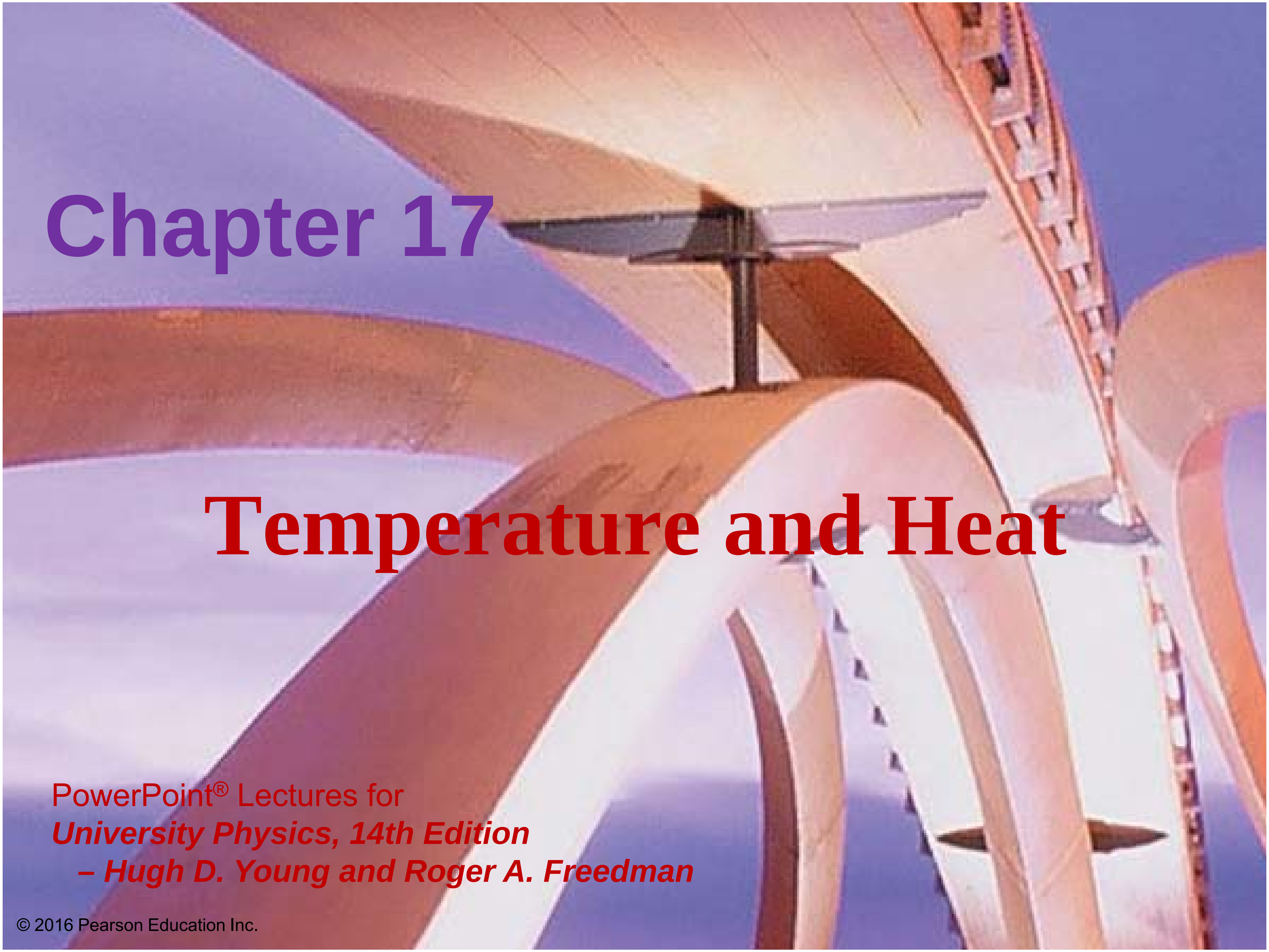


Chapter 17

Temperature and Heat

PowerPoint® Lectures for
University Physics, 14th Edition
– Hugh D. Young and Roger A. Freedman

Learning Goals for Chapter 17

Looking forward at …

- the meaning of thermal equilibrium, and what thermometers really measure.
- the physics behind the absolute, or Kelvin, temperature scale.
- how the dimensions of an object change as a result of a temperature change.
- how to do calculations that involve heat flow, temperature changes, and changes of phase.
- how heat is transferred by conduction, convection, and radiation.

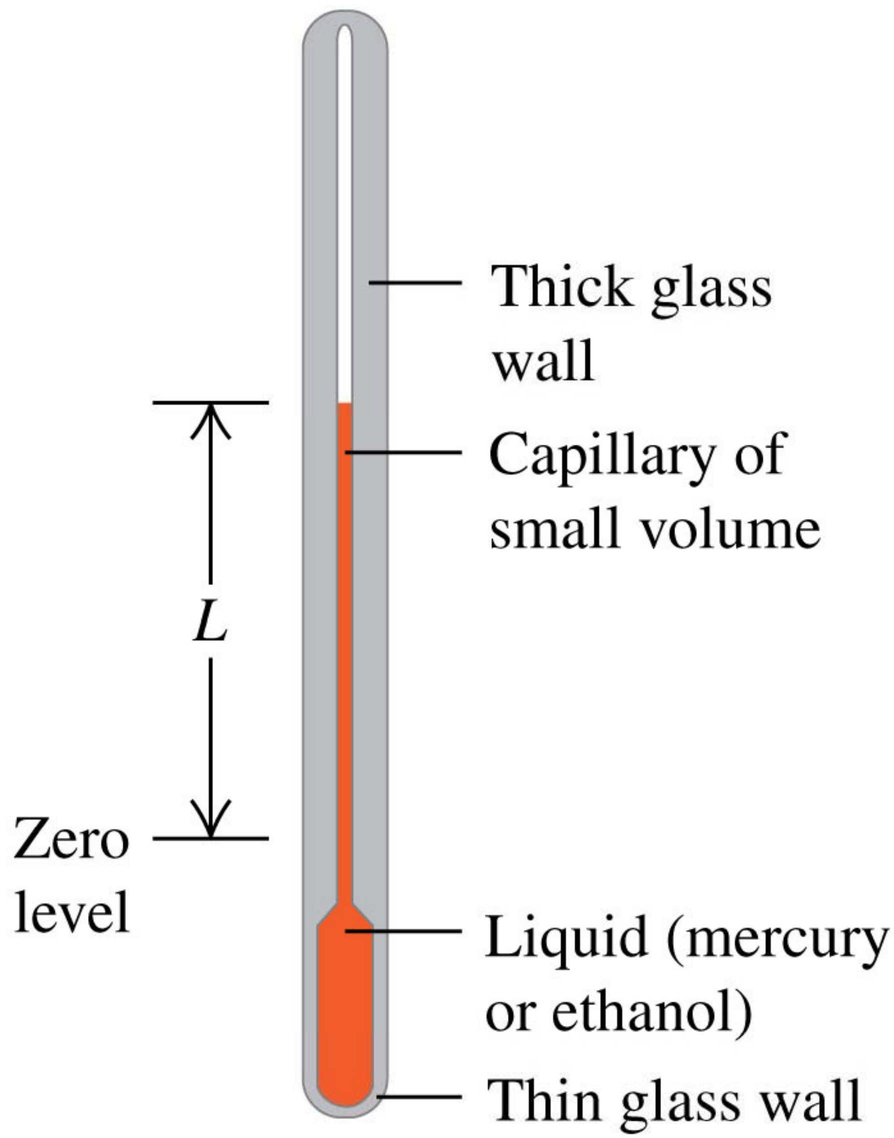
Introduction

- Does molten iron at 1500°C contain heat?
- The terms "temperature" and "heat" have very different meanings, even though most people use them interchangeably.

- In this chapter, we'll focus on large-scale, or *macroscopic*, objects, but in the next chapter we'll look at the *microscopic* scale.

Temperature and thermal equilibrium

- We use a **thermometer** to measure **temperature**.
- For example, the volume of the liquid in the thermometer to the right changes with temperature.
- Two systems are in **thermal equilibrium** if and only if they have the same temperature.



Other types of thermometers

- A temporal artery thermometer measures infrared radiation from the skin that overlies one of the important arteries in the head.
- Although the thermometer cover touches the skin, the infrared detector inside the cover does not.

