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

Teacher Support

Teacher Support The Learning Objectives in this section will help your students master the following standards:

- (6) Science concepts. The student knows that changes occur within a physical system and applies the laws of conservation of energy and momentum. The student is expected to:
  - (E) describe how the macroscopic properties of a thermodynamic system such as temperature, specific heat, and pressure are related to the molecular level of matter, including kinetic or potential energy of atoms.

In addition, the High School Physics Laboratory Manual addresses content in this section in the lab titled: Thermodynamics, as well as the following standards:

- (6) Science concepts. The student knows that changes occur within a physical system and applies the laws of conservation of energy and momentum. The student is expected to:
  - (E) describe how the macroscopic properties of a thermodynamic system such as temperature, specific heat, and pressure are related to the molecular level of matter, including kinetic or potential energy of atoms;
  - (G) analyze and explain everyday examples that illustrate the laws of thermodynamics, including the law of conservation of energy and the law of entropy.

Section Key Terms

Teacher Support

Teacher Support [BL] [OL][AL] Check prior knowledge of terms such as heat, temperature, and temperature scales.

[OL] Ask students what contains more heat—a bucketful of warm water or a spoonful of boiling water. From this ask them to define heat. Ask them which one has a higher temperature.

Misconception Alert

Dispel any notions that heat content is solely dependent on 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.

Teacher Support

Teacher Support

Teacher Demonstration

You can show that temperature is related to the kinetic energy of molecules by a simple demonstration. Take an eraser and rub it vigorously against any surface. Then feel it against your skin. Is it hot?

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 °C for the Celsius scale, and its unit is the degree Celsius (°C).

On the Fahrenheit scale, the freezing point of water is at 32 °F, and the boiling point is at 212 °F . The unit of temperature on this scale is the degree Fahrenheit (°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).

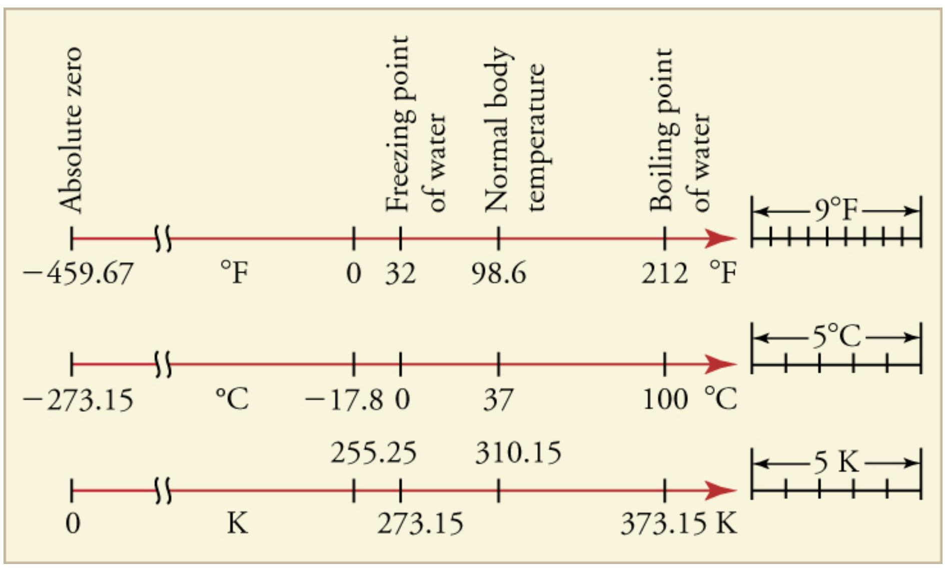

Figure 11.2 Relationships between the Fahrenheit, Celsius, and Kelvin temperature scales, rounded to the nearest degree. The relative sizes of the scales are also shown.

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.

Teacher Support

Teacher Support [BL][OL][AL] Ask students in which case each scale would be most convenient to use.

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.

Teacher Support

Teacher Support [AL]Ask why absolute zero has never been recorded. Discuss if atoms and molecules can ever be completely motionless.

