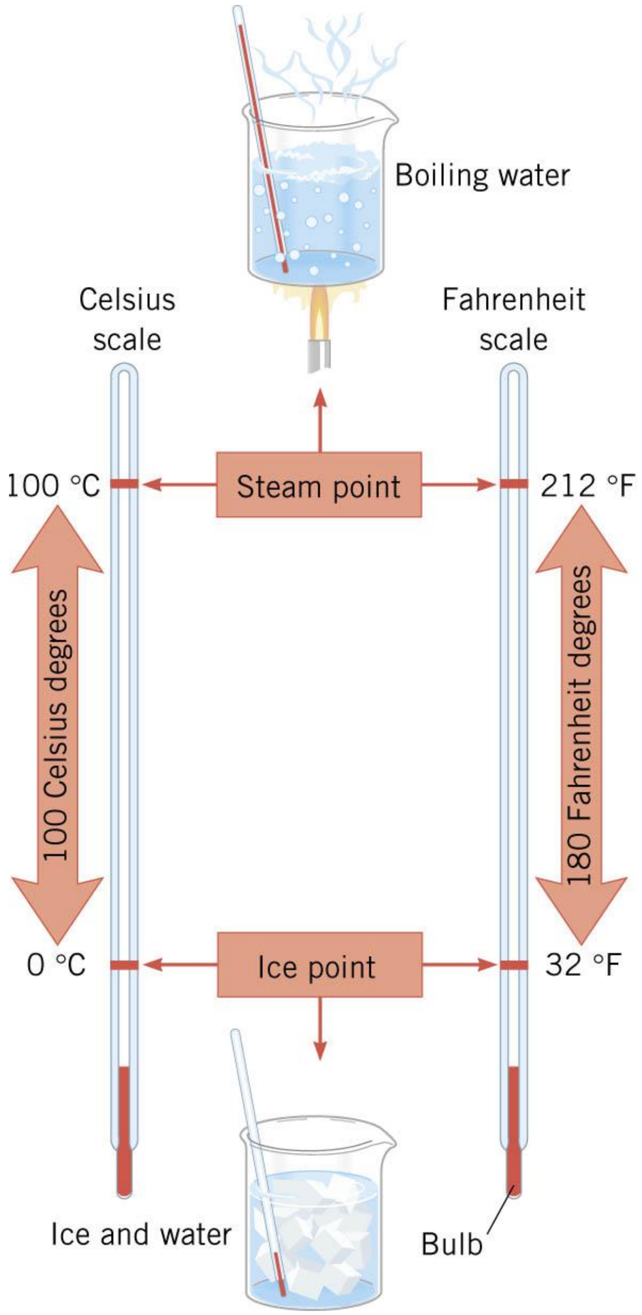
Chapter 12

Temperature and Heat

12.1 *Common Temperature Scales*



Temperatures are reported in degrees **Celsius** or degrees **Fahrenheit**.

Temperature changes, on the other hand, are reported in **Celsius** degrees or **Fahrenheit** degrees:

$$1\,\text{C}^\circ = \frac{9}{5}\,\text{F}^\circ$$

12.1 *Common Temperature Scales*

Example 1 Converting from a Fahrenheit to a Celsius Temperature

A healthy person has an oral temperature of 98.6ºF. What would this reading be on the Celsius scale?

degrees above ice point

$$98.6^\circ\,\mathrm{F} - 32^\circ\,\mathrm{F} = 66.6\,\mathrm{F}^\circ$$

$$\Downarrow$$

$$\left(66.6\,\mathrm{F}^\circ\right)\left(\frac{1\,\mathrm{C}^\circ}{\frac{9}{5}\,\mathrm{F}^\circ}\right) = 37.0\,\mathrm{C}^\circ$$

$$\Downarrow$$

$$0\,\mathrm{C}^\circ + 37.0\,\mathrm{C}^\circ = 37.0^\circ\,\mathrm{C}$$

ice point

12.1 Common Temperature Scales

Example 2 Converting from a Celsius to a Fahrenheit Temperature

A time and temperature sign on a bank indicates that the outdoor temperature is -20.0ºC. Find the corresponding temperature on the Fahrenheit scale.

degrees below ice point

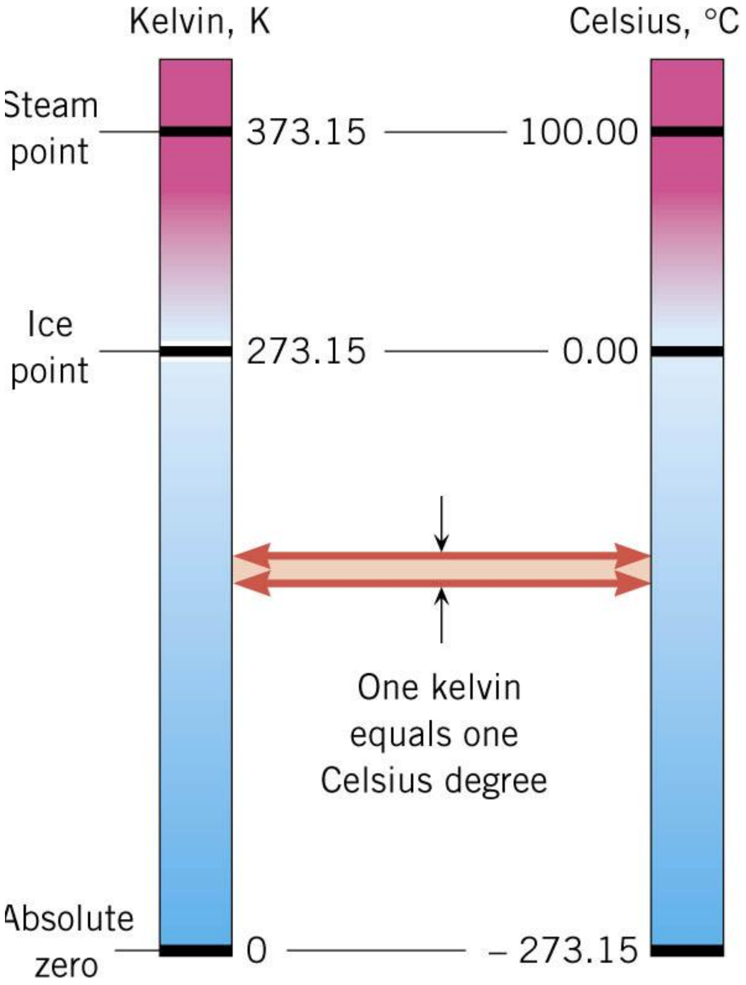
$$\left(20.0\,\mathrm{C}^{\circ}\right)\left(\frac{\frac{9}{5}\,\mathrm{F}^{\circ}}{1\,\mathrm{C}^{\circ}}\right)=36.0\,\mathrm{F}^{\circ}$$

$$\Downarrow$$

$$32.0\,\mathrm{F}^{\circ}-36.0\,\mathrm{F}^{\circ}=-4.0^{\circ}\,\mathrm{F}$$

ice point

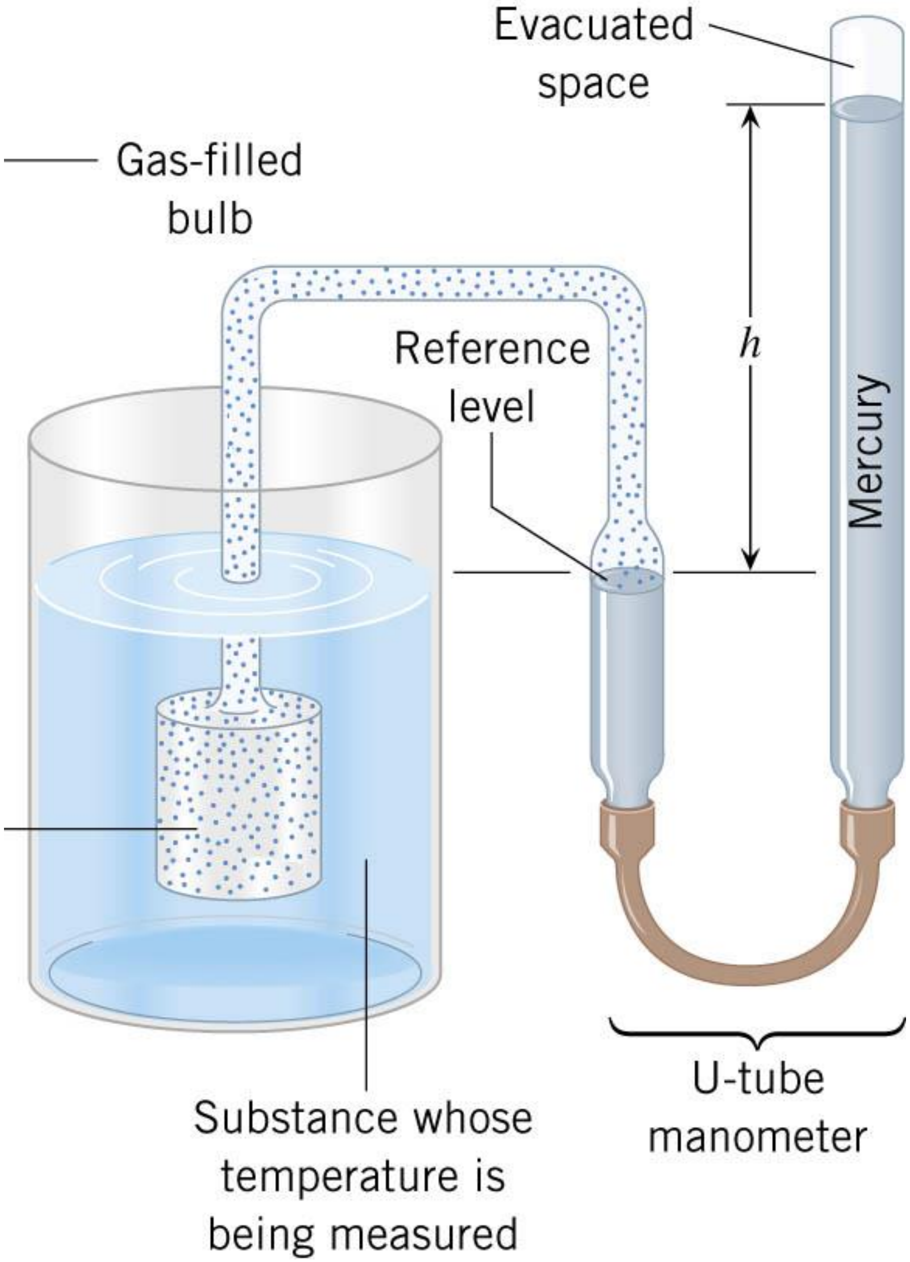
12.2 The Kelvin Temperature Scale



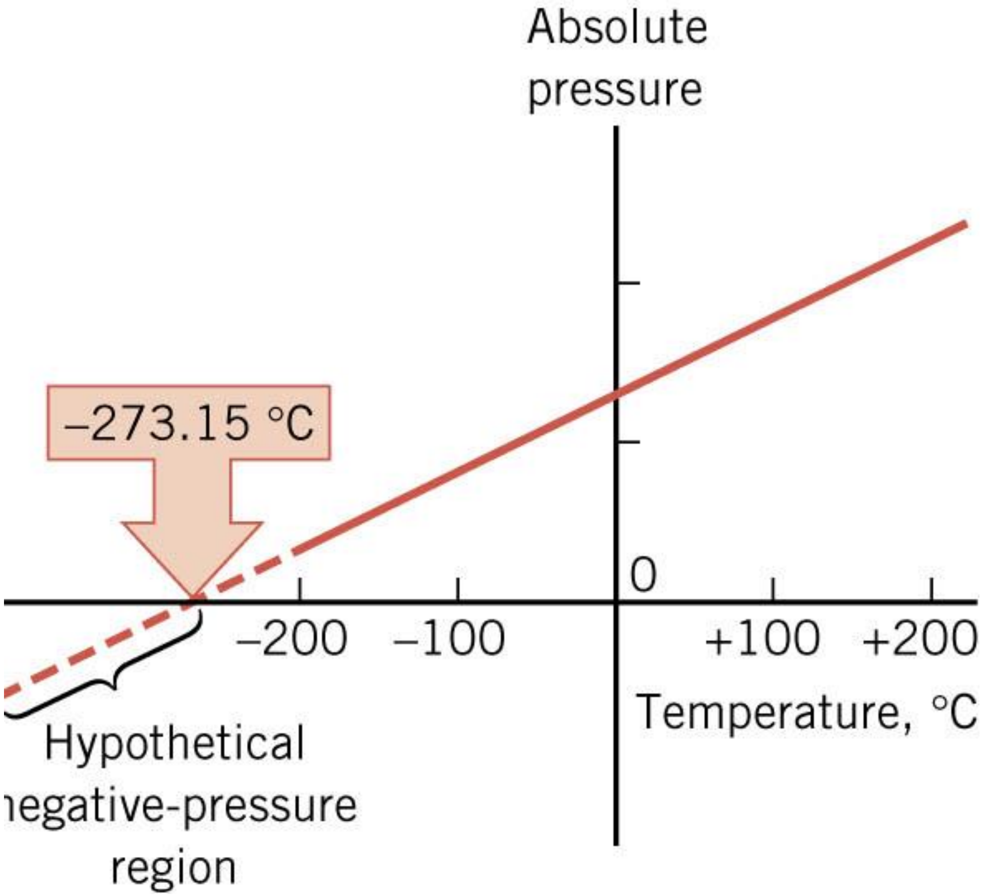
Kelvin temperature

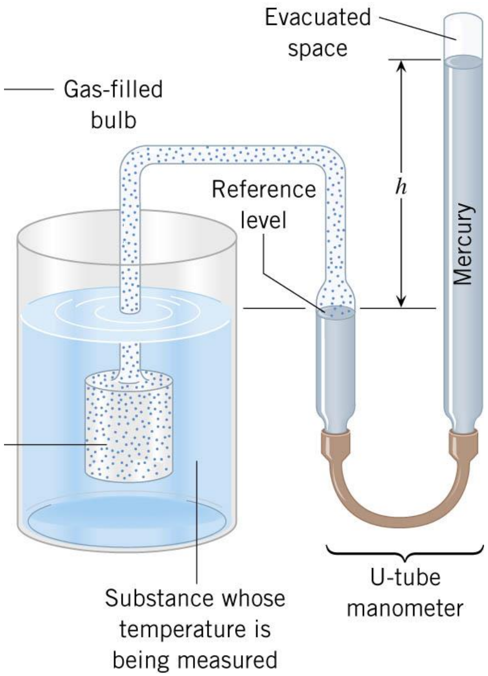
$$T = T_c + 273.15$$

A ***constant-volume gas thermometer***.



