Chapter 12

Temperature and Heat

continued

THE IDEAL GAS LAW

The absolute pressure of an ideal gas is directly proportional to the Kelvin temperature and the number of moles (n) of the gas and is inversely proportional to the volume of the gas.

$$P = \frac{nRT}{V}$$

$$\boxed{PV = nRT}$$

$$\boxed{R = 8.31\ \mathrm{J}/(\mathrm{mol}\cdot\mathrm{K})}$$

Another form for the Ideal Gas Law using the number of atoms (N)

$$PV = nRT$$

$$= N\left(\frac{R}{N_A}\right)T$$

$$\boxed{N = nN_A}$$

$$\boxed{PV = Nk_BT}$$

Boltzmann's constant

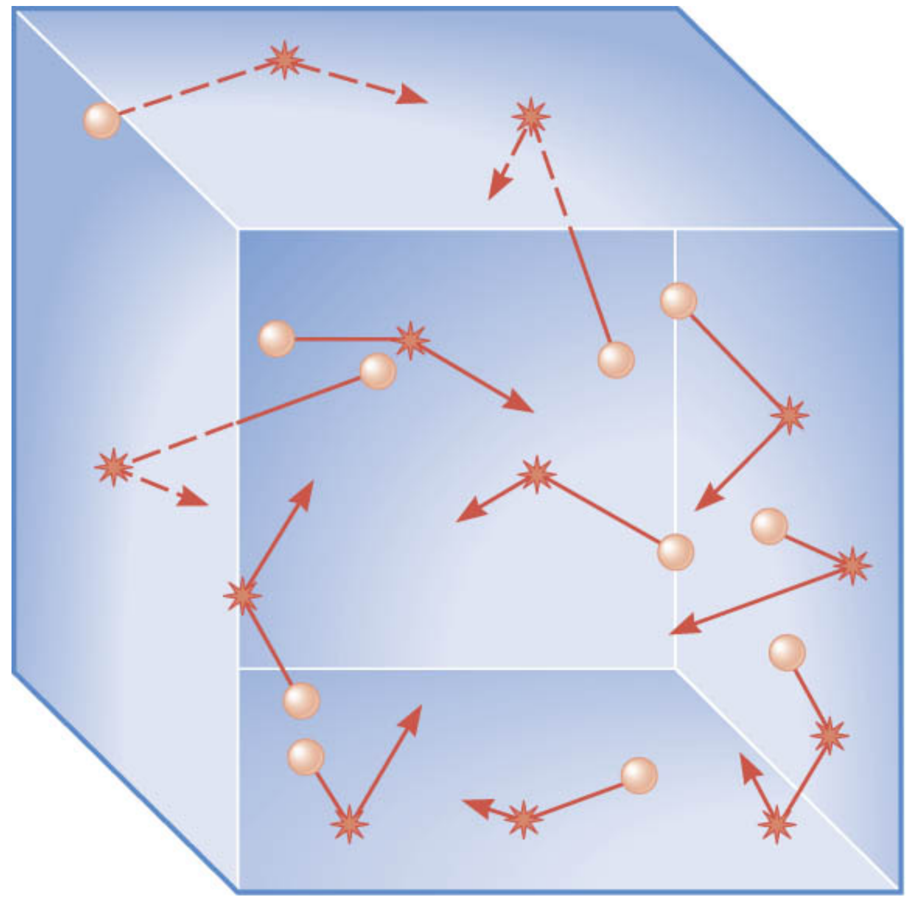
$$\boxed{k_B = \frac{R}{N_A} = \frac{8.31\,\mathrm{J}/(\mathrm{mol}\cdot\mathrm{K})}{6.022\times10^{23}\mathrm{mol}^{-1}} = 1.38\times10^{-23}\ \mathrm{J}/\mathrm{K}}$$

