**Temperature**

With most measurements, the number zero has a standard interpretation. For example, if you are driving your car at a speed of zero, it does not matter whether that is meters per second, miles per hour, or kilometers per hour; they are all the same. Likewise, there is no distinction between zero liters, zero cubic meters, and zero gallons; all unit systems are in agreement on the value of zero.

A major exception to the rule is temperature. On a temperature scale, the value of zero may have no special meaning. Daniel Fahrenheit defined zero degrees to be the temperature of a mixture of salt and ice, while Anders Celsius took zero to be the highest temperature at which water freezes under standard pressure. Both choices are somewhat arbitrary; neither can claim to be the “true” meaning of zero.

Suppose we were to graph Fahrenheit temperatures versus Celsius temperatures. What shape would the graph have? Fortunately, the Fahrenheit and Celsius scales are enough alike that the graph is a straight line. As is well known, the ice point of water is 0°C or 32°F while the steam point of water is 100°C or 212°F. These two points appear on the graph of \( F \) versus \( C \).

As is known from high school algebra, the equation of a line is \( y = mx + b \), but in this example it is better to call it \( F = mC + b \). The slope of the line is

\[
m = \frac{212 - 32}{100 - 0} = \frac{9}{5}
\]

and \( b \) (the \( y \)-intercept) is 32. Thus the equation of the line is

\[
F = \frac{9}{5}C + 32
\]

**Example** A scoop of ice cream has a temperature of \(-10°C\). What is this temperature on the Fahrenheit scale?

\[
F = \frac{9}{5}C + 32 = \frac{9}{5}(-10) = 32 = 14°F
\]

By solving the equation \( F = C \), we can see if there is any temperature that has the same value on both the Fahrenheit and Celsius scales. We get

\[
F = C
\]

\[
\frac{9}{5}C + 32 = C
\]
from which we find \( C = -40 \). Thus, at the bone-chilling temperature of \(-40 \) degrees, your Fahrenheit and Celsius thermometers would read the same value. Since mercury solidifies at \(-39^\circ C\), your mercury thermometers may also be broken.

The fact that \(-40\) is the same on both scales is the basis of the following two conversion formulas.

\[
F = (C + 40) \cdot \frac{9}{5} - 40
\]
\[
C = (F + 40) \cdot \frac{5}{9} - 40
\]

These equations are easy to remember and allow us to convert from one scale to the other.

By now you can appreciate that there is no intrinsic advantage in using either the Fahrenheit or Celsius scale; they are just different ways of measuring the same thing. In addition, they both share the disadvantage of having an arbitrary zero point. When William Thompson created his temperature scale he decided to correct this deficiency. On Thompson’s scale (the Kelvin scale), zero corresponds to the lowest possible temperature of any substance. At this extreme low temperature, the Celsius scale reads \(-273.15\) and the Fahrenheit scale is \(-459.67\) but the Kelvin scale reads a perfect zero.

The conversion from Celsius temperature to Kelvin temperature is

\[
K = C + 273.15
\]

The conversion from Fahrenheit to Kelvin is

\[
K = (F + 40) \cdot \frac{5}{9} - 40 + 273.15
\]

As a solid increases in temperature, its length will increase by an amount \( \Delta L \). The amount of increase depends on the original length \( L_0 \) of the solid, the change in temperature \( \Delta T \), and the type of material involved. The increase in length satisfies the equation

\[
\Delta L = \alpha L_0 \Delta T
\]

where \( \alpha \) is a property of the particular material and is known as the coefficient of linear expansion.

**Example**  Aluminum has a coefficient of linear expansion of \( \alpha = 23 \times 10^{-6} \text{ (C}^\circ\text{)}^{-1} \). What is the change in length of a 0.50-m bar of aluminum when its temperature changes by 15\(^\circ\text{C}\)?

\[
\Delta L = \alpha L_0 \Delta T = (23 \times 10^{-6}) (0.50)(15) = 1.7 \times 10^{-4} \text{ m}
\]
Heat

Heat is the energy exchanged between objects due to the difference in their temperatures. Since heat is energy, it is naturally expressed in joules. It may also be measured in terms of a unit known as the calorie. The relationship between calorie and joule is

\[ 1 \text{ cal} = 4.186 \text{ J} \]

The word “calorie” is used frequently on food labels to indicate the energy value of the food. This dietary calorie is actually a kilocalorie or one thousand ordinary calories.

Adding heat to an object can raise its temperature. The change in temperature \( \Delta T \) of mass \( m \) when an amount of heat \( Q \) is added is given by the equation

\[ Q = cm\Delta T \]

where \( c \) is a property of the material known as the specific heat capacity.

