Both scales start at 0 $°$ for freezing, so we can create a simple formula to convert between temperatures on the two scales.

Solution

1. Derive a formula to convert from one scale to the other.

$$T_{°\text{R}} = \frac{0.80°\text{R}}{°\text{C}} \times T_{°\text{C}} \tag{11.5}$$

2. Plug the known value into the equation and solve.

$$T_{°\text{R}} = \frac{0.80°\text{R}}{°\text{C}} \times 25\ °\text{C} = 20°\text{R} \tag{11.6}$$

Discussion

As this example shows, relative temperature scales are somewhat arbitrary. If you wanted, you could create your own temperature scale!

Practice Problems

1. What is 12.0 °C in kelvins?
   a. 112.0 K
   b. 273.2 K
   c. 12.0 K
   d. 285.2 K

2. What is 32.0 °C in degrees Fahrenheit?
   a. 57.6 °F
   b. 25.6 °F
   c. 305.2 °F
   d. 89.6 °F

TIPS FOR SUCCESS

Sometimes it is not so easy to guess the temperature of the air accurately. Why is this? Factors such as humidity and wind speed affect how hot or cold we feel. Wind removes thermal energy from our bodies at a faster rate than usual, making us feel colder than we otherwise would; on a cold day, you may have heard the TV weather person refer to the *wind chill*.
On humid summer days, people tend to feel hotter because sweat doesn't evaporate from the skin as efficiently as it does on dry days, when the evaporation of sweat cools us off.

Check Your Understanding

3. What is thermal energy?
   a. The thermal energy is the average potential energy of the particles in a system.
   b. The thermal energy is the total sum of the potential energies of the particles in a system.
   c. The thermal energy is the average kinetic energy of the particles due to the interaction among the particles in a system.
   d. The thermal energy is the average kinetic energy of the particles in a system.

4. What is used to measure temperature?

a. a galvanometer
b. a manometer
c. a thermometer
d. a voltmeter

11.2 Heat, Specific Heat, and Heat Transfer

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Explain heat, heat capacity, and specific heat
- Distinguish between conduction, convection, and radiation
- Solve problems involving specific heat and heat transfer

Section Key Terms

conduction	convection	heat capacity	radiation	specific heat

Heat Transfer, Specific Heat, and Heat Capacity

We learned in the previous section that temperature is proportional to the average kinetic energy of atoms and molecules in a substance, and that the average internal kinetic energy of a substance is higher when the substance's temperature is higher.

If two objects at different temperatures are brought in contact with each other, energy is transferred from the hotter object (that is, the object with the greater temperature) to the colder (lower temperature) object, until both objects are at the same temperature. There is no net heat transfer once the temperatures are equal because the amount of heat transferred from one object to the other is the same as the amount of heat returned. One of the major effects of heat transfer is temperature change: Heating increases the temperature while cooling decreases it. Experiments show that the heat transferred to or from a substance depends on three factors—the change in the substance's temperature, the mass of the substance, and certain physical properties related to the phase of the substance.

The equation for heat transfer Q is

$$Q = mc\Delta T, \tag{11.7}$$

where m is the mass of the substance and ΔT is the change in its temperature, in units of Celsius or Kelvin. The symbol c stands for **specific heat**, and depends on the material and phase. The specific heat is the amount of heat necessary to change the temperature of 1.00 kg of mass by 1.00 °C. The specific heat c is a property of the substance; its SI unit is J/(kg · K) or J/(kg · $°\text{C}$). The temperature change (ΔT) is the same in units of kelvins and degrees Celsius (but not degrees Fahrenheit). Specific heat is closely related to the concept of **heat capacity**. Heat capacity is the amount of heat necessary to change the temperature of a substance by 1.00 $°\text{C}$. In equation form, heat capacity C is $C = mc$, where m is mass and c is specific heat. Note that heat capacity is the same as specific heat, but without any dependence on mass. Consequently, two objects made up of the same material but with different masses will have different heat capacities. This is because the heat capacity is a property of an object, but specific heat is a property of *any* object made of the same material.

Values of specific heat must be looked up in tables, because there is no simple way to calculate them. Table 11.2 gives the values of specific heat for a few substances as a handy reference. We see from this table that the specific heat of water is five times that of glass, which means that it takes five times as much heat to raise the temperature of 1 kg of water than to raise the temperature of 1 kg of glass by the same number of degrees.

Substances	Specific Heat (*c*)
Solids	J/(kg ·$°\text{C}$)
Aluminum	900

Table 11.2 Specific Heats of Various Substances.