12.2 The Kelvin Temperature Scale

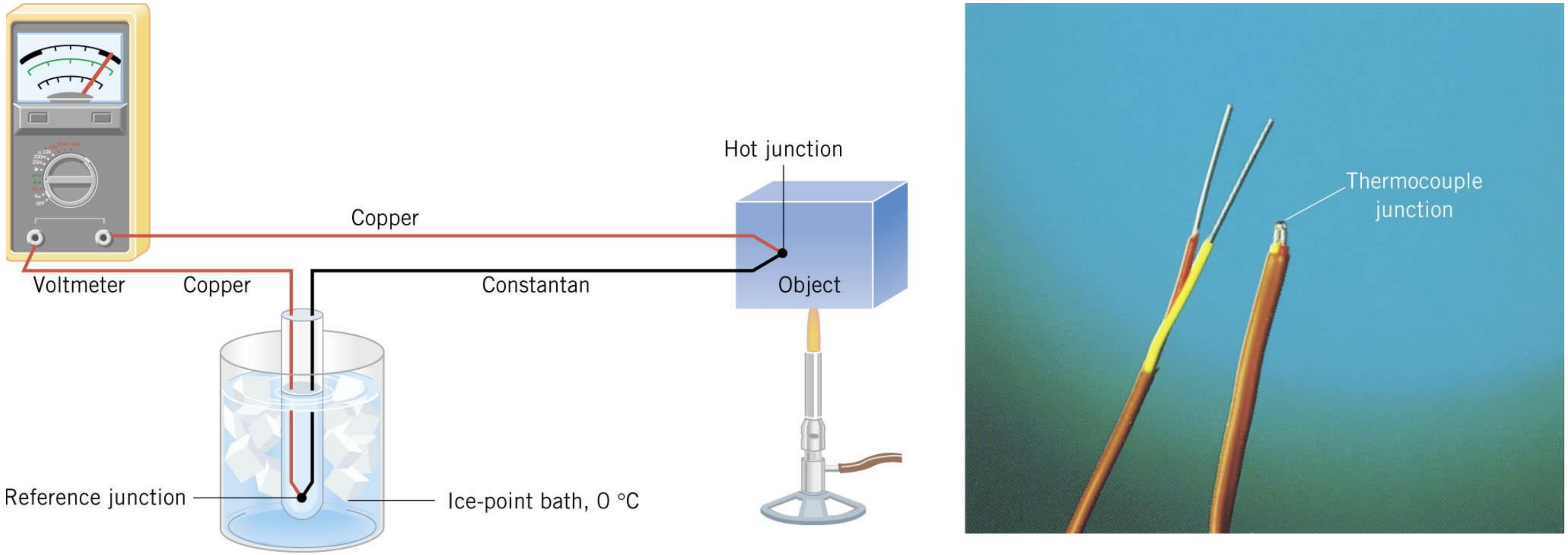




absolute zero point = -273.15^{o}C

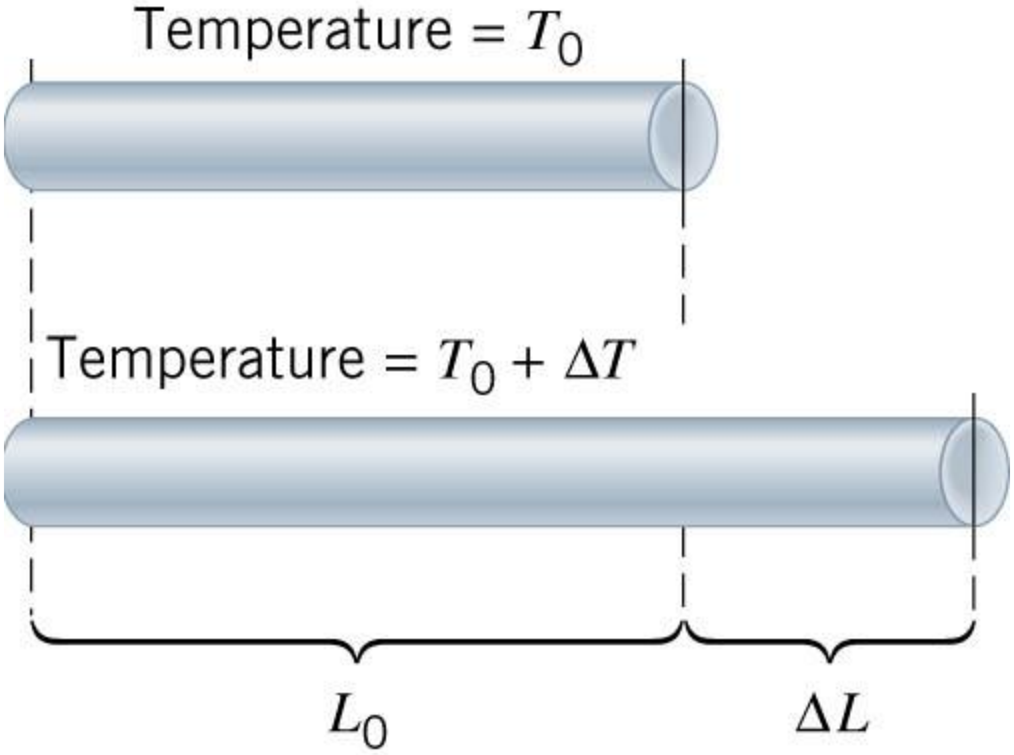
12.3 Thermometers

Thermometers make use of the change in some physical property with temperature. A property that changes with temperature is called a ***thermometric property***.

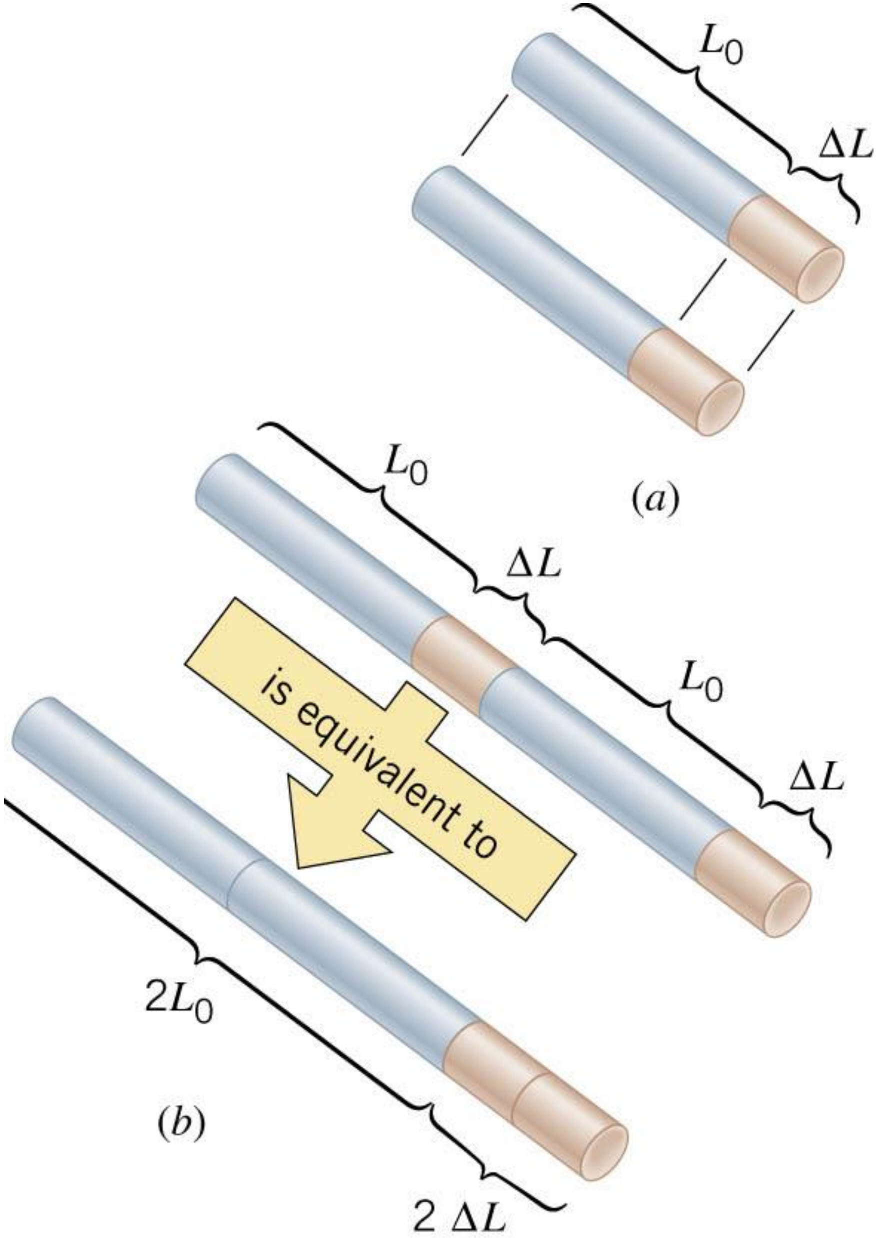


(*a*) (*b*)

NORMAL SOLIDS



12.4 Linear Thermal Expansion

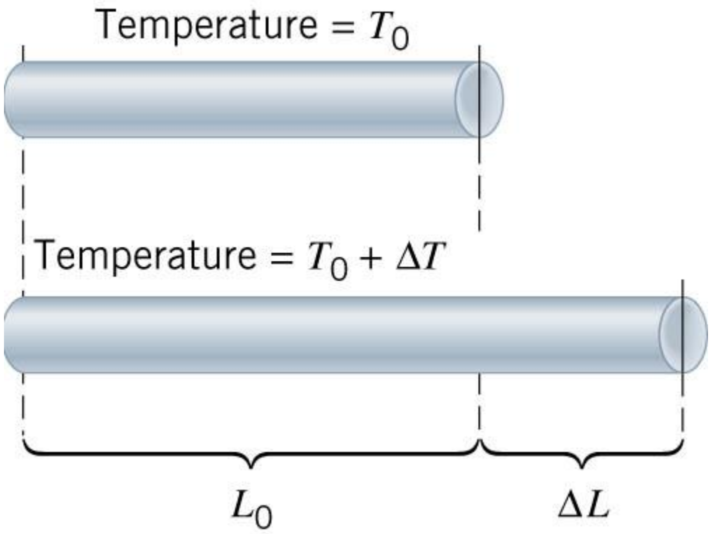


$$\Delta L \propto L_o$$

12.4 Linear Thermal Expansion

LINEAR THERMAL EXPANSION OF A SOLID

The length of an object changes when its temperature changes:



$$\Delta L = \alpha L_o \Delta T$$

coefficient of
linear expansion

Common Unit for the Coefficient of Linear Expansion: $\frac{1}{C^\circ} = \left(C^\circ\right)^{-1}$

12.4 Linear Thermal Expansion

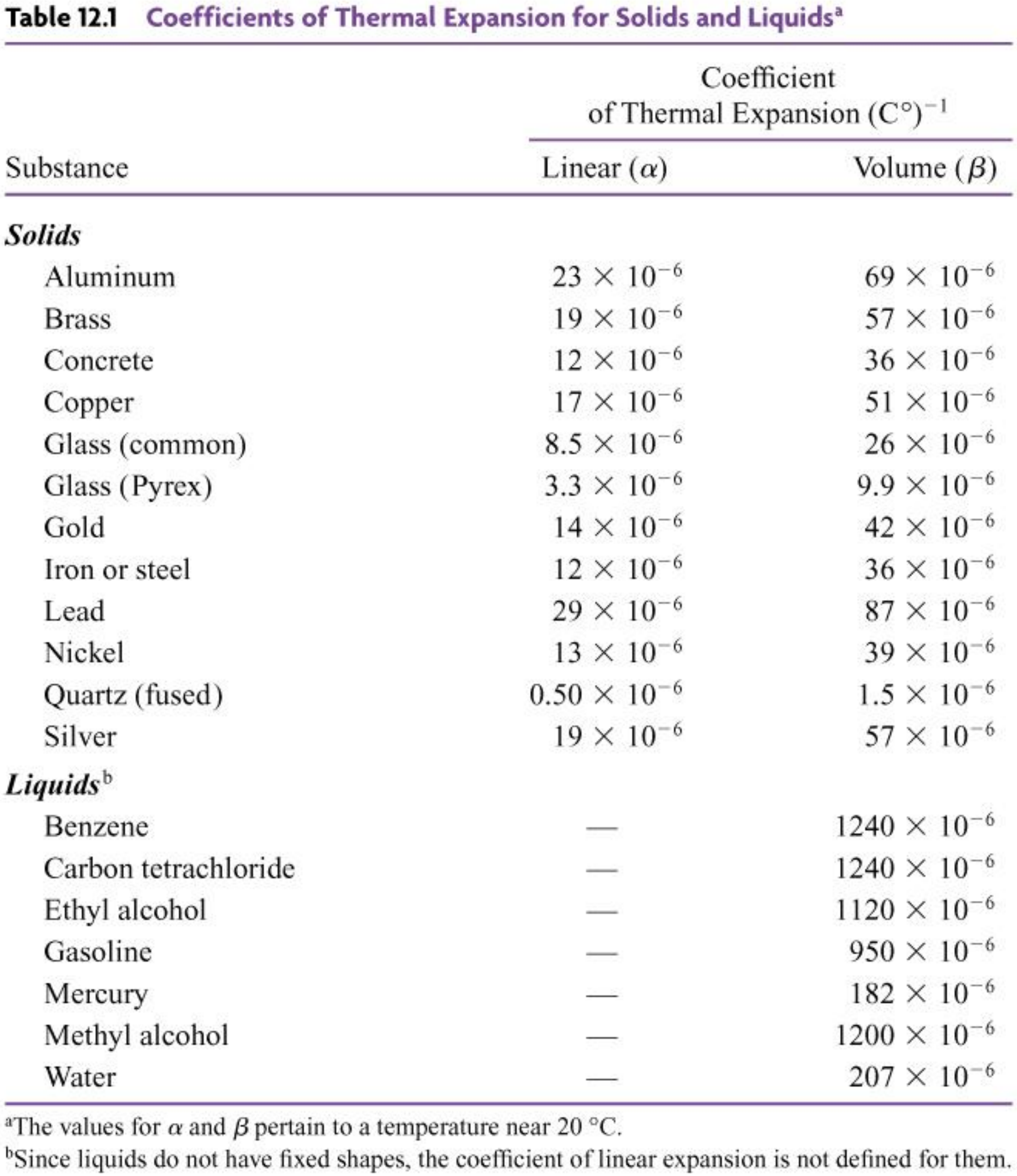


Table 12.1 Coefficients of Thermal Expansion for Solids and Liquids[a]