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

Watch Physics: Comparing Celsius and Fahrenheit Temperature Scales. This video makes a comparison between the Celsius and Fahrenheit temperature scales.

Click to view content

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.

Teacher Support

Teacher Support Students can use the process described in this video as a means of comparing different temperature scales. Point out to them that all they need to know are the temperatures on each scale of a single property, such as the boiling and freezing points of a liquid, whether it be water, ethanol, or tetrachloromethane.

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	$T_{\circ\mathrm{F}} = \frac{9}{5}T_{\circ\mathrm{C}} + 32$
Fahrenheit to Celsius	$T_{\circ\mathrm{C}} = \frac{5}{9}\left(T_{\circ\mathrm{F}} - 32\right)$
Celsius to Kelvin	$T_{\mathrm{K}} = T_{\circ\mathrm{C}} + \ 273.15$
Kelvin to Celsius	$T_{\circ\mathrm{C}} = T_{\mathrm{K}} - 273.15$
Fahrenheit to Kelvin	$T_{\mathrm{K}} = \frac{5}{9}\left(T_{\circ\mathrm{F}} - 32\right) + 273.15$
Kelvin to Fahrenheit	$T_{\circ\mathrm{F}} = \frac{9}{5}\left(T_{\mathrm{K}} - 273.15\right) + 32$

Table 11.1 Temperature Conversions

Teacher Support

Teacher Support [BL][OL][AL] Ask students which is more—a difference of 5 °F or a difference of 5 °C . Now ask them the same for 5 °C and 5 °F . A difference in temperature for Kelvin and that for Celsius are the same. The same is not true for Celsius and Fahrenheit.

Worked Example

Converting between Temperature Scales: Room Temperature *Room temperature* is generally defined to be 25 °C. (a) What is room temperature in °F? (b) What is it in K?

Teacher Support

Teacher Support In an alcohol-in-glass thermometer, alcohol molecules absorb energy by heat, and as the intermolecular distances increase, the bulk alcohol expands. Ask students the temperature range for which this thermometer shows an accurate reading. Why is this the case? Ask them if it is possible to design a thermometer with any other substance. Why or why not?

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

- $T_{^\circ\mathrm{F}} = \frac{9}{5}T_{^\circ\mathrm{C}} + 32.$

  11.1

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

- $T_{^\circ\mathrm{F}} = \frac{9}{5}25\ ^\circ\mathrm{C} + 32 = 77\ ^\circ\mathrm{F}$

  11.2

Solution for (b)

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

- $T_{\mathrm{K}} = T_{^\circ\mathrm{C}} +\ 273.15.$

  11.3

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

- T_{K}= 25 °C + 273.15 = 298K

  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 18^{th} and 19^{th} centuries. On the Reaumur temperature scale, the freezing point of water is 0 °R and the boiling temperature is 80 °R. If "room temperature" is 25 °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 °R . On the Celsius scale, it is 100 °C . Therefore, 100 °C = 80 °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.

- $T_{^\circ\mathrm{R}} = \frac{0.80^\circ\mathrm{R}}{^\circ\mathrm{C}} \times T_{^\circ\mathrm{C}}$

  11.5

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

- $T_{^\circ\mathrm{R}} = \frac{0.80^\circ\mathrm{R}}{^\circ\mathrm{C}} \times 25\ ^\circ\mathrm{C} = 20^\circ\mathrm{R}$

  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.

Teacher Support

Teacher Support Ask students how wind chill works. Will it work on any surface or just the human body? The rate of heat loss for any object depends on the temperature difference between the object and its surroundings. When heat transfers energy away from the object, it warms a layer of air around it. Wind disrupts this layer, replacing it with cooler air. This, in turn, increases the rate of heat loss.

Misconception Alert

Wind chill can only increase the rate of cooling. It can never cool an object to a temperature below the ambient temperature.

Check Your Understanding

Teacher Support

Teacher Support Use these questions to assess student achievement of the section's learning objectives. If students are struggling with a specific objective, these questions will help identify which and direct students to the relevant content.

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