Q17.1

The illustration shows a thermometer that uses a column of liquid (usually mercury or ethanol) to measure air temperature. In thermal equilibrium, this thermometer measures the temperature of

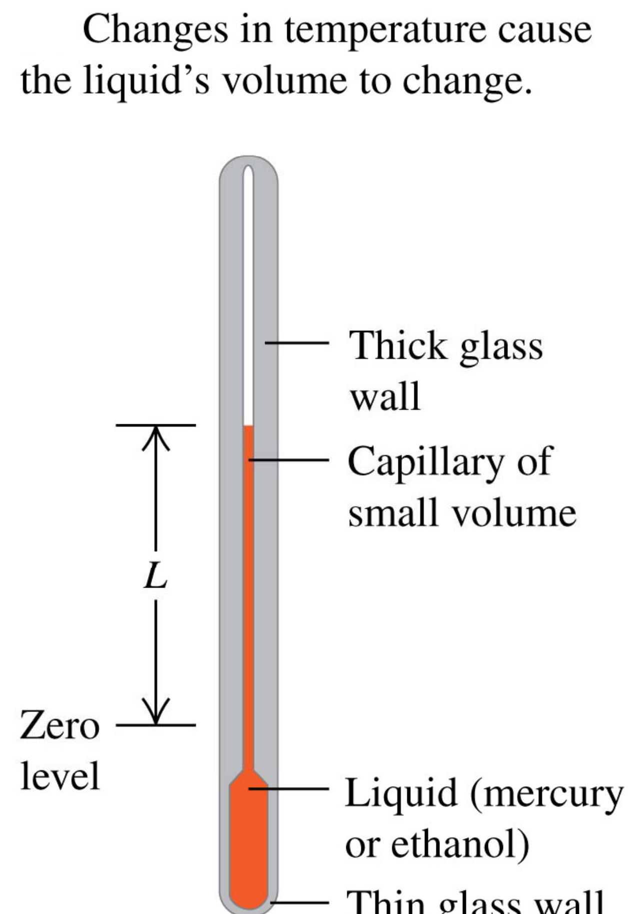
A. the column of liquid.

B. the glass that encloses the liquid.

C. the air outside the thermometer.

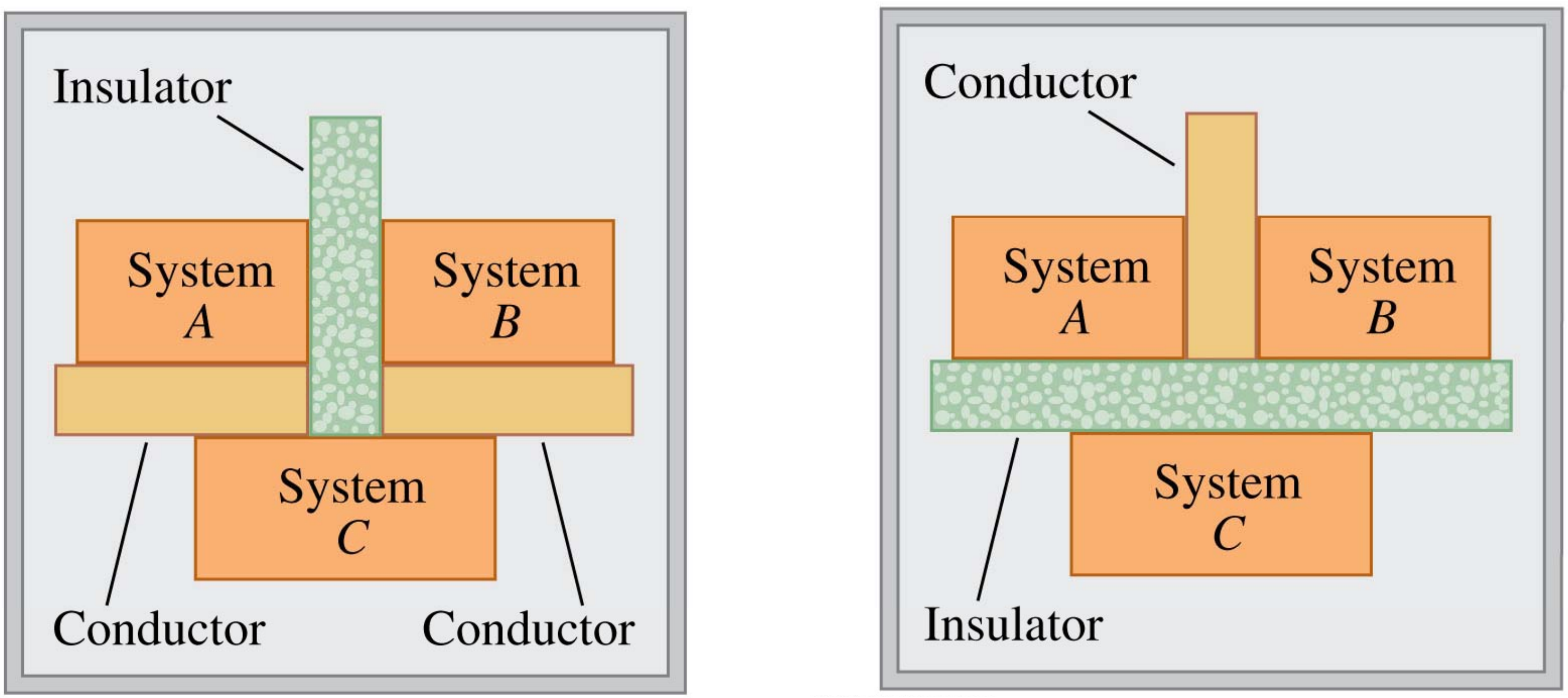
D. both A and B.

E. all of A, B, and C.



The zeroth law of thermodynamics

- If C is initially in thermal equilibrium with both A and B, then A and B are in thermal equilibrium with each other.



(a) If systems A and B are each in thermal equilibrium with system C ...

(b) ... then systems A and B are in thermal equilibrium with each other.

Temperature scales

- On the *Celsius* (or *centigrade*) *temperature scale*, 0°C is the freezing point of pure water and 100°C is its boiling point.
- On the *Fahrenheit temperature scale*, 32°F is the freezing point of pure water and 212°F is its boiling point.
- To convert from Celsius to Fahrenheit:

Fahrenheit temperature

$$T_F = \tfrac{9}{5}T_C + 32°$$

Celsius temperature

- To convert from Fahrenheit to Celsius:

Celsius temperature

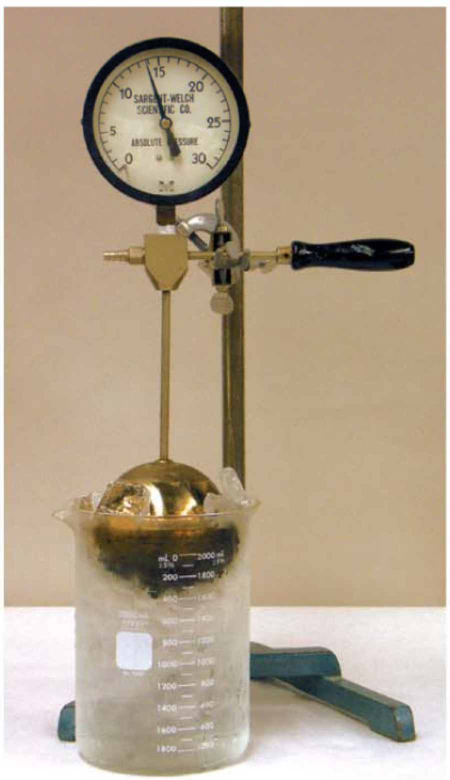
$$T_C = \tfrac{5}{9}(T_F - 32°)$$

Fahrenheit temperature

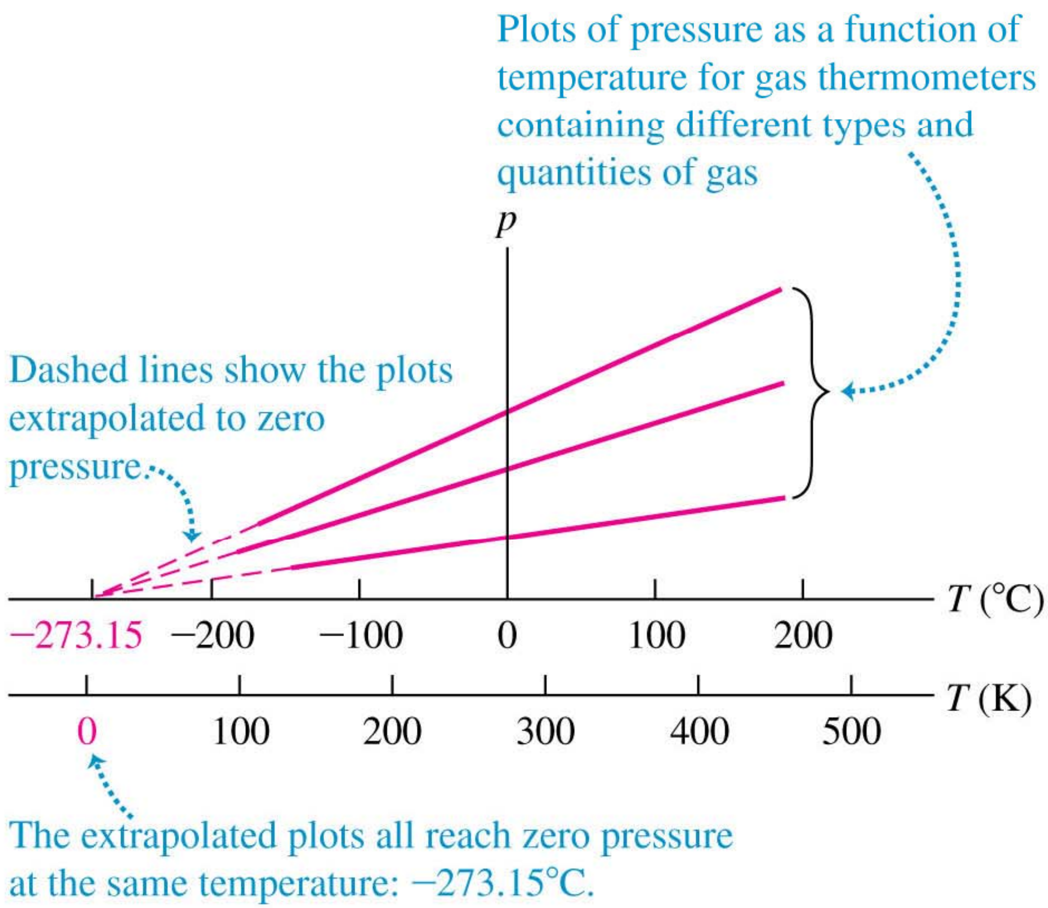
Absolute zero

- There is a temperature, −273.15°C, at which the absolute pressure of any gas would become zero.