Example  
Aluminum has a specific heat capacity of \( 900 \text{ J/(kg} \cdot \text{C}^\circ) \). How much heat is required to raise the temperature of 10 kg of aluminum by 50\(^\circ\)C?

\[ Q = cm\Delta T = (900)(10)(50) = 450000 \text{ J} \]

Conceptual Questions

Example (page 364: 1) For the highest accuracy, would you choose an aluminum or a steel tape rule for year-round use? Why?

Aluminum has a coefficient of linear expansion of \( 23 \times 10^{-6} \text{ (C}^\circ)^{-1} \). Steel has a coefficient of \( 12 \times 10^{-6} \text{ (C}^\circ)^{-1} \). Choose steel for less variability.

Example (page 365: 3) A circular hole is cut through a flat aluminum plate. A spherical brass ball has a diameter that is slightly smaller than the diameter of the hole. The plate and the ball have the same temperature at all times. Should the plate and ball both be heated or both be cooled to prevent the ball from falling through the hole? Give your reasoning.

The coefficient of linear expansion for aluminum in \( \text{(C}^\circ)^{-1} \) is \( 23 \times 10^{-6} \); for brass it is \( 19 \times 10^{-6} \). Since aluminum has the higher coefficient of expansion, heating would cause the hole to enlarge faster than the sphere. Cooling would cause the hole to shrink faster than the sphere. Therefore the objects should be cooled.
Example  (page 365: 5) At a certain temperature, a rod is hung from an aluminum frame, as the drawing shows. A small gap exists between the rod and the floor. The frame and rod are heated uniformly. Explain whether the rod will ever touch the floor, assuming that the rod is made from (a) aluminum and (b) lead.

If the rod is made from aluminum, the gap will never close since the frame and rod expand at the same rate. If the rod is made from lead, the gap may close since the lead expands faster than the aluminum.

Problems

Example  (page 366: 2) On the moon the surface temperature ranges from 375 K during the day to $1.00 \times 10^2$ K at night. What are these temperatures on the (a) Celsius and (b) Fahrenheit scales?

(a) $C = K - 273.15$

day: $C = 375 - 273.15 = 101.85^\circ C$

night: $C = 100 - 273.15 = -173.15^\circ C$

(b) $F = (C + 40) \cdot \frac{9}{5} - 40$

day: $F = (101.85 + 40) \cdot \frac{9}{5} - 40 = 215.33^\circ F$

night: $F = (-173.15 + 40) \cdot \frac{9}{5} - 40 = -279.67^\circ F$

Example  (page 366: 10) The Concorde is 62 m long when its temperature is 23°C. In flight, the outer skin of this supersonic aircraft can reach 105°C due to air friction. The coefficient of linear expansion of the skin is $2.0 \times 10^{-5}$ (°C)$^{-1}$. Find the amount by which the Concorde expands.

$$\Delta L = \alpha L_0 \Delta T = (2.0 \times 10^{-5})(62)(105 - 23) = 0.10 \text{ m}$$
Example (page 366: 16) As the drawing shows, two thin strips of metal are bolted together at one end and have the same temperature. One is steel, and the other is aluminum. The steel strip is 0.10% longer than the aluminum strip. By how much should the temperature of the strips be increased, so that the strips have the same length?

If \( L_0 \) is the original length of the aluminum strip, then \( 1.001L_0 \) is the original length of the steel strip. After the strips are heated, the length of the aluminum strip is

\[
L_a = L_0 + \Delta L = L_0 + \alpha_a L_0 \Delta T
\]

The final length of the steel strip is

\[
L_s = 1.001L_0 + \alpha_s 1.001L_0 \Delta T
\]

We want the two lengths to be the same:

\[
L_0 + \alpha_a L_0 \Delta T = 1.001L_0 + \alpha_s 1.001L_0 \Delta T
\]

\[
\alpha_a L_0 \Delta T - \alpha_s 1.001L_0 \Delta T = 1.001L_0 - L_0
\]

\[
\Delta T L_0 (\alpha_a - \alpha_s 1.001) = 0.001L_0
\]

\[
\Delta T = \frac{0.001}{\alpha_a - \alpha_s 1.001} = \frac{0.001}{23 \times 10^{-6} - (12 \times 10^{-6})(1.001)} = 91 \degree C
\]

Example (page 367: 28) A lead object and a quartz object each have the same initial volume. The volume of each increases by the same amount, because the temperature increases. If the temperature of the lead object increases by 4.0\degree C, by how much does the temperature of the quartz object increase?

The change in volume is given by

\[
\Delta V = \beta V_0 \Delta T
\]

We want the two changes in volume to be equal:
\[ \beta_L V_0 \Delta T_L = \beta_Q V_0 \Delta T_Q \]

\[ \Delta T_Q = \frac{\beta_L \Delta T_L}{\beta_Q} = \frac{(87 \times 10^{-6})(4.0)}{1.5 \times 10^{-6}} = 230 \text{°C} \]