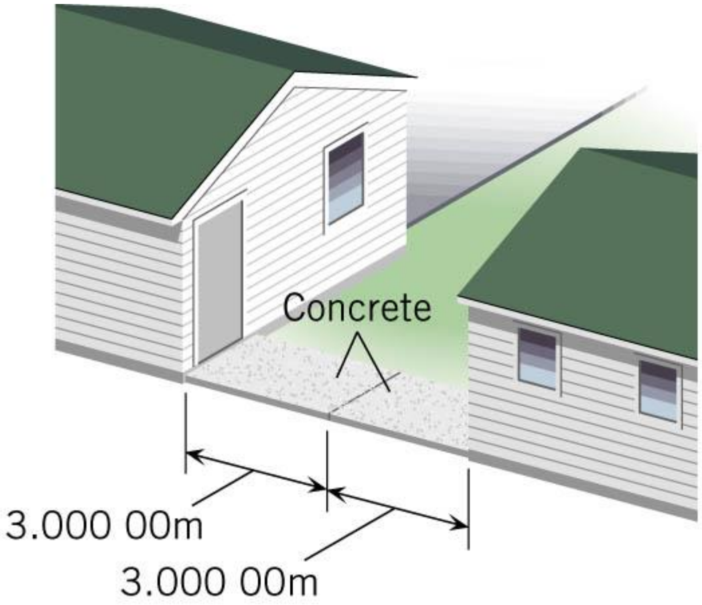
Substance	Coefficient of Thermal Expansion $(C^\circ)^{-1}$ Linear (α)	Volume (β)
Solids		
Aluminum	23×10^{-6}	69×10^{-6}
Brass	19×10^{-6}	57×10^{-6}
Concrete	12×10^{-6}	36×10^{-6}
Copper	17×10^{-6}	51×10^{-6}
Glass (common)	8.5×10^{-6}	26×10^{-6}
Glass (Pyrex)	3.3×10^{-6}	9.9×10^{-6}
Gold	14×10^{-6}	42×10^{-6}
Iron or steel	12×10^{-6}	36×10^{-6}
Lead	29×10^{-6}	87×10^{-6}
Nickel	13×10^{-6}	39×10^{-6}
Quartz (fused)	0.50×10^{-6}	1.5×10^{-6}
Silver	19×10^{-6}	57×10^{-6}
Liquids[b]		
Benzene	—	1240×10^{-6}
Carbon tetrachloride	—	1240×10^{-6}
Ethyl alcohol	—	1120×10^{-6}
Gasoline	—	950×10^{-6}
Mercury	—	182×10^{-6}
Methyl alcohol	—	1200×10^{-6}
Water	—	207×10^{-6}

[a] The values for α and β pertain to a temperature near 20 °C.

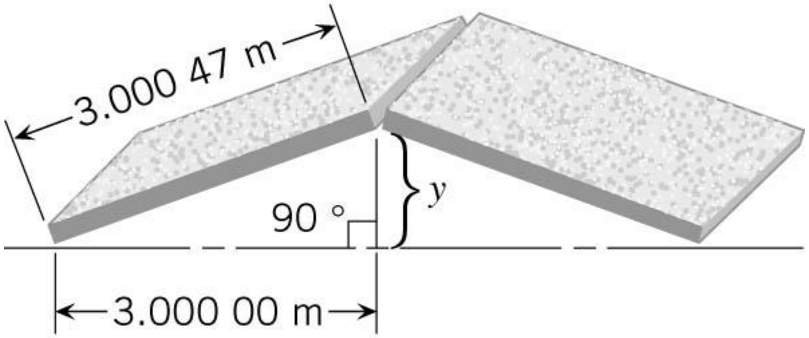
[b] Since liquids do not have fixed shapes, the coefficient of linear expansion is not defined for them.

Example 3 The Buckling of a Sidewalk

A concrete sidewalk is constructed between two buildings on a day when the temperatu is 25°C. As the temperature rises to 38°C, the slabs expand, but no space is provided for thermal expansion. Determine the distance *y* in part (b) of the drawing.

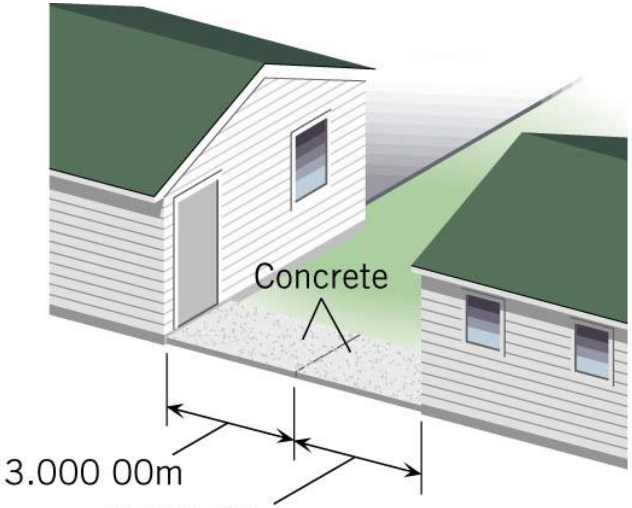


(*a*)

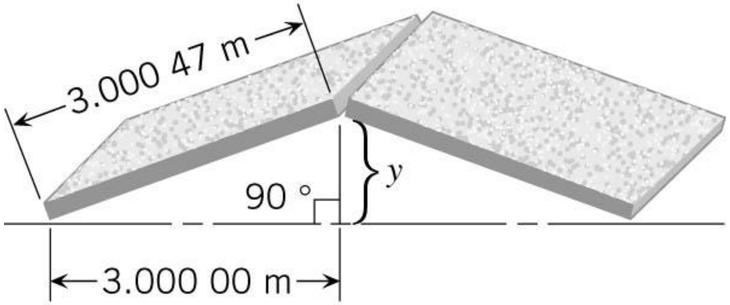


(*b*)

12.4 Linear Thermal Expansion



(a)



(b)

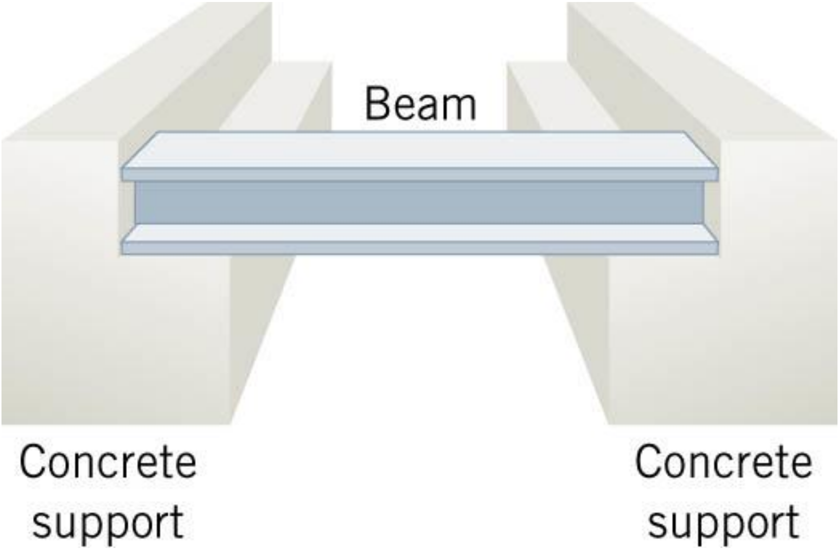
$$\Delta L = \alpha L_o \Delta T$$

$$= \left[12\times10^{-6}\left(\text{C}^\circ\right)^{-1}\right](3.0\text{ m})\left(13\text{ C}^\circ\right) = 0.00047\text{ m}$$

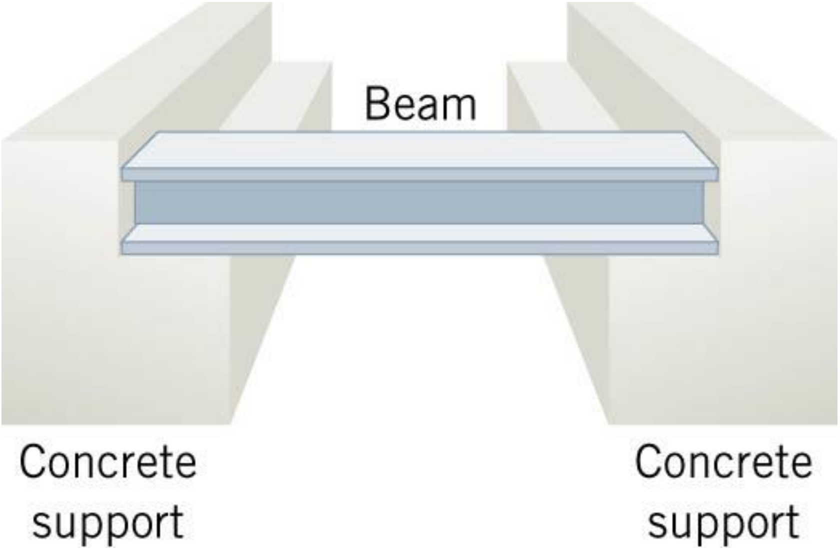
$$y = \sqrt{(3.00047\text{ m})^2 - (3.00000\text{ m})^2} = 0.053\text{ m}$$

Example 4 The Stress on a Steel Beam

The beam is mounted between two concrete supports when the temperature is 23°C. What compressional stress must the concrete supports apply to each end of the beam, if they are to keep the beam from expanding when the temperature rises to 42°C?



12.4 Linear Thermal Expansion

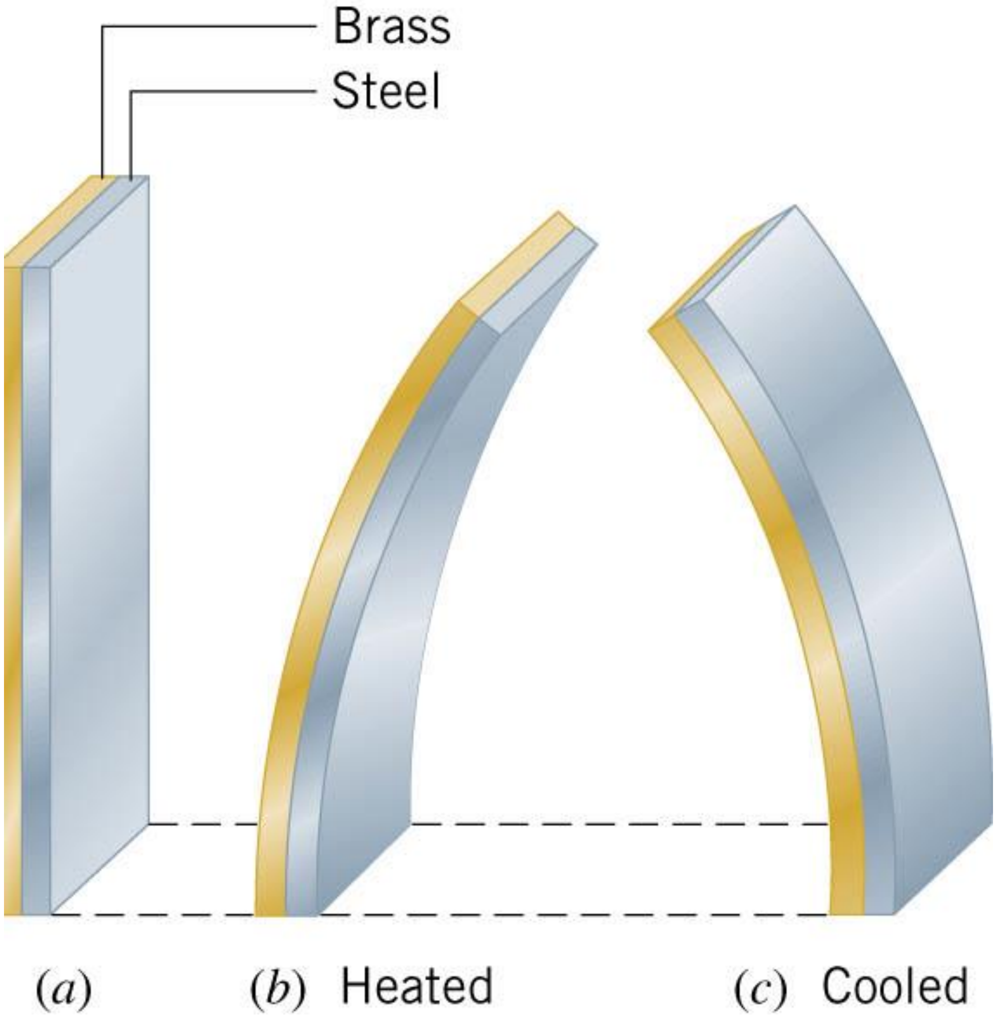


$$\Delta L = \alpha L_o \Delta T$$

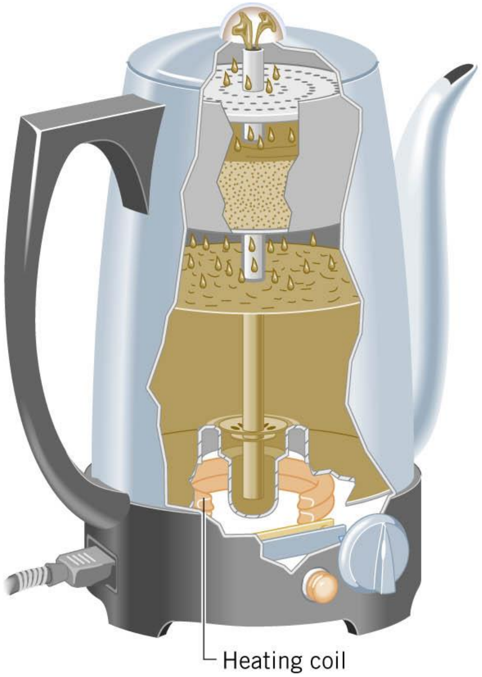
$$\text{Stress} = \frac{F}{A} = Y\frac{\Delta L}{L_o} = Y\alpha\,\Delta T$$