(a) A constant-volume gas thermometer



(b) Graphs of pressure versus temperature at constant volume for three different types and quantities of gas

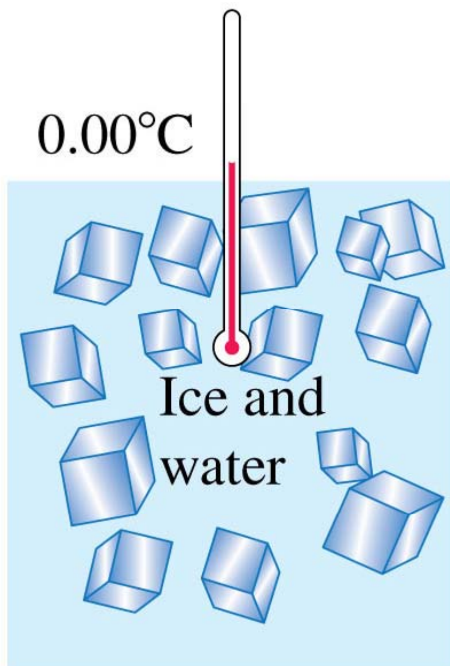


Temperature scales

- On the *Kelvin* (or *absolute*) *temperature scale*, 0 K is the extrapolated temperature at which a gas would exert no pressure.

- To convert from Celsius to Kelvin:

Kelvin temperature $\rightarrow$ $$T_K = T_C + 273.15$$ $\leftarrow$ Celsius temperature



Kelvin temperatures are measured in kelvins ...

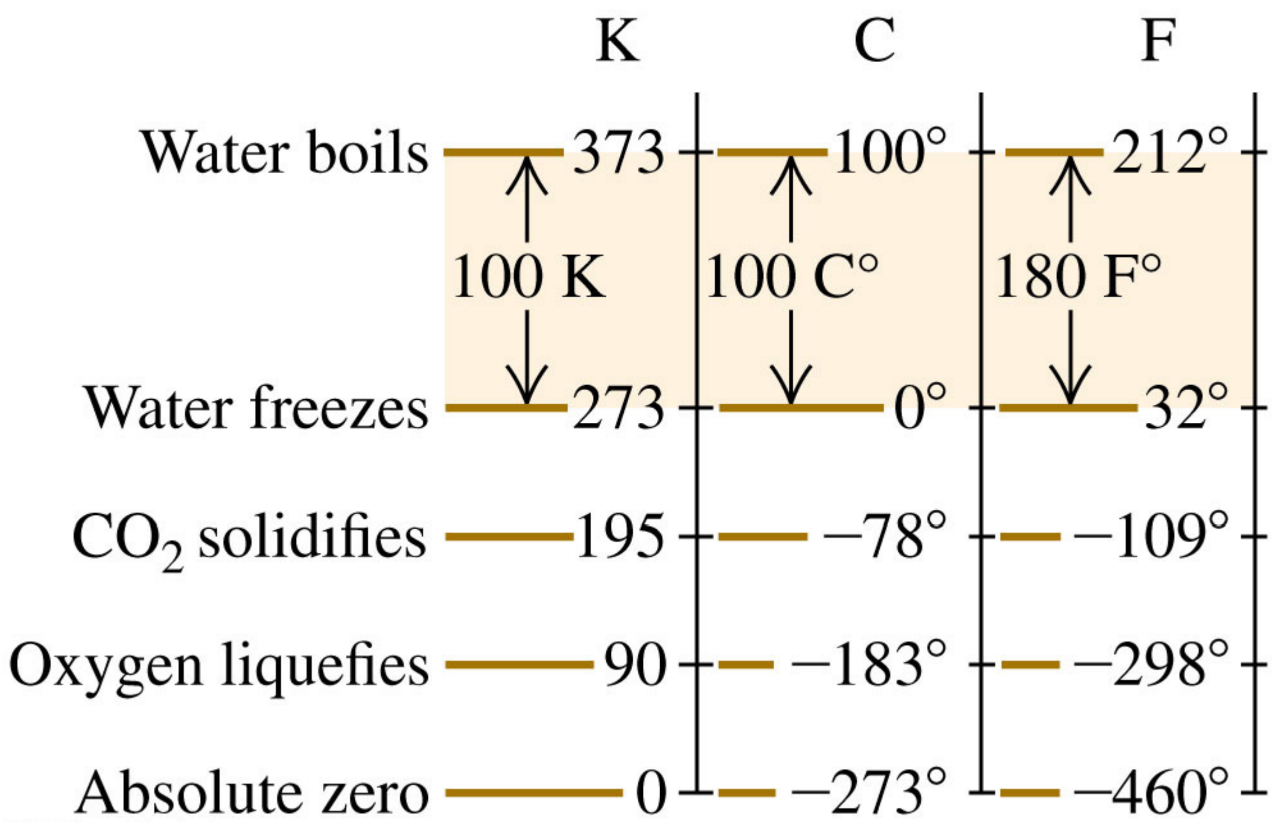
$T = 273.15\ \mathrm{K}$ ◀ **RIGHT!**

... *not* “degrees” kelvin.

$T = 273.15\ \cancel{^\circ\mathrm{K}}$ ◀ **WRONG**

Temperature conversions

- Below are relationships among Kelvin (K), Celsius (C), and Fahrenheit (F) temperature scales. Temperatures have been rounded off to the nearest degree.



Exercise

Rank the following temperatures from highest to lowest.

A. 20.0° F

B. 20.0° C

C. 20.0 K

D. –80.0° F

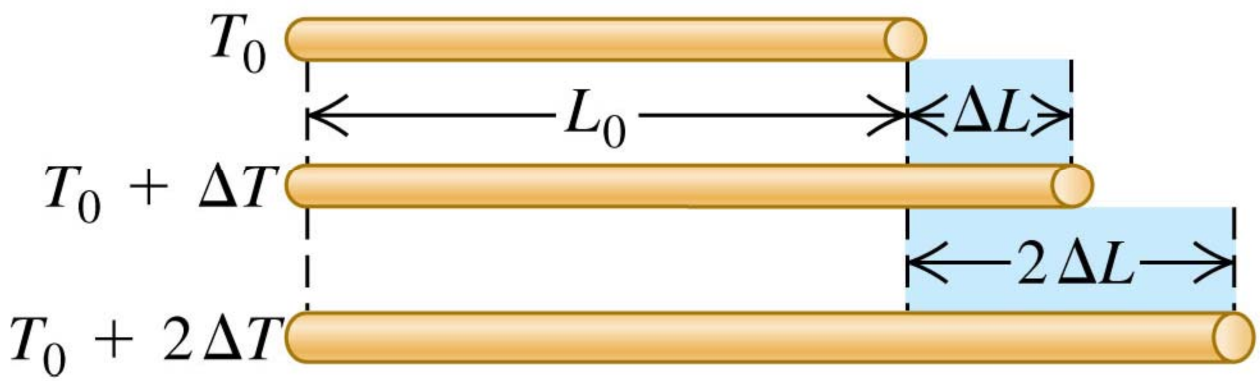
E. –80.0° C

Linear thermal expansion

- Increasing the temperature of a rod causes it to expand.
- For moderate changes in temperature, the change in length is given by:

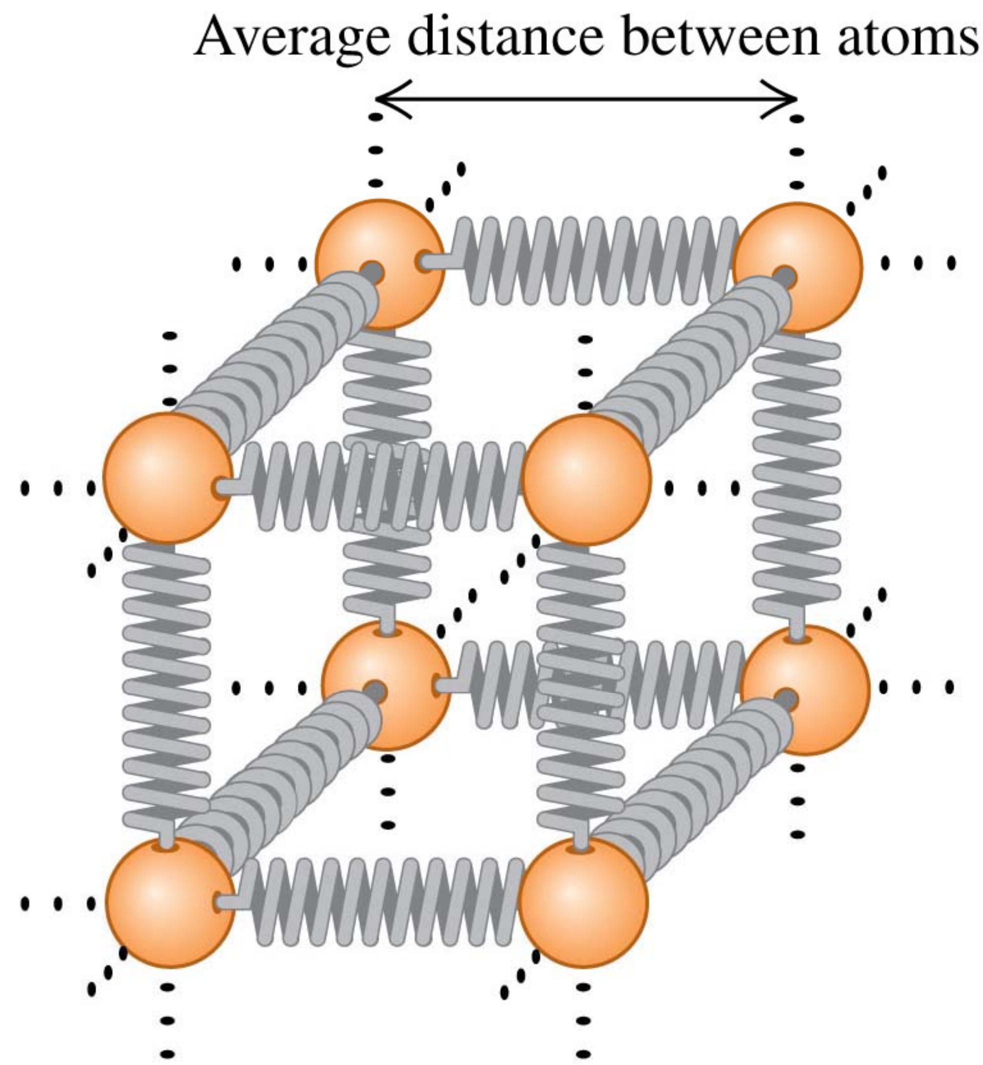
Linear thermal expansion:

$$\underbrace{\Delta L}_{\text{Change in length}} = \underbrace{\alpha}_{\text{Coefficient of linear expansion}} \overbrace{L_0}^{\text{Original length}} \underbrace{\Delta T}_{\text{Temperature change}}$$



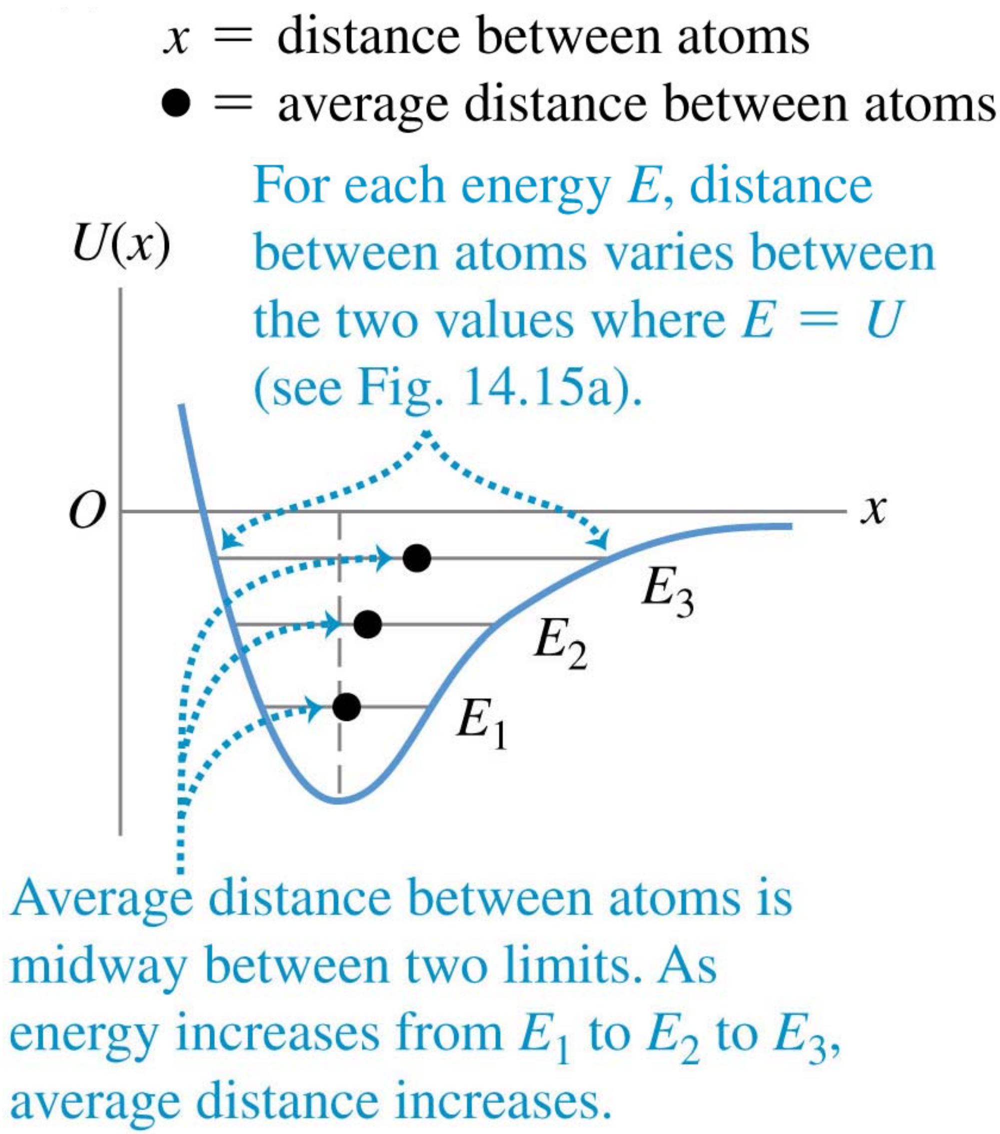
Molecular basis for thermal expansion

- We can understand linear expansion if we model the atoms as being held together by springs.
- When the temperature increases, the average distance between atoms also increases.
- As the atoms get farther apart, every dimension increases.



Molecular basis for thermal expansion

- A graph of the “spring” potential energy versus distance between neighboring atoms is not symmetrical.
- As the energy increases and the atoms oscillate with greater amplitude, the average distance increases.



Expanding holes and volume expansion

- If an object has a hole in it, the hole also expands with the object, as shown.
- The hole does *not shrink*.
- The change in volume due to thermal expansion is given by $\Delta V = \beta V_0 \Delta T$, where β is the **coefficient of volume expansion** and is equal to 3α. **(Why?)**