When temperature is involved, a letter $k = k_B$, Boltzmann's constant

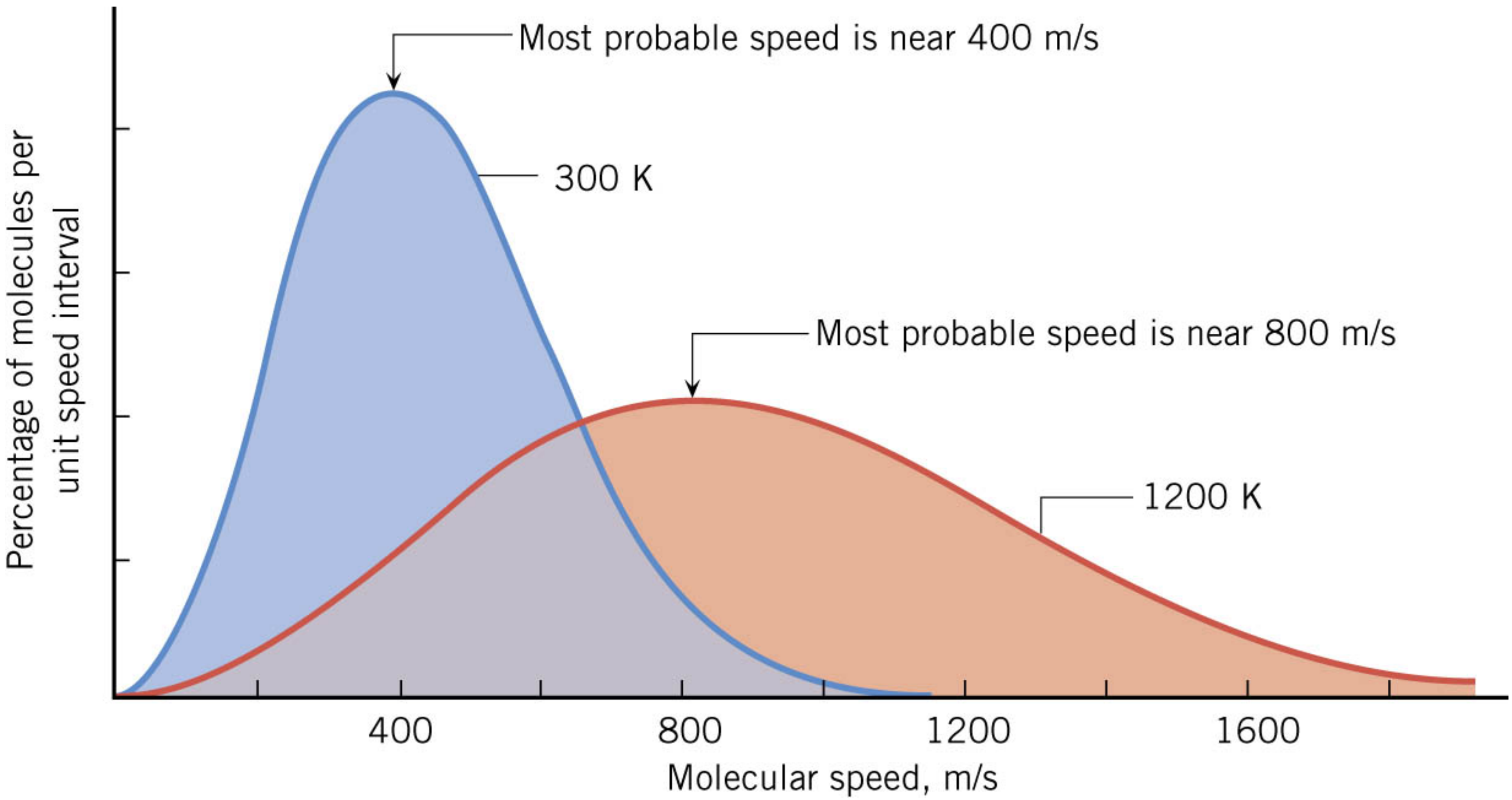
The particles are in constant, random motion, colliding with each other and with the walls of the container.

Each collision changes the particle's speed.

As a result, the atoms and molecules have different speeds.