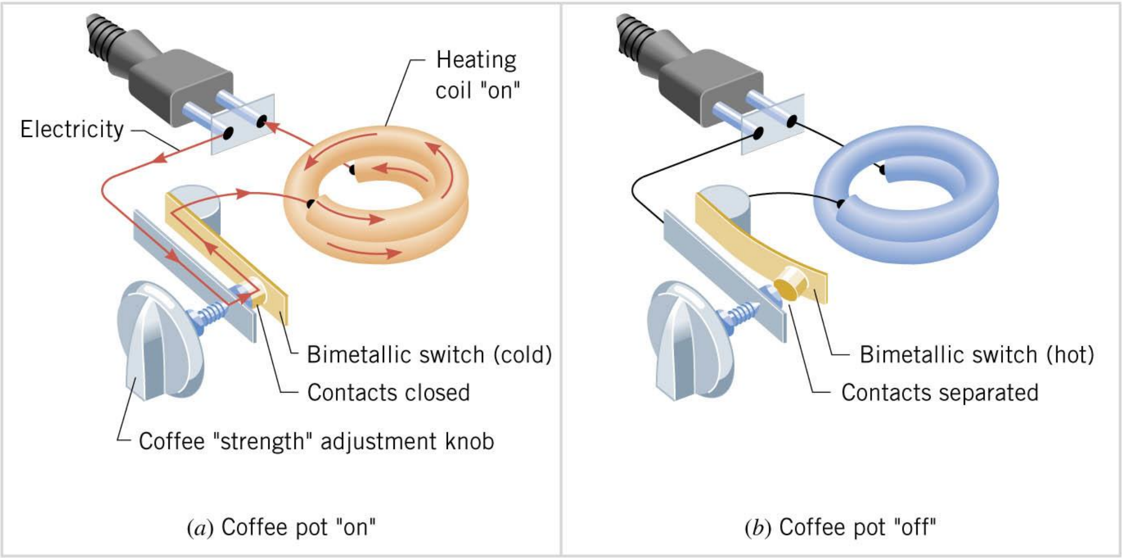
$$= \left(2.0\times10^{11}\ \text{N/m}^2\right)\left[12\times10^{-6}\left(\text{C}^\circ\right)^{-1}\right]\left(19\,\text{C}^\circ\right) = 4.7\times10^{7}\ \text{N/m}^2$$

THE BIMETALLIC STRIP



12.4 Linear Thermal Expansion





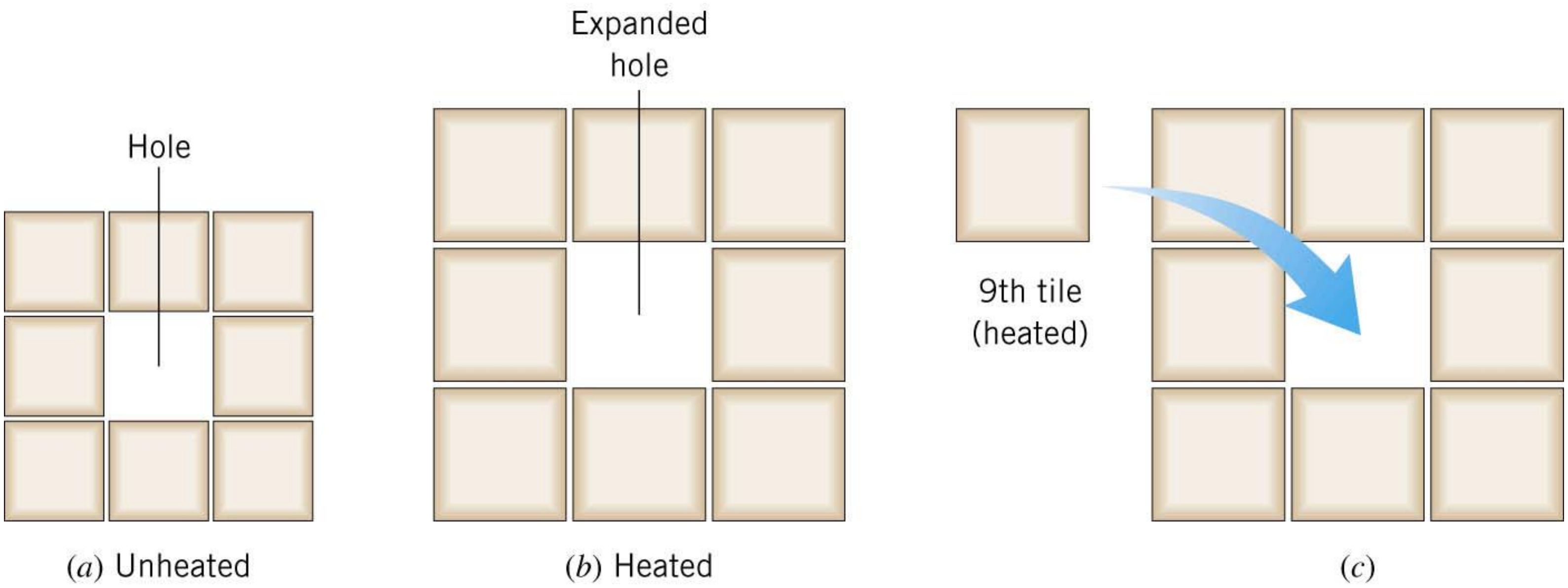
(*a*) Coffee pot "on"

(*b*) Coffee pot "off"

THE EXPANSION OF HOLES

***Conceptual Example 5* The Expansion of Holes**

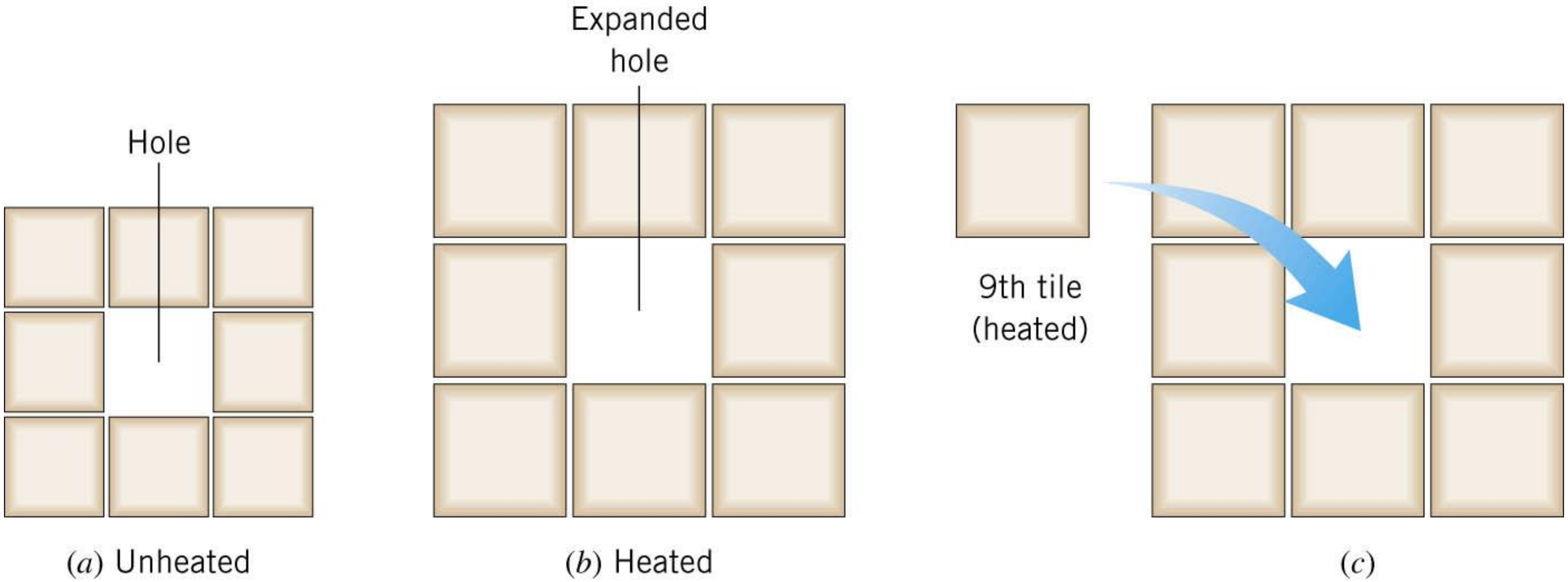
The figure shows eight square tiles that are arranged to form a square pattern with a hold in the center. If the tiled are heated, what happens to the size of the hole?



(*a*) Unheated (*b*) Heated (*c*)

12.4 Linear Thermal Expansion

A hole in a piece of solid material expands when heated and contracts when cooled, just as if it were filled with the material that surrounds it.



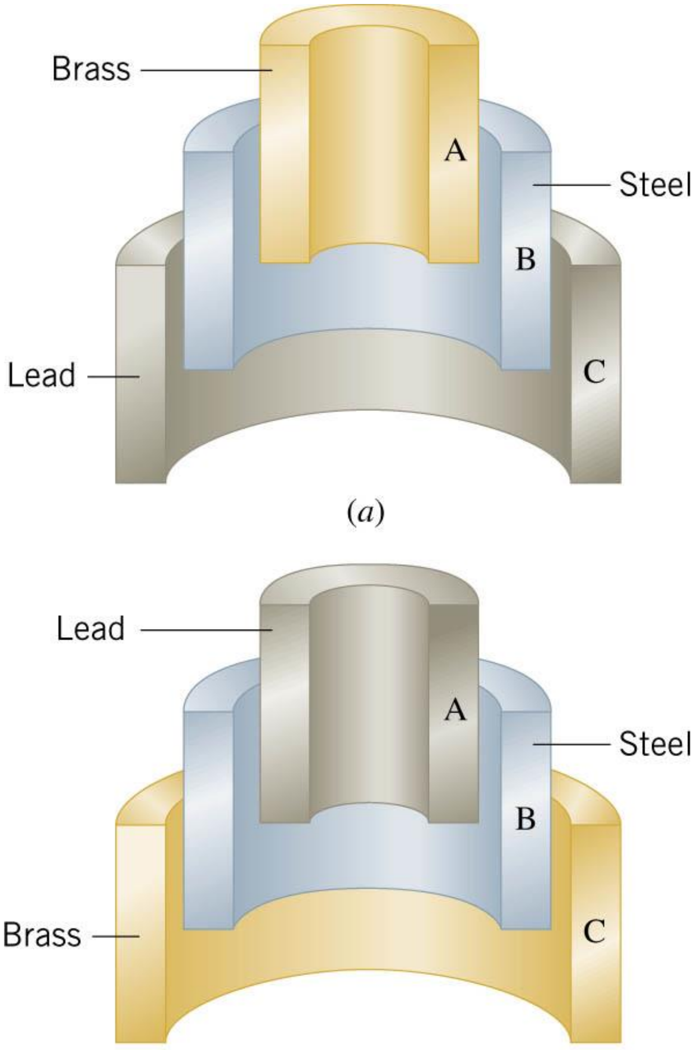
(*a*) Unheated (*b*) Heated (*c*)

Conceptual Example 7 Expanding Cylinders

Each cylinder is made from a different material. All three have the same temperature and they barely fit inside each other.

As the cylinders are heated to the same, but higher, temperature, cylinder C falls off, while cylinder A becomes tightly wedged to cylinder B.

Which cylinder is made from which material?