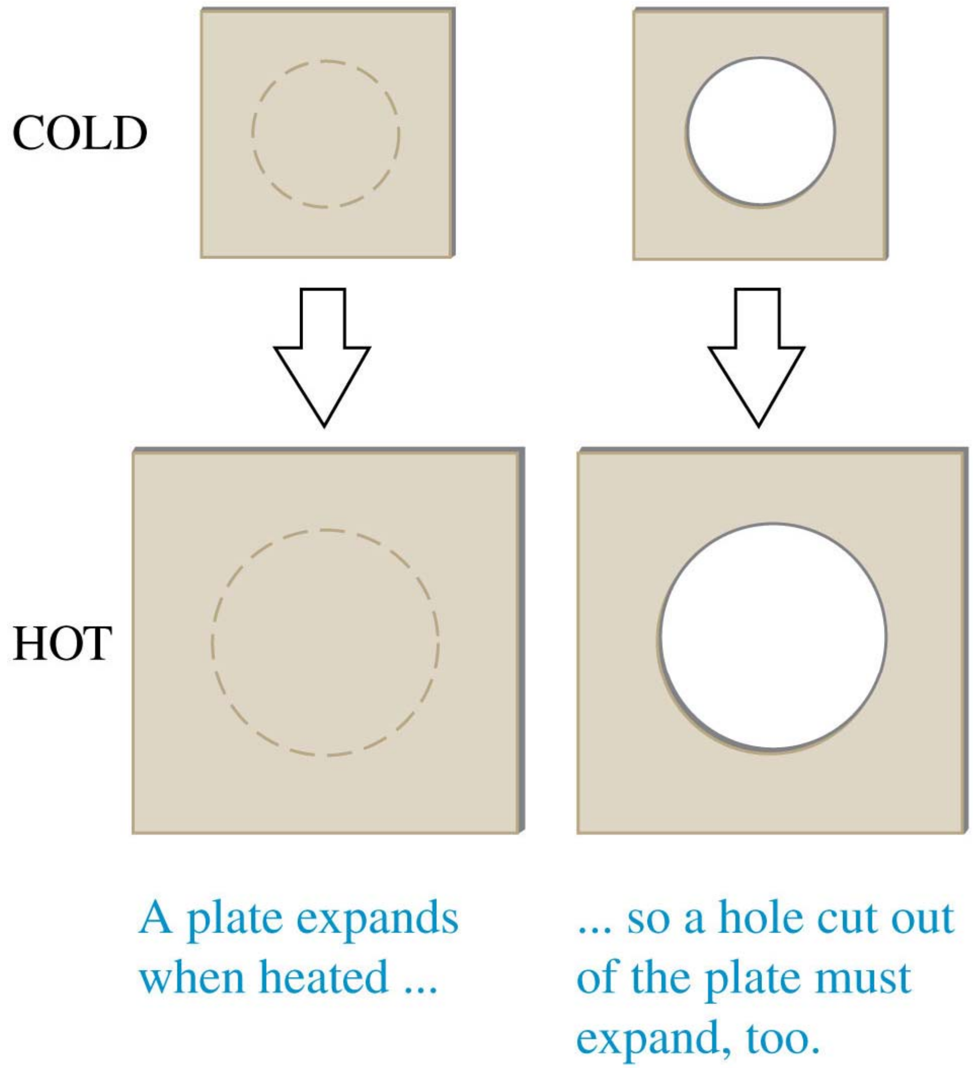


Table 17.1: Coefficients of linear expansion

Material	α [K^{-1} or $(C°)^{-1}$]
Aluminum	2.4×10^{-5}
Brass	2.0×10^{-5}
Copper	1.7×10^{-5}
Glass	$0.4–0.9 \times 10^{-5}$
Invar (nickel–iron alloy)	0.09×10^{-5}
Quartz (fused)	0.04×10^{-5}
Steel	1.2×10^{-5}

Table 17.2: Coefficients of volume expansion

$$\beta = 3\alpha.$$

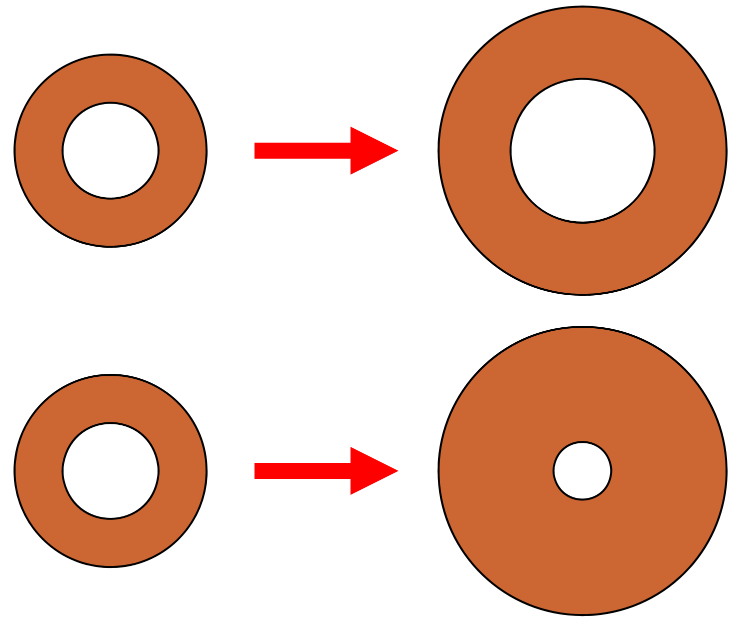
Solids	$\boldsymbol{\beta}$ **[$\mathbf{K^{-1}}$ or $\mathbf{(C°)^{-1}}$]**
Aluminum	7.2×10^{-5}
Brass	6.0×10^{-5}
Copper	5.1×10^{-5}
Glass	$1.2\text{–}2.7 \times 10^{-5}$
Invar	0.27×10^{-5}
Quartz (fused)	0.12×10^{-5}
Steel	3.6×10^{-5}

Q17.3

A solid object has a hole in it. Which of these illustrations more correctly shows how the size of the object and the hole change as the temperature increases?

#1

#2



A. illustration #1

B. illustration #2

C. The answer depends on the material of which the object is made.

D. The answer depends on how much the temperature increases.

E. Both C and D are correct.

Q17.4

When the temperature of a certain solid, rectangular object increases by ΔT, the length of one side of the object increases by 0.010% = 1.0×10^{-4} of the original length. The increase in *volume* of the object due to this temperature increase is

A. 0.010% = 1.0×10^{-4} of the original volume.

B. $(0.010)^3$% = 0.0000010% = 1.0×10^{-8} of the original volume.

C. $(1.0 \times 10^{-4})^3$ = 0.00000000010% = 1.0×10^{-12} of the original volume.

D. 0.030% = 3.0×10^{-4} of the original volume.

E. Not enough information is given to decide.

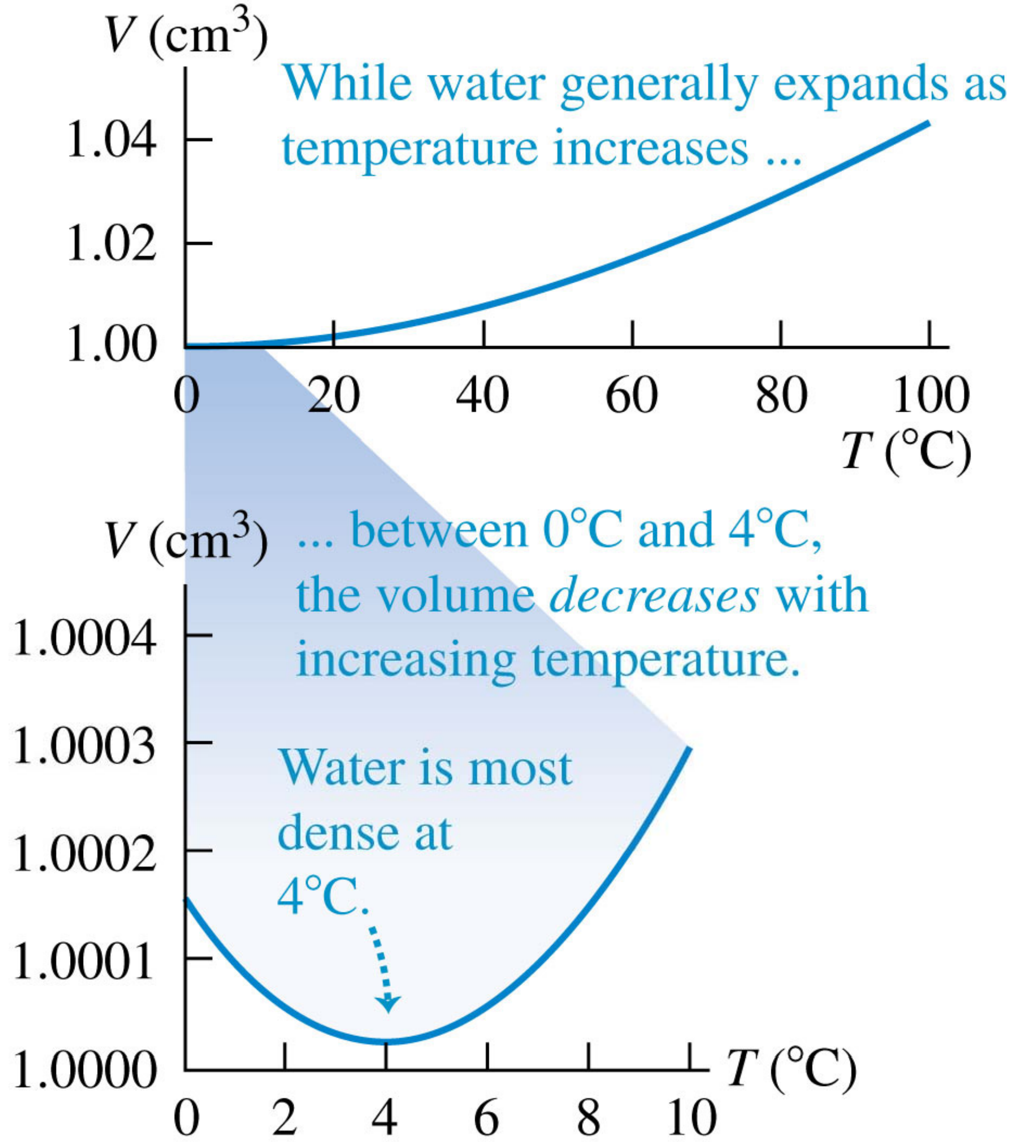
Example of thermal expansion

- This railroad track has a gap between segments to allow for thermal expansion.
- On hot days, the segments expand and fill in the gap.
- If there were no gaps, the track could buckle under very hot conditions.

More examples?

Thermal expansion of water

- Between 0°C and 4°C, water *decreases* in volume with increasing temperature.
- Because of this anomalous behavior, lakes freeze from the top down instead of from the bottom up.



Thermal stress

- If we change the temperature of a rod but prevent it from expanding or contracting, *thermal stress* develops.