(*a*)

(*b*)

12.5 Volume Thermal Expansion

VOLUME THERMAL EXPANSION

The volume of an object changes when its temperature changes:

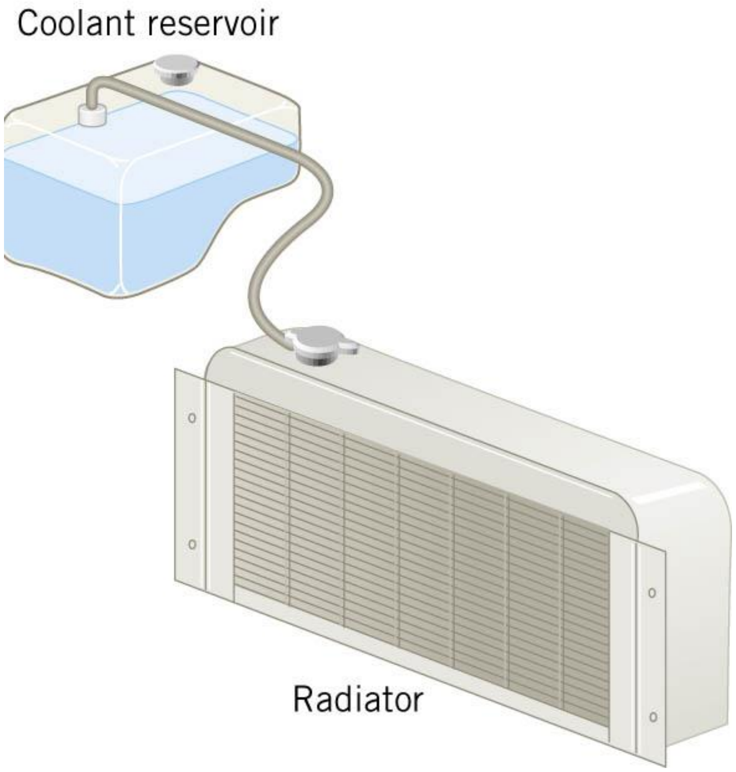
$$\Delta V = \beta V_o \Delta T$$

coefficient of volume expansion

Common Unit for the Coefficient of Volume Expansion: $\frac{1}{\mathrm{C}^\circ} = \left(\mathrm{C}^\circ\right)^{-1}$

Example 8 An Automobile Radiator

A small plastic container, called the coolant reservoir, catches the radiator fluid that overflows when an automobile engine becomes hot. The radiator is made of copper and the coolant has an expansion coefficient of $4.0\times10^{-4}\ (\mathrm{C}^{\mathrm{o}})^{-1}$. If the radiator is filled to its 15-quart capacity when the engine is cold (6°C), how much overflow will spill into the reservoir when the coolant reaches its operating temperature (92°C)?

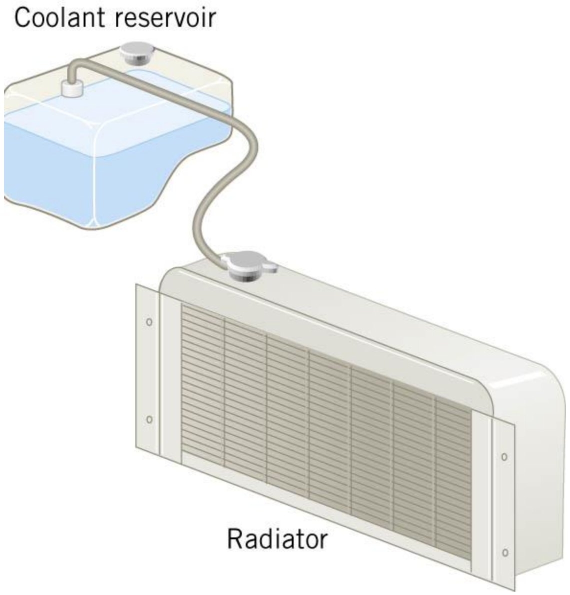


12.5 Volume Thermal Expansion

$$\Delta V_{\text{coolant}} = \left(4.10\times10^{-4}\left(\text{C}^\circ\right)^{-1}\right)\left(15\text{ quarts}\right)\left(86\text{ C}^\circ\right) = 0.53\text{ quarts}$$

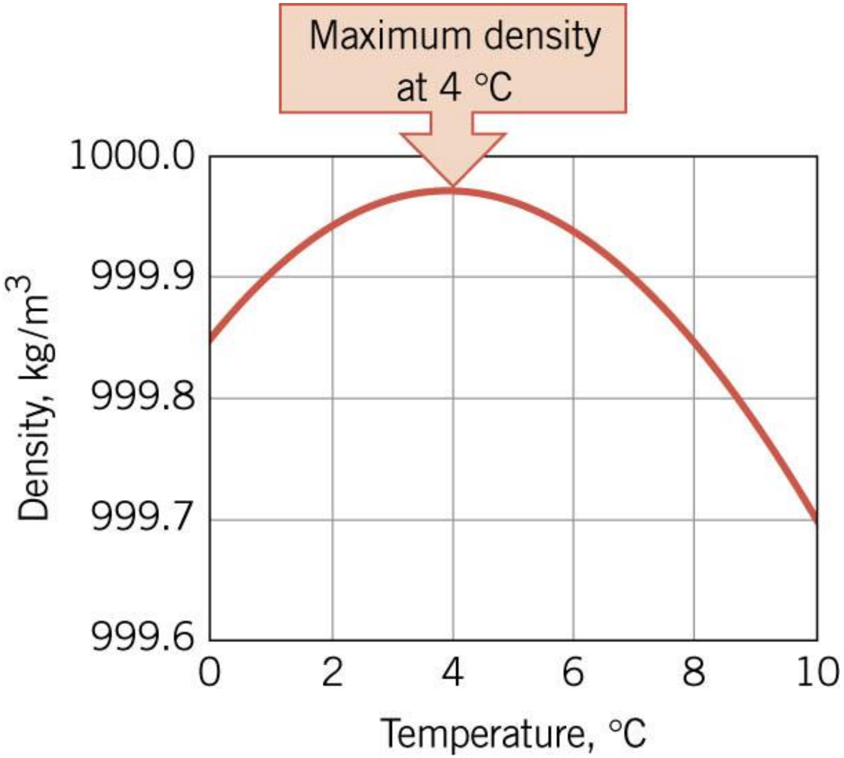
$$\Delta V_{\text{radiator}} = \left(51\times10^{-6}\left(\text{C}^\circ\right)^{-1}\right)\left(15\text{ quarts}\right)\left(86\text{ C}^\circ\right) = 0.066\text{ quarts}$$

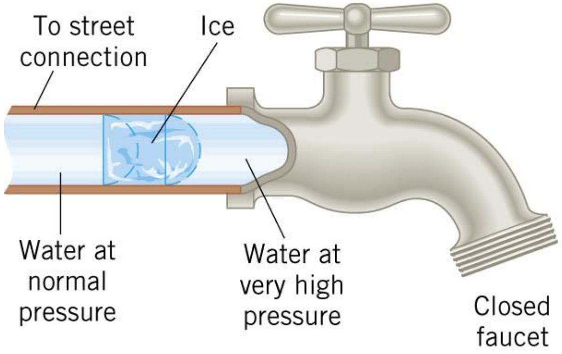
$$\Delta V_{\text{spill}} = 0.53\text{ quarts} - 0.066\text{ quarts} = 0.46\text{ quarts}$$



12.5 Volume Thermal Expansion

Expansion of water.



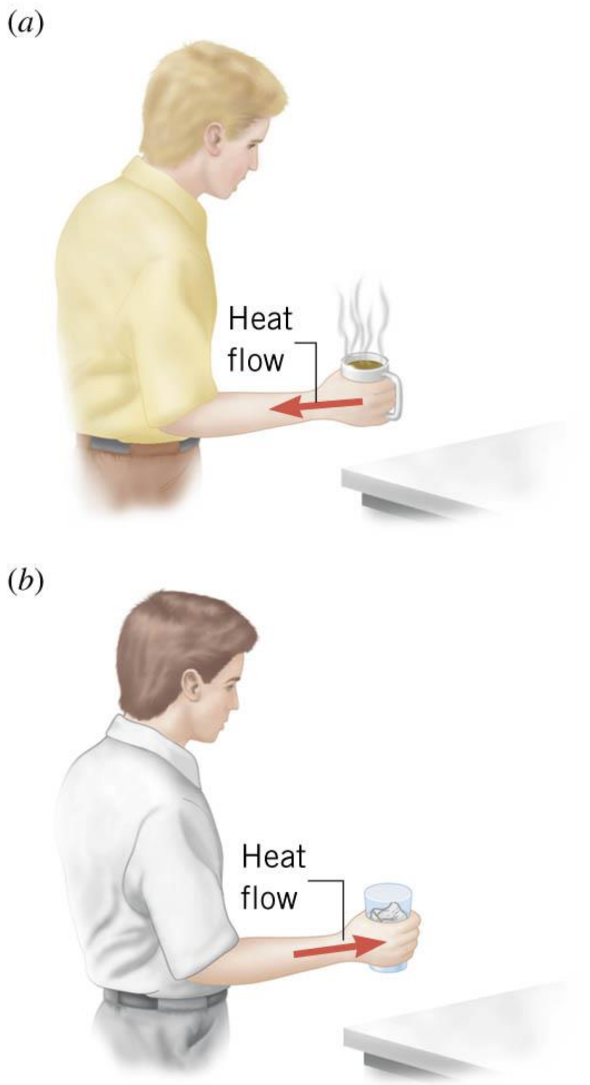


12.6 Heat and Internal Energy

DEFINITION OF HEAT

Heat is energy that flows from a higher-temperature object to a lower-temperature object because of a difference in temperatures.

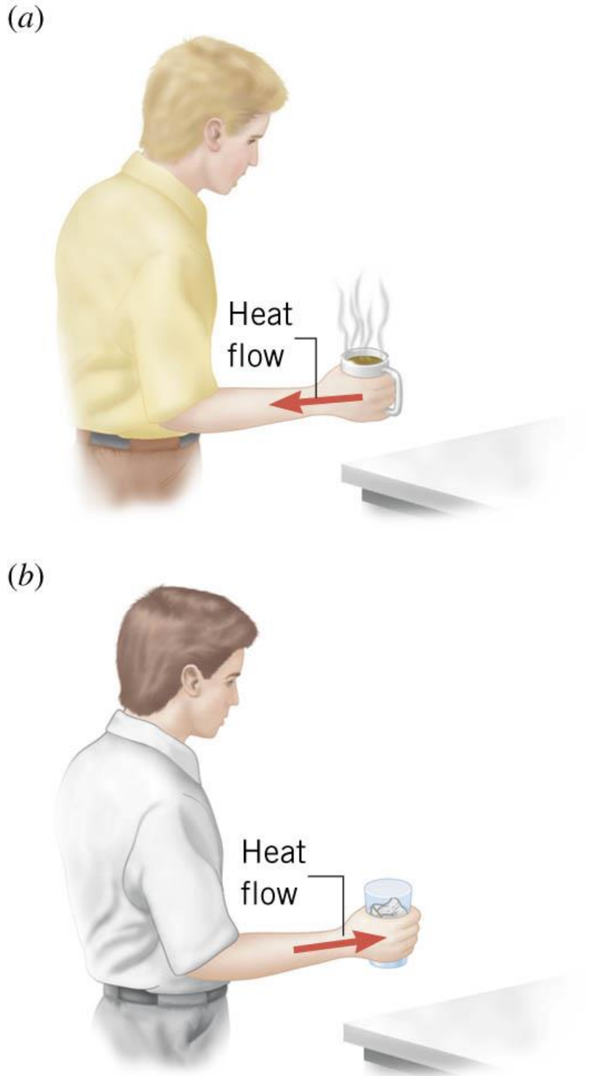
SI Unit of Heat: joule (J)



12.6 *Heat and Internal Energy*

The heat that flows from hot to cold originates in the *internal energy* of the hot substance.

It is not correct to say that a substance contains heat.



12.7 *Heat and Temperature Change: Specific Heat Capacity*

SOLIDS AND LIQUIDS

HEAT SUPPLIED OR REMOVED IN CHANGING THE TEMPERATURE OF A SUBSTANCE

The heat that must be supplied or removed to change the temperature of a substance is

$$Q = m\underset{\uparrow}{c}\Delta T$$

specific heat capacity

Common Unit for Specific Heat Capacity: J/(kg·C°)

12.7 Heat and Temperature Change: Specific Heat Capacity

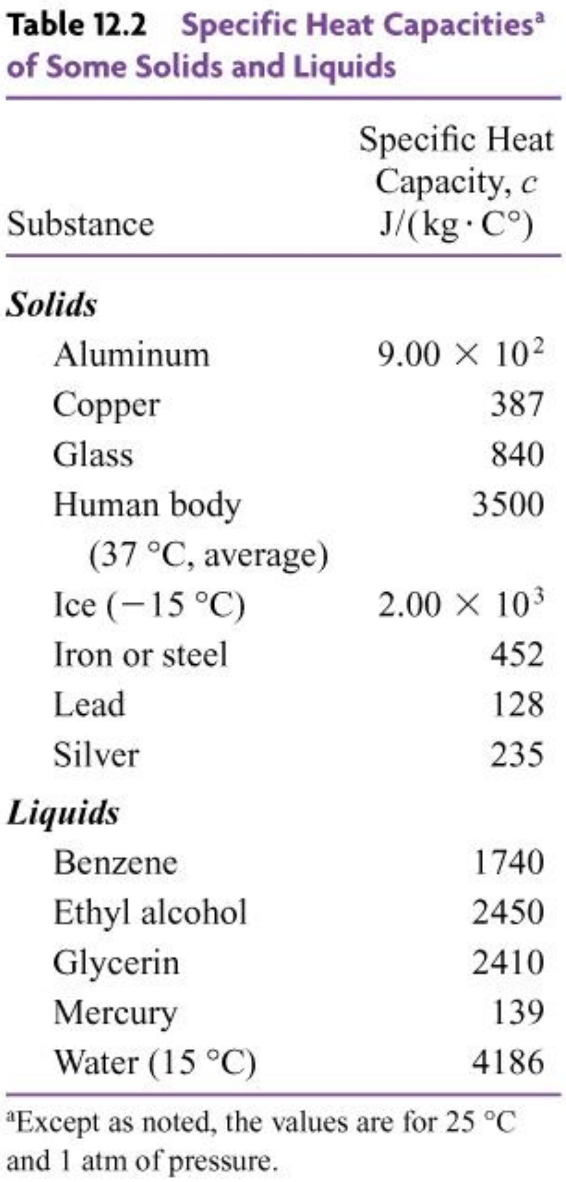


Table 12.2 Specific Heat Capacities[a] of Some Solids and Liquids

Substance	Specific Heat Capacity, c J/(kg · C°)
Solids	
Aluminum	9.00×10^2
Copper	387
Glass	840
Human body (37 °C, average)	3500
Ice (−15 °C)	2.00×10^3
Iron or steel	452
Lead	128
Silver	235
Liquids	
Benzene	1740
Ethyl alcohol	2450
Glycerin	2410
Mercury	139
Water (15 °C)	4186

[a] Except as noted, the values are for 25 °C and 1 atm of pressure.

12.7 Heat and Temperature Change: Specific Heat Capacity

Example 9 **A Hot Jogger**

In a half-hour, a 65-kg jogger can generate $8.0\text{x}10^5$J of heat. This heat is removed from the body by a variety of means, including the body's own temperature-regulating mechanisms. If the heat were not removed, how much would the body temperature increase?

$$Q = mc\Delta T$$

$$\Delta T = \frac{Q}{mc} = \frac{8.0\times 10^5\,\mathrm{J}}{(65\,\mathrm{kg})\left[3500\,\mathrm{J}/(\mathrm{kg}\cdot\mathrm{C}^\circ)\right]} = 3.5\,\mathrm{C}^\circ$$

12.7 *Heat and Temperature Change: Specific Heat Capacity*

GASES

The value of the specific heat of a gas depends on whether the pressure or volume is held constant.

This distinction is not important for solids.

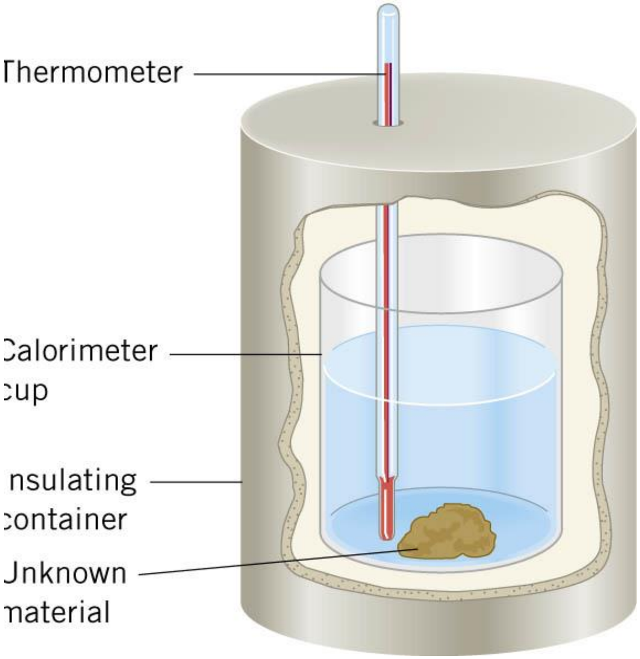
OTHER UNITS

1 kcal = 4186 joules

1 cal = 4.186 joules

12.7 *Heat and Temperature Change: Specific Heat Capacity*

CALORIMETRY

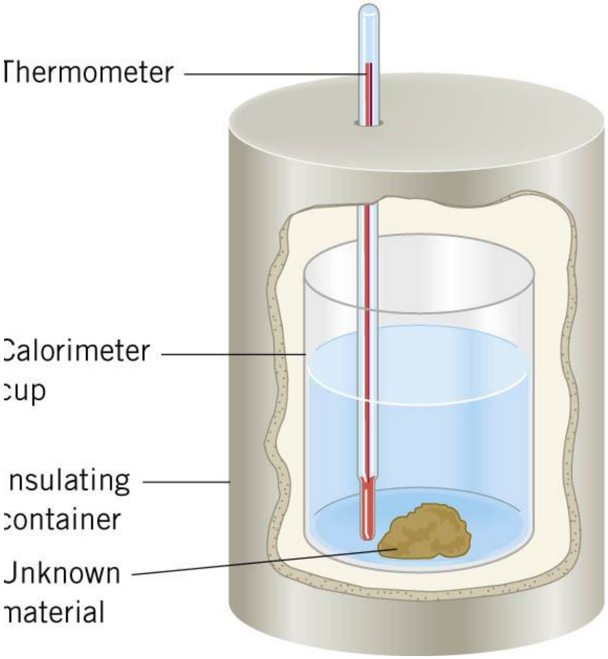


If there is no heat loss to the surroundings, the heat lost by the hotter object equals the heat gained by the cooler ones.

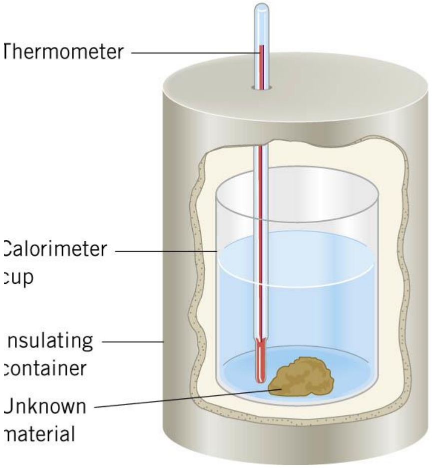
Example 12 Measuring the Specific Heat Capacity

The calorimeter is made of 0.15 kg of aluminum and contains 0.20 kg of water. Initially, the water and cup have the same temperature of 18.0°C. A 0.040 kg mass of unknown material is heated to a temperature of 97.0°C and then added to the water.

After thermal equilibrium is reached, the temperature of the water, the cup, and the material is 22.0°C. Ignoring the small amount of heat gained by the thermometer, find the specific heat capacity of the unknown material.



12.7 Heat and Temperature Change: Specific Heat Capacity



$$\left(mc\Delta T\right)_{\text{Al}} + \left(mc\Delta T\right)_{\text{water}} = \left(mc\Delta T\right)_{\text{unknown}}$$

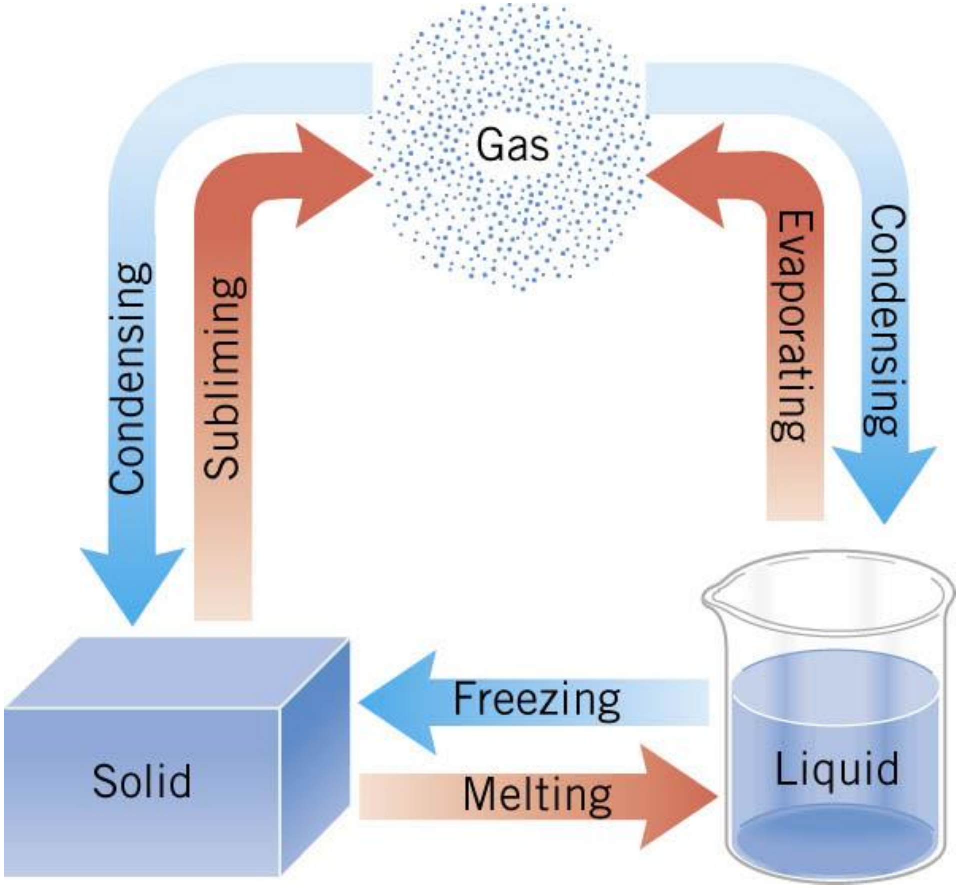
⇓

$$c_{\text{unknown}} = \frac{\left(mc\Delta T\right)_{\text{Al}} + \left(mc\Delta T\right)_{\text{water}}}{\left(m\Delta T\right)_{\text{unknown}}}$$

$$= \frac{\left[9.00\times10^{2}\ \text{J}/\left(\text{kg}\cdot\text{C}^{\circ}\right)\right]\left(0.15\ \text{kg}\right)\left(4.0\ \text{C}^{\circ}\right) + \left[4186\ \text{J}/\left(\text{kg}\cdot\text{C}^{\circ}\right)\right]\left(0.20\ \text{kg}\right)\left(4.0\ \text{C}^{\circ}\right)}{\left(0.040\ \text{kg}\right)\left(75.0\ \text{C}^{\circ}\right)}$$

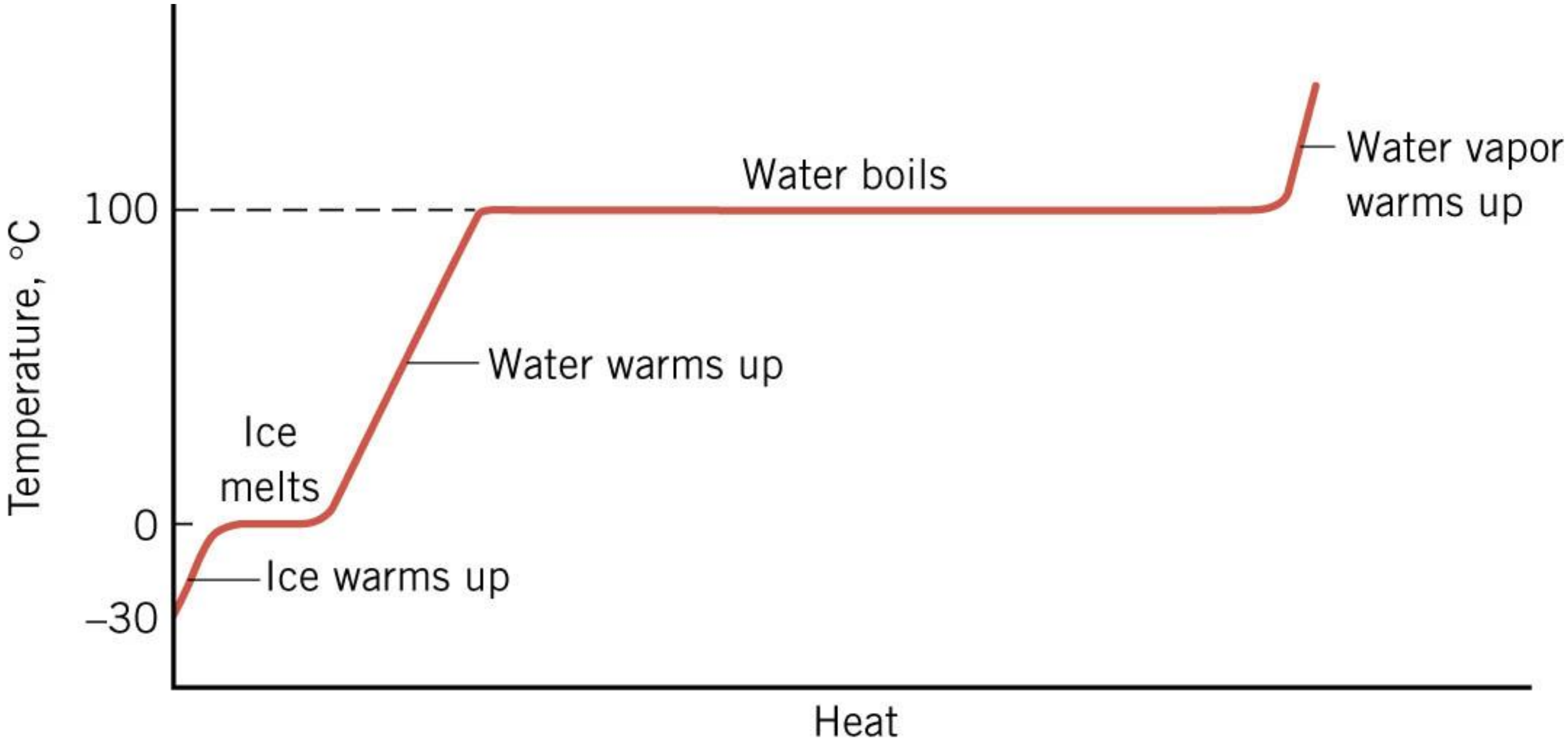
$$= 1300\ \text{J}/\left(\text{kg}\cdot\text{C}^{\circ}\right)$$

THE PHASES OF MATTER



12.8 Heat and Phase Change: Latent Heat

During a phase change, the temperature of the mixture does not change (provided the system is in thermal equilibrium).



Conceptual Example 13 **Saving Energy**

Suppose you are cooking spaghetti for dinner, and the instructions say “boil pasta in water for 10 minutes.” To cook spaghetti in an open pot using the least amount of energy, should you turn up the burner to its fullest so the water vigorously boils, or should you turn down the burner so the water barely boils?

12.8 Heat and Phase Change: Latent Heat

HEAT SUPPLIED OR REMOVED IN CHANGING THE PHASE OF A SUBSTANCE

The heat that must be supplied or removed to change the phase of a mass *m* of a substance is

$$Q = m\underset{\text{latent heat}}{L}$$

SI Units of Latent Heat: J/kg

12.8 Heat and Phase Change: Latent Heat

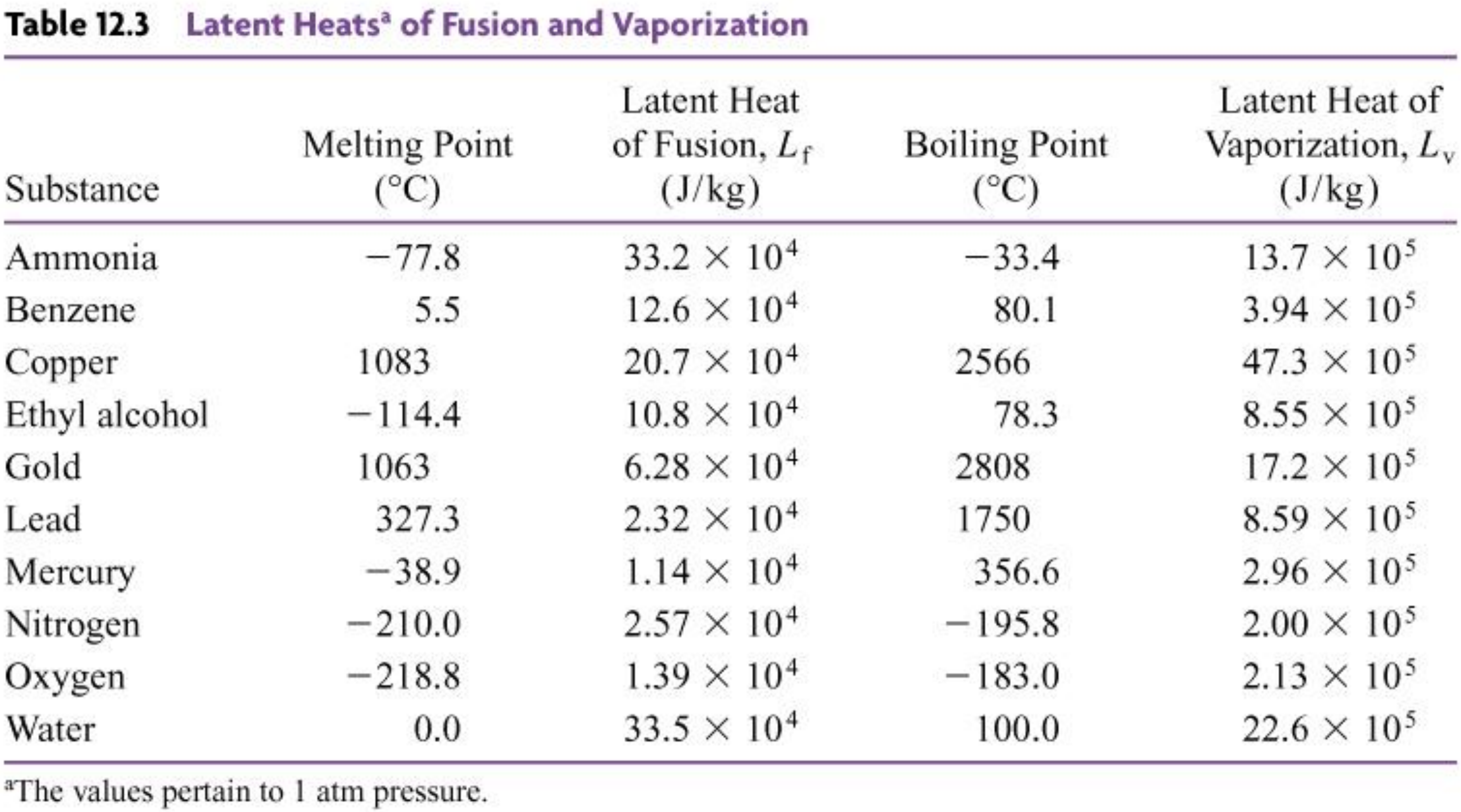


Table 12.3 Latent Heats[a] of Fusion and Vaporization

Substance	Melting Point (°C)	Latent Heat of Fusion, L_f (J/kg)	Boiling Point (°C)	Latent Heat of Vaporization, L_v (J/kg)
Ammonia	−77.8	33.2×10^4	−33.4	13.7×10^5
Benzene	5.5	12.6×10^4	80.1	3.94×10^5
Copper	1083	20.7×10^4	2566	47.3×10^5
Ethyl alcohol	−114.4	10.8×10^4	78.3	8.55×10^5
Gold	1063	6.28×10^4	2808	17.2×10^5
Lead	327.3	2.32×10^4	1750	8.59×10^5
Mercury	−38.9	1.14×10^4	356.6	2.96×10^5
Nitrogen	−210.0	2.57×10^4	−195.8	2.00×10^5
Oxygen	−218.8	1.39×10^4	−183.0	2.13×10^5
Water	0.0	33.5×10^4	100.0	22.6×10^5

[a] The values pertain to 1 atm pressure.

Example 14 Ice-cold Lemonade

Ice at 0°C is placed in a Styrofoam cup containing 0.32 kg of lemonade at 27°C. The specific heat capacity of lemonade is virtually the same as that of water. After the ice and lemonade reach an equilibrium temperature, some ice still remains. Find the mass of the melted ice. Assume that mass of the cup is so small that it absorbs a negligible amount of heat.

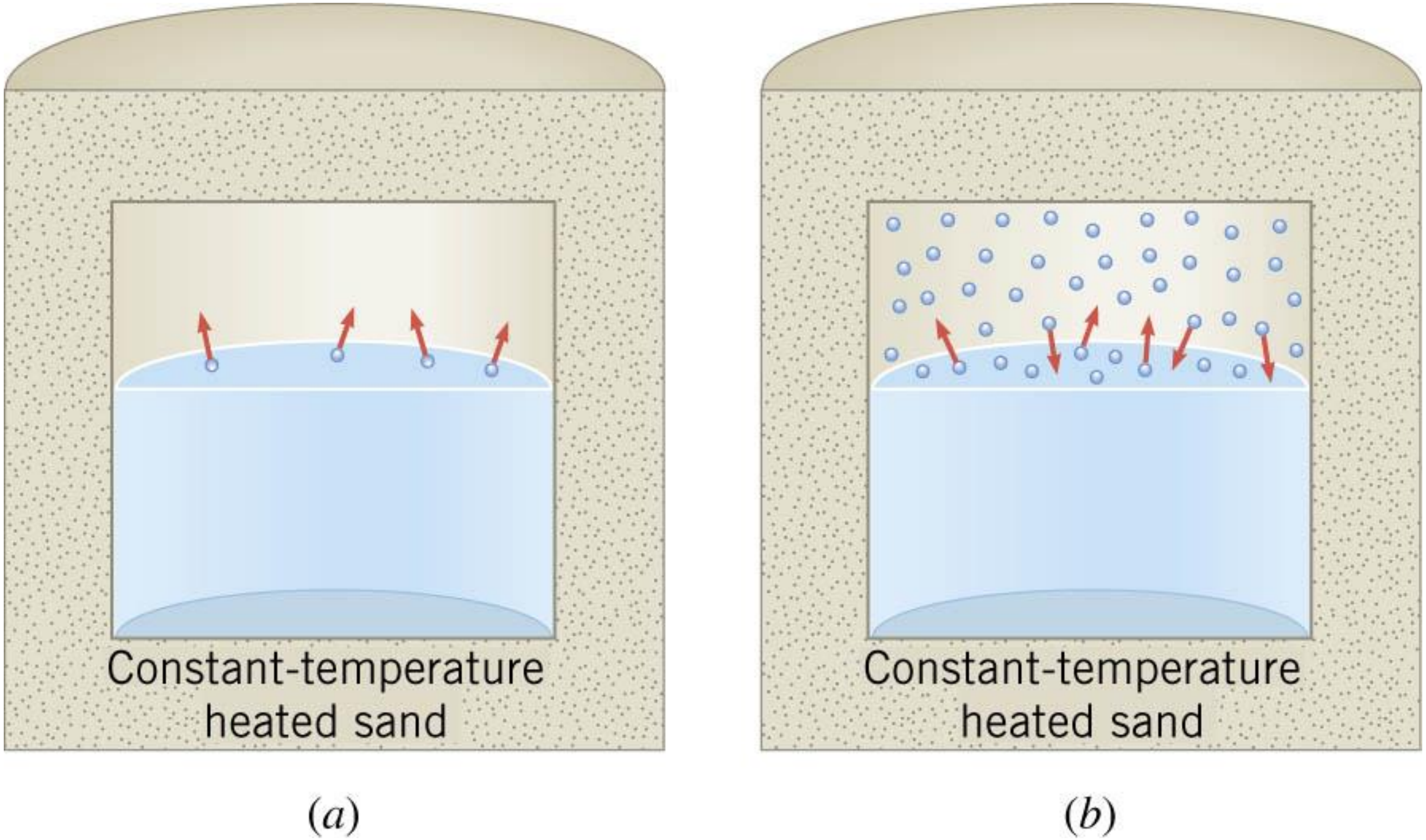
$$\underbrace{\left(mL_f\right)_{\text{ice}}}_{\substack{\text{Heat gained} \\ \text{by melted ice}}} = \underbrace{\left(cm\Delta T\right)_{\text{lemonade}}}_{\substack{\text{Heat lost by} \\ \text{lemonade}}}$$

$$\underbrace{\left(mL_f\right)_{\text{ice}}}_{\substack{\text{Heat gained}\\ \text{by melted ice}}} = \underbrace{\left(cm\Delta T\right)_{\text{lemonade}}}_{\substack{\text{Heat lost by}\\ \text{lemonade}}}$$

$$m_{\text{ice melted}} = \frac{\left(cm\Delta T\right)_{\text{lemonade}}}{\mathrm{L_f}}$$

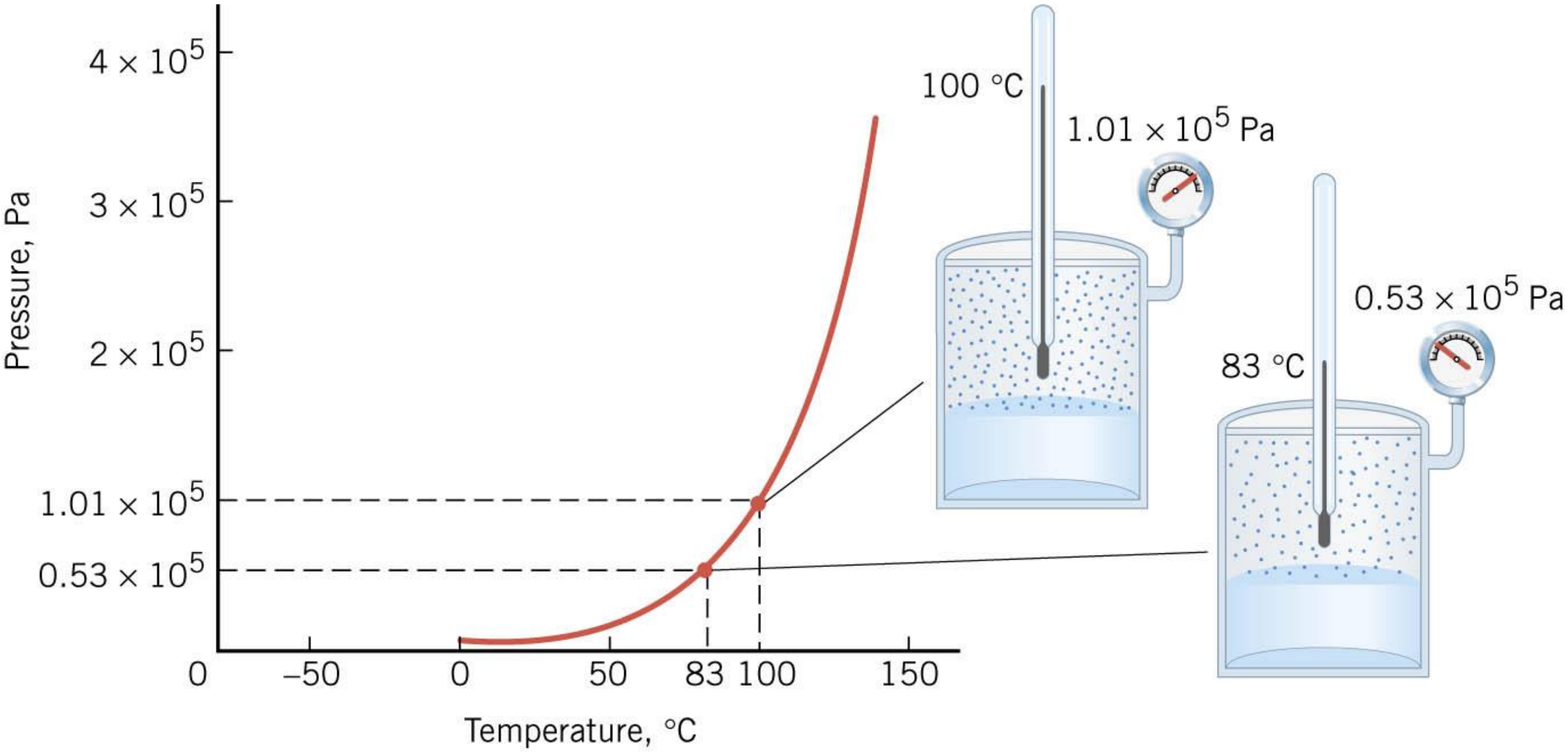
$$= \frac{\left[4186\,\mathrm{J}/\left(\mathrm{kg}\cdot\mathrm{C}^\circ\right)\right]\left(0.32\,\mathrm{kg}\right)\left(27^\circ\mathrm{C}-0^\circ\mathrm{C}\right)}{3.35\times10^5\,\mathrm{J/kg}} = 0.11\,\mathrm{kg}$$

12.9 Equilibrium Between Phases of Matter



The pressure of vapor that coexists in equilibrium with the liquid is called the ***equilibrium vapor pressure*** of the liquid.

12.9 Equilibrium Between Phases of Matter

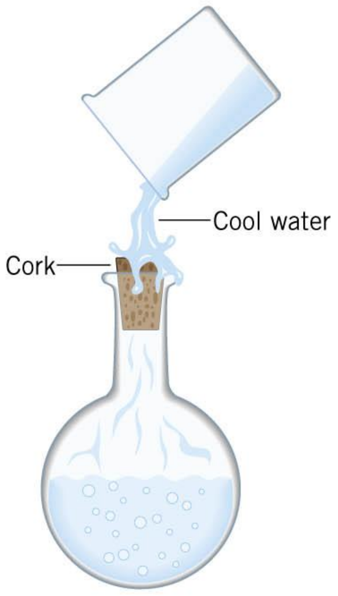


Only when the temperature and vapor pressure correspond to a point on the curved line do the liquid and vapor phases coexist in equilibrium.