Thermal stress:

$$\frac{F}{A} = -Y\alpha\,\Delta T$$

Force needed to keep length of rod constant

Young's modulus

Temperature change

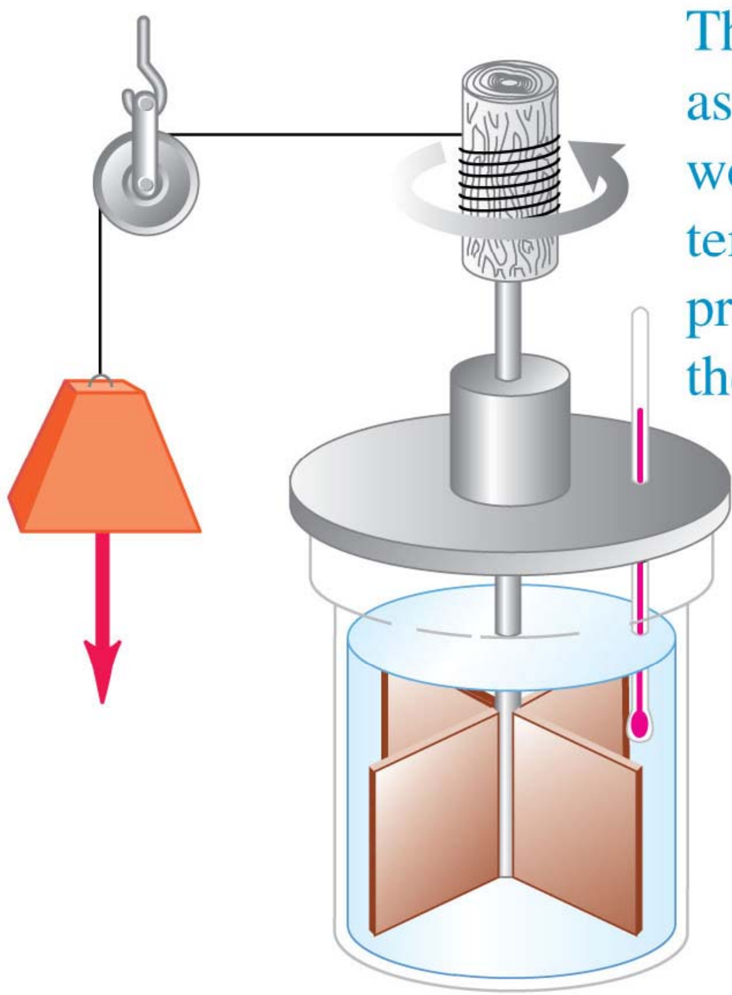
Coefficient of linear expansion

Cross-sectional area of rod

- Expansion joints on bridges are needed to accommodate changes in length that result from thermal expansion.

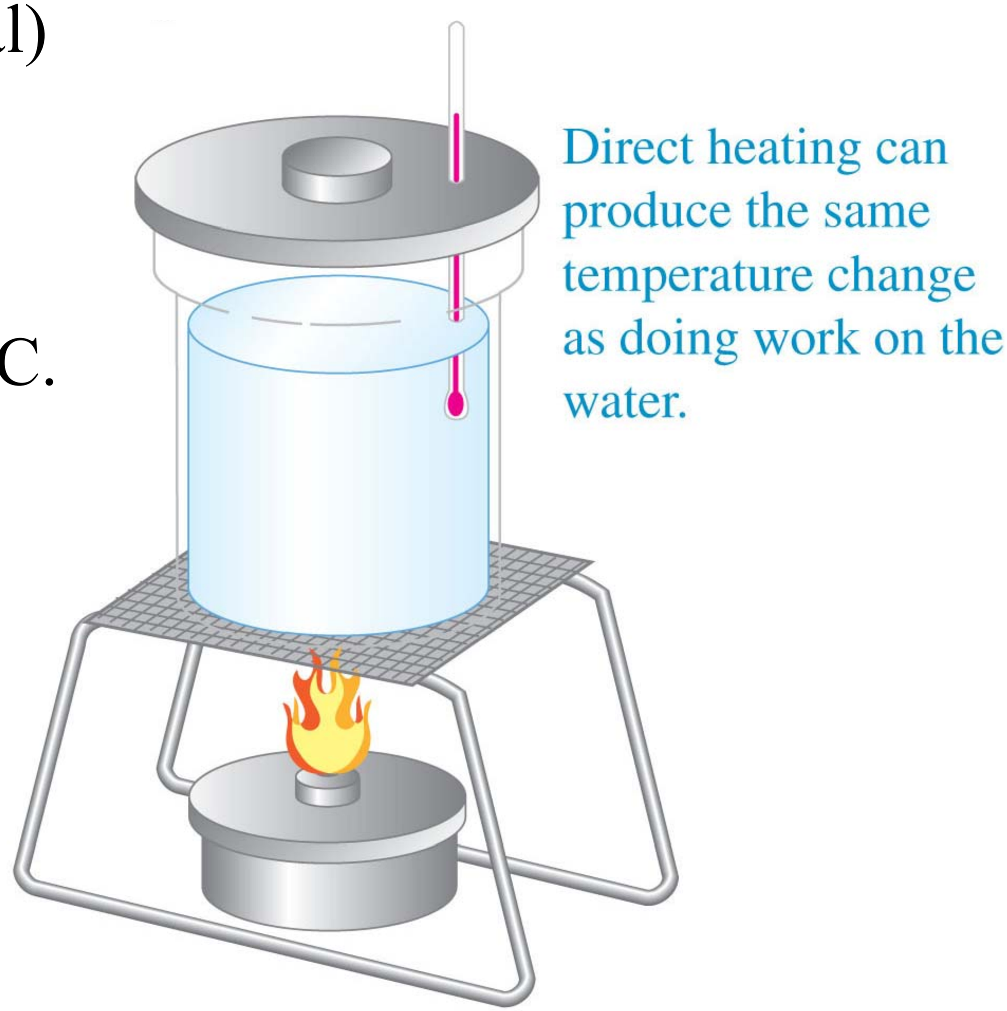
Quantity of heat

- Sir James Joule (1818–1889) studied how water can be warmed by vigorous stirring with a paddle wheel.



Quantity of heat

- The same temperature change caused by stirring can also be caused by putting the water in contact with some hotter body.
- The **calorie** (abbreviated cal) is the amount of heat required to raise the temperature of 1 gram of water from 14.5°C to 15.5°C.



Specific heat

- The quantity of heat Q required to increase the temperature of a mass m of a certain material by ΔT is:

Heat required to change temperature of a certain mass

Mass of material

$$Q = mc\,\Delta T$$

Temperature change

Specific heat of material

- The **specific heat** c has different values for different materials.
- The specific heat of water is approximately 4190 J/kg · K.

Molar heat capacity

- The quantity of heat Q required to increase the temperature of n moles of a certain material by ΔT is:

Heat required to change temperature of a certain number of moles $\cdots\rightarrow$

$$Q = nC\,\Delta T$$

Number of moles of material

Temperature change

Molar heat capacity of material

- The **molar heat capacity** C has different values for different materials.

- The molar heat capacity of water is approximately 75.4 J/mol · K.

Table 17.3: Specific heats and molar heat capacities

Substance	Specific Heat, c (J/kg · K)	Molar Mass, M (kg/mol)	Molar Heat Capacity, C (J/mol · K)
Aluminum	910	0.0270	24.6
Beryllium	1970	0.00901	17.7
Copper	390	0.0635	24.8
Ethanol	2428	0.0461	111.9
Ethylene glycol	2386	0.0620	148.0
Ice (near 0°C)	2100	0.0180	37.8
Iron	470	0.0559	26.3
Lead	130	0.207	26.9
Marble ($CaCO_3$)	879	0.100	87.9
Mercury	138	0.201	27.7
Salt (NaCl)	879	0.0585	51.4
Silver	234	0.108	25.3
Water (liquid)	4190	0.0180	75.4

Q17.5

You wish to increase the temperature of a 1.00-kg block of a certain solid substance from 20° C to 25° C. (The block remains solid as its temperature increases.) To calculate the amount of heat required to do this, you need to know

A. the specific heat of the substance.

B. the molar heat capacity of the substance.

C. the heat of fusion of the substance.

D. the thermal conductivity of the substance.

E. more than one of the above.

Phase changes

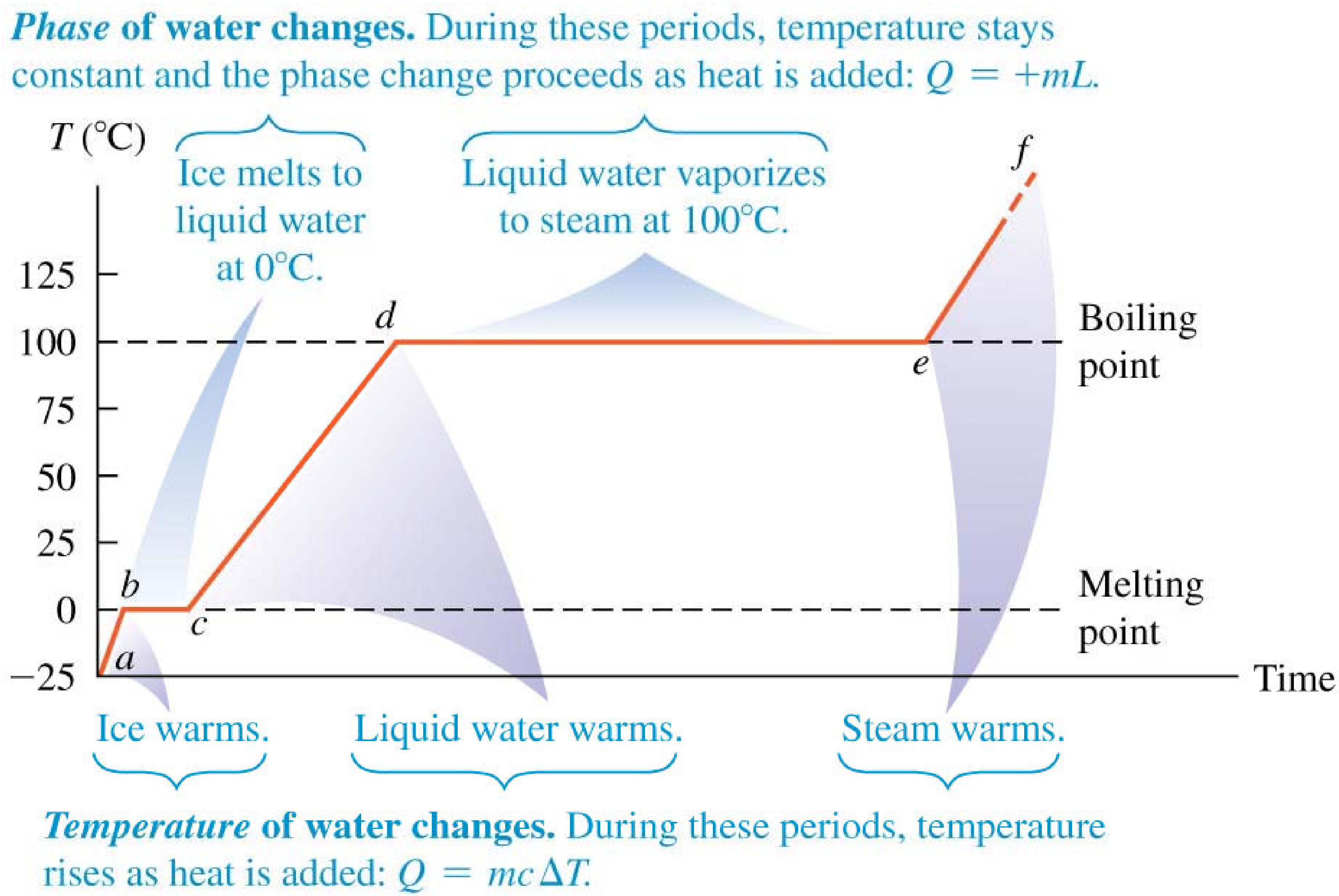
- The **phases** (or states) of matter are solid, liquid, and gas.
- A **phase change** is a transition from one phase to another.
- The temperature does not change during a phase change.
- The **latent heat**, L, is the heat per unit mass that is transferred in a phase change.

Mass of material that changes phase

Heat transfer in a phase change $Q = \pm mL$ Latent heat for this phase change

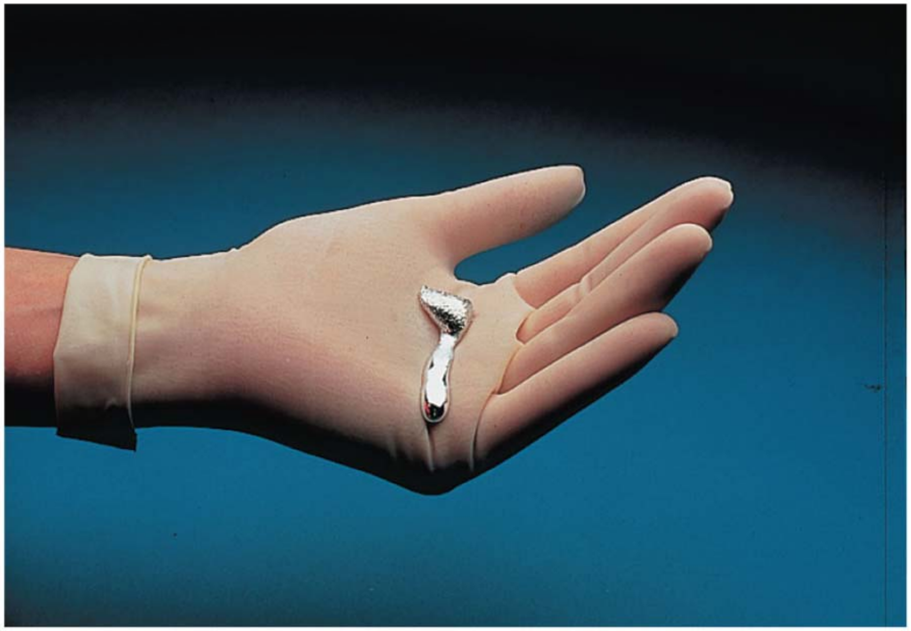
+ if heat enters material, − if heat leaves

Heat added to ice at a constant rate



Heat of fusion

- The metal gallium, shown here melting in a person's hand, is one of the few elements that melts at room temperature.



- Its melting temperature is 29.8°C, and its **heat of fusion** is $L_f = 8.04 \times 10^4$ J/kg.

Heat of vaporization

- The water may be warm and it may be a hot day, but these children will feel cold when they first step out of the swimming pool.
- That's because as water evaporates from their skin, it removes the **heat of vaporization** from their bodies.
- To stay warm, they will need to dry off immediately.

Heat of fusion and vaporization

TABLE 17.4 Heats of Fusion and Vaporization

Substance	Normal Melting Point K	Normal Melting Point °C	Heat of Fusion, L_f (J/kg)	Normal Boiling Point K	Normal Boiling Point °C	Heat of Vaporization, L_v (J/kg)
Helium	*	*	*	4.216	−268.93	20.9×10^3
Hydrogen	13.84	−259.31	58.6×10^3	20.26	−252.89	452×10^3
Nitrogen	63.18	−209.97	25.5×10^3	77.34	−195.8	201×10^3
Oxygen	54.36	−218.79	13.8×10^3	90.18	−183.0	213×10^3
Ethanol	159	−114	104.2×10^3	351	78	854×10^3
Mercury	234	−39	11.8×10^3	630	357	272×10^3
Water	273.15	0.00	334×10^3	373.15	100.00	2256×10^3
Sulfur	392	119	38.1×10^3	717.75	444.60	326×10^3
Lead	600.5	327.3	24.5×10^3	2023	1750	871×10^3
Antimony	903.65	630.50	165×10^3	1713	1440	561×10^3
Silver	1233.95	960.80	88.3×10^3	2466	2193	2336×10^3
Gold	1336.15	1063.00	64.5×10^3	2933	2660	1578×10^3
Copper	1356	1083	134×10^3	1460	1187	5069×10^3

*A pressure in excess of 25 atmospheres is required to make helium solidify. At 1 atmosphere pressure, helium remains a liquid down to absolute zero.

Q17.6

A pitcher contains 0.50 kg of liquid water at 0° C and 0.50 kg of ice at 0° C. You let heat flow into the pitcher until there is 0.75 kg of liquid water and 0.25 kg of ice. During this process, the temperature of the ice-water mixture

A. increases slightly.

B. decreases slightly.

C. first increases slightly, then decreases slightly.

D. remains the same.

E. The answer depends on the rate at which heat flows.

Exercises

1. You have 750 g of water at 10ºC in a large insulated beaker. How much boiling water at 100ºC must you add to this beaker so that the final temperature of the mixture will be 75ºC?

2. How much heat is required to convert 18.0 g of ice at -10.0ºC to steam at 100.0ºC? Express your answer in joules, calories.

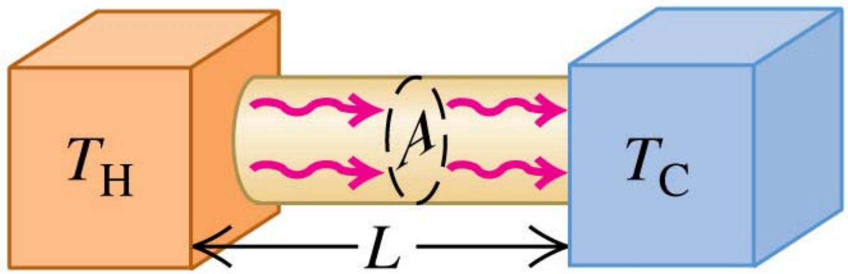
3. A copper pot with a mass of 0.500 kg containing 0.170 kg of water, and both are at 20.0 ºC. A 0.250-kg block of iron at 85.0ºC is dropped into the pot. Find the final temperature of the system, assuming no heat loss to the surroundings.

Mechanisms of heat transfer

- In nature, energy naturally flows from higher temperature objects to lower temperature objects; this is called **heat transfer**.
- The three mechanisms of heat transfer are **conduction**, **convection**, and **radiation**.
- *Conduction* occurs within a body or between two bodies in contact.
- *Convection* depends on motion of mass from one region of space to another.
- *Radiation* is heat transfer by electromagnetic radiation, such as sunshine, with no need for matter to be present in the space between bodies.