Conceptual Example 16 **How to Boil Water That is Cooling Down**

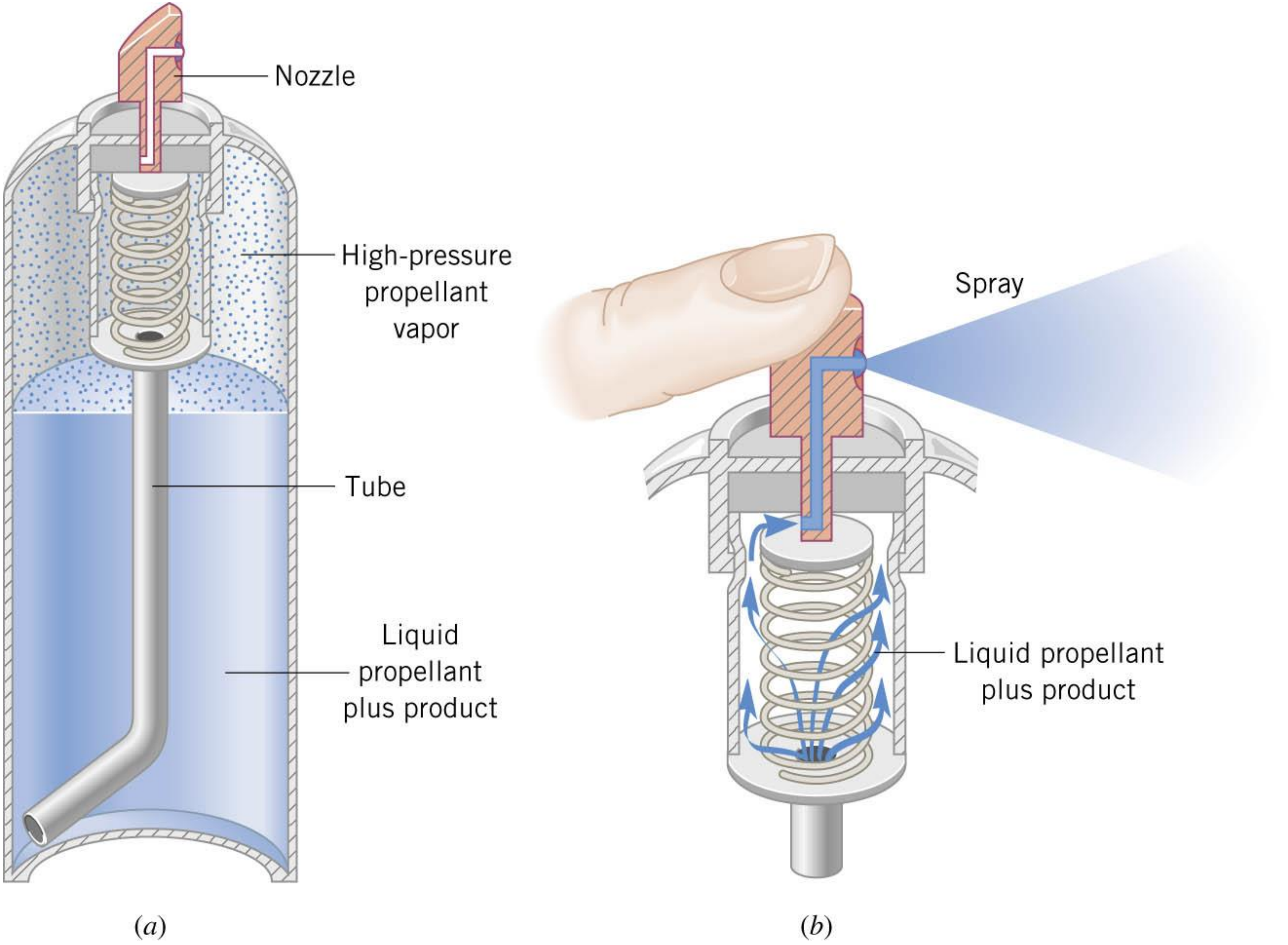
Shortly after the flask is removed from the burner, the boiling stops. A cork is then placed in the neck of the flask to seal it. To restart the boiling, should you pour hot or cold water over the neck of the flask?

(*a*) Water boiling



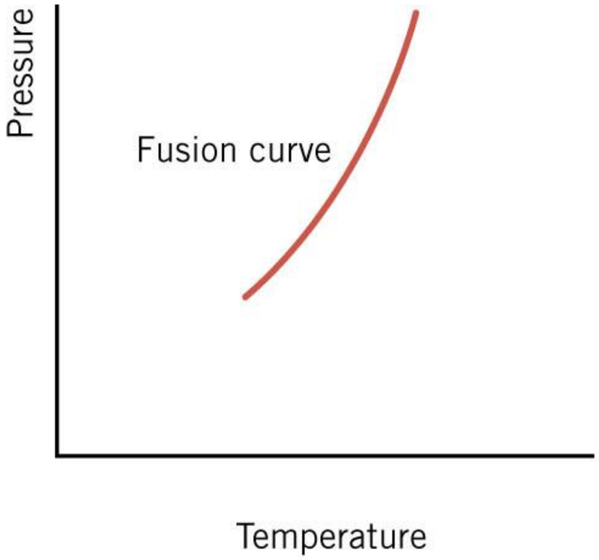
(*b*) Water boiling again

12.9 Equilibrium Between Phases of Matter

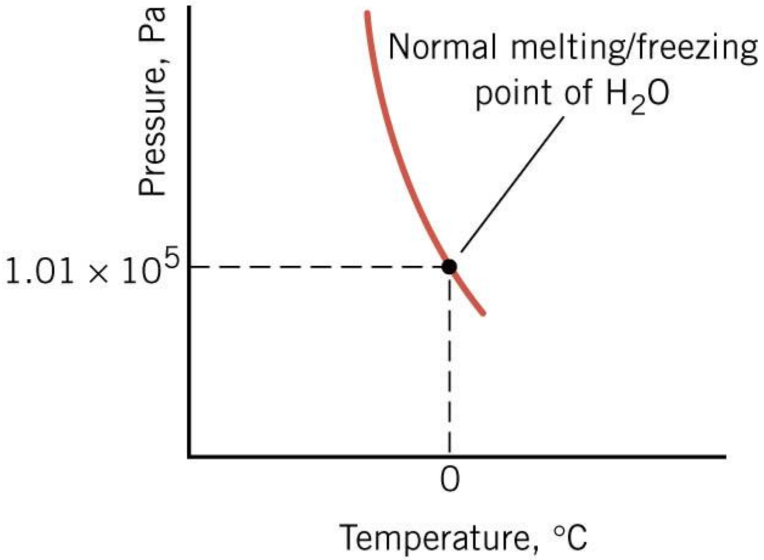


12.9 Equilibrium Between Phases of Matter

As is the case for liquid/vapor equilibrium, a solid can be in equilibrium with its liquid phase only at specific conditions of temperature and pressure.



(*a*)



(*b*)

12.10 Humidity

Air is a mixture of gases.

The total pressure is the sum of the ***partial pressures*** of the component gases.

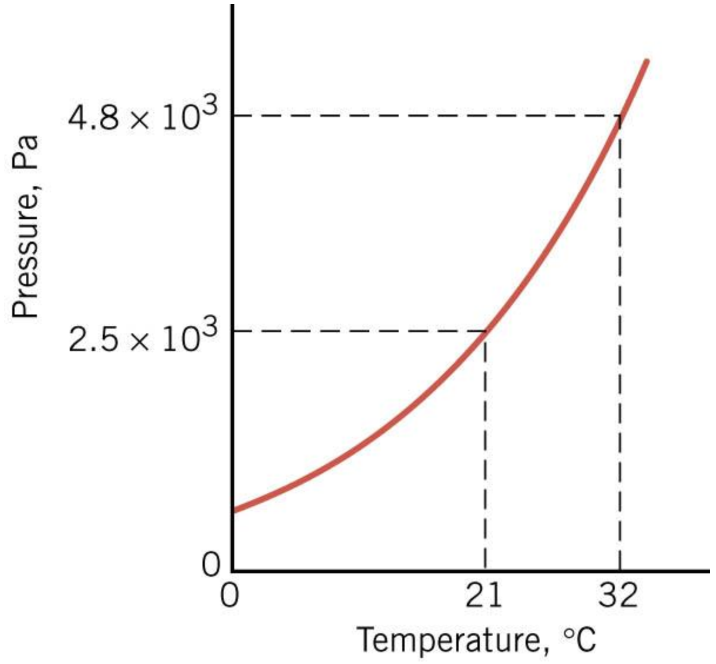
The partial pressure of water vapor depends on weather conditions. It can be as low as zero or as high as the vapor pressure of water at the given temperature.

To provide an indication of how much water vapor is in the air, weather forecasters usually give the ***relative humidity:***

$$\left(\text{Percent relative humidity}\right)=\frac{\left(\text{Partial pressure of water vapor}\right)}{\left(\text{Equilibrium vapor pressure of water at existing temperature}\right)}\times 100$$

Example 17 Relative Humidities

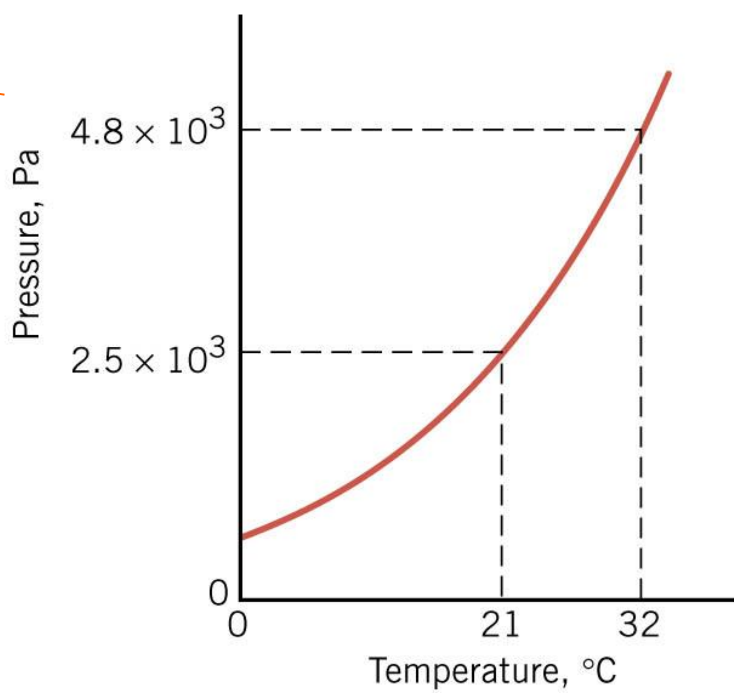
One day, the partial pressure of water vapor is 2.0×10^3 Pa. Using the vaporization curve, determine the relative humidity if the temperature is 32°C.



12.10 Humidity

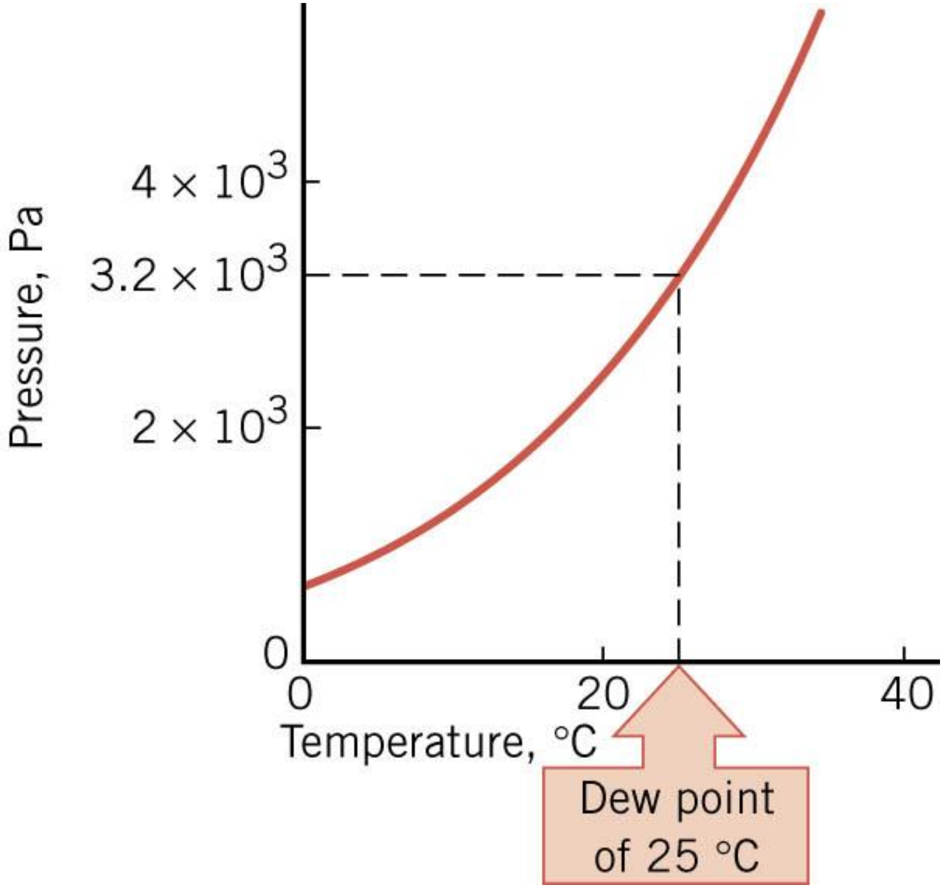
$$\left(\text{Percent relative humidity}\right)=\frac{\left(\text{Partial pressure of water vapor}\right)}{\left(\text{Equilibrium vapor pressure of water at existing temperature}\right)}\times 100$$

$$\text{Relative humidity}=\frac{2.0\times 10^{3}\ \text{Pa}}{4.8\times 10^{3}\ \text{Pa}}\times 100=42\%$$



12.10 **Humidity**

The temperature at which the relative humidity is 100% is called the dew point.



12.10 *Humidity*