Conduction of heat

- In conduction, heat flows from a higher to a lower temperature.
- Consider a solid rod of conducting material with cross-sectional area A and length L.
- The left end of the rod is kept at a temperature T_H and the right end at a lower temperature T_C.



- The rate that heat is transferred is:

Rate of heat flow

Temperatures of hot and cold ends of rod

Heat current in conduction

$$H = \frac{dQ}{dt} = kA\frac{T_H - T_C}{L}$$

Length of rod

Thermal conductivity of rod material

Cross-sectional area of rod

Thermal conductivities of some common substances

Substance	***k*** **(W/m · K)**
Silver	406
Copper	385
Aluminum	205
Wood	0.12 – 0.04
Concrete	0.8
Fiberglass	0.04
Styrofoam	0.027

Q17.7

A chair has a wooden seat but metal legs. The chair legs feel colder to the touch than does the seat. Why is this?

A. The metal is at a lower temperature than the wood.

B. The metal has a higher specific heat than the wood.

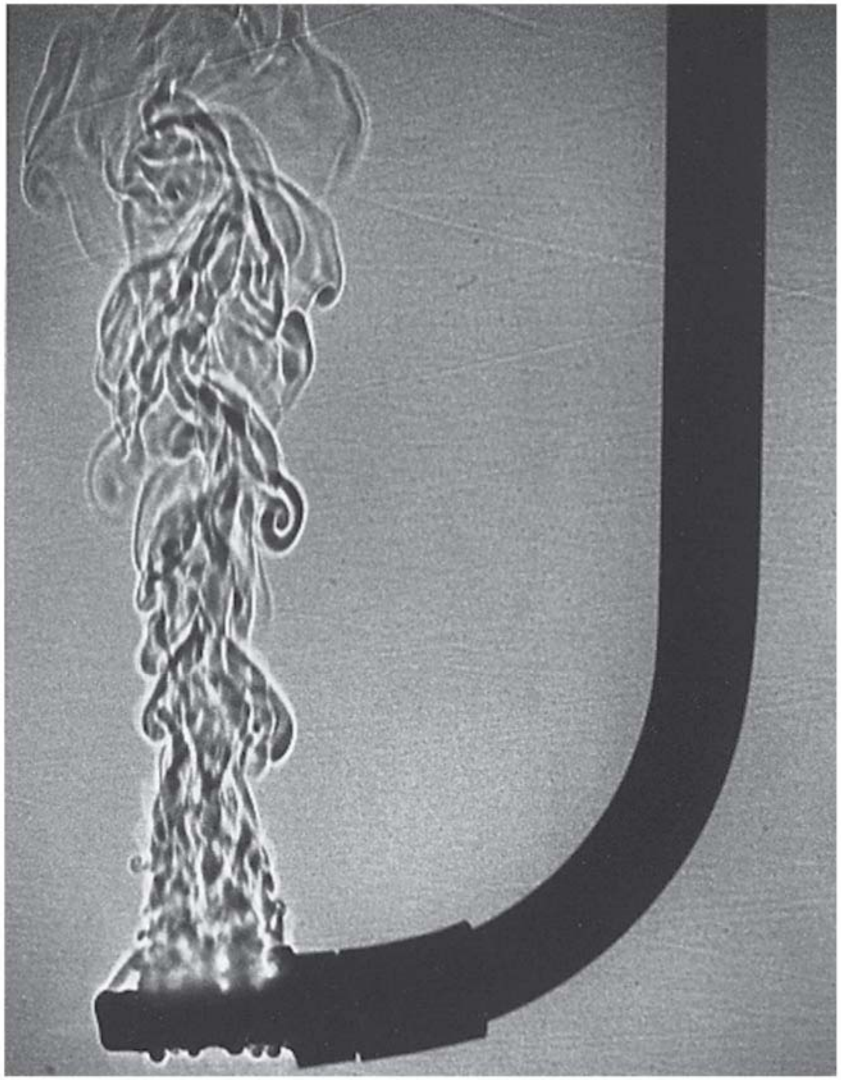
C. The metal has a lower specific heat than the wood.

D. The metal has a higher thermal conductivity than the wood.

E. The metal has a lower thermal conductivity than the wood.

Convection of heat

- **Convection** is the transfer of heat by the mass motion of fluid.
- A heating element in the tip of this submerged tube warms the surrounding water, producing a complex pattern of free convection.



Radiation of heat

- **Radiation** is the transfer of heat by electromagnetic waves, such as visible light or infrared.
- This false-color infrared photograph reveals radiation emitted by various parts of the man's body.

- The strongest emission comes from the warmest areas, while there is very little emission from the bottle of cold beverage.
- **Stefan-Boltzmann law**: The *heat current* in radiation is:

Area of emitting surface

Heat current in radiation

Emissivity of surface

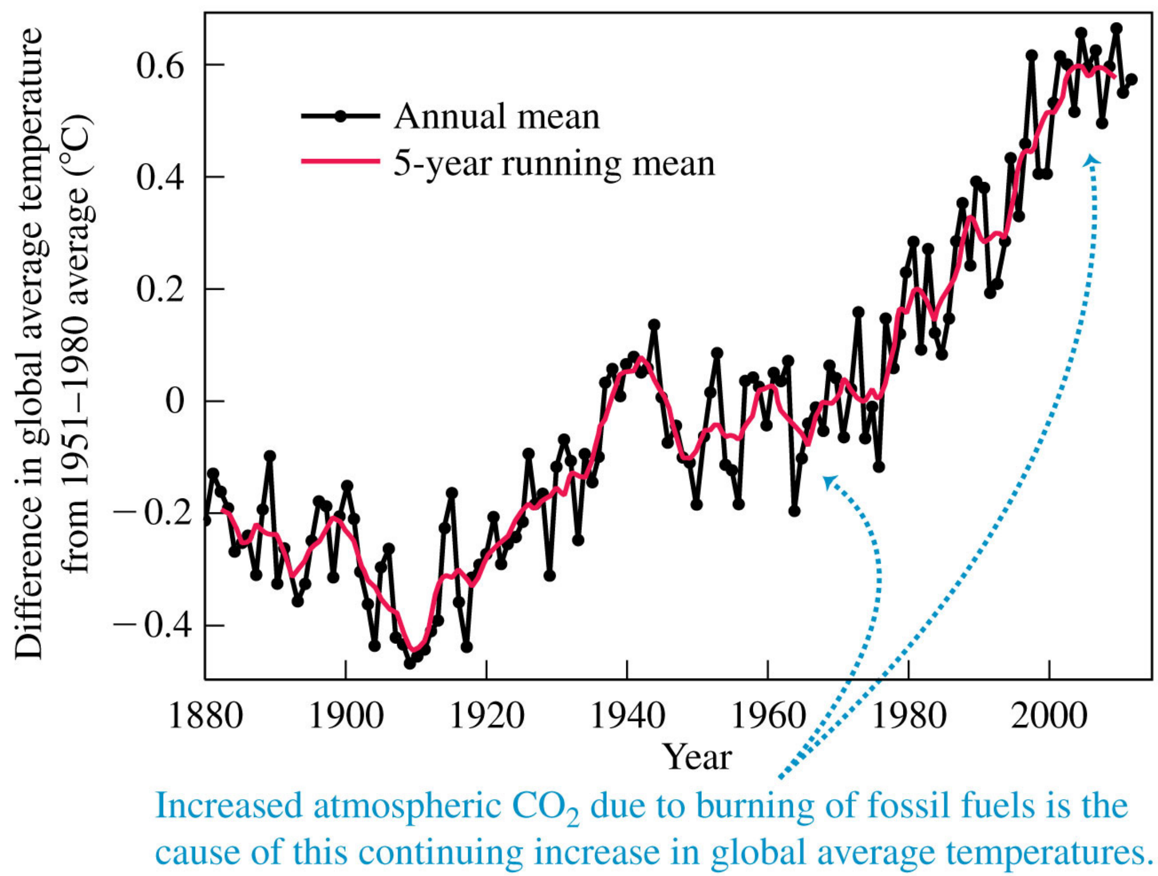
$$H = Ae\sigma T^4$$

Absolute temperature of surface

Stefan–Boltzmann constant

Radiation and climate change

- The energy radiated by the earth's surface is mostly infrared.
- CO_2 molecules in our atmosphere readily absorb some of this infrared radiation and reradiate part of it back down toward the surface.



Exercises

1. One end of an insulated metal rod is maintained at 100.0ºC, and the other end is maintained at 0.00ºC by an ice-water mixture. The rod is 60.0 cm long and has a cross-sectional area of 1.25 cm^2. The heat conducted by the rod melts 8.50 g of ice in 10.0 min. Find the thermal conductivity of the metal.

2. A spherical pot contains 0.75 L of hot coffee (essentially water) at an initial temperature of 95ºC. The pot has an emissivity of 0.60, and the surroundings are at 20.0ºC. Calculate the coffee's rate of heat loss by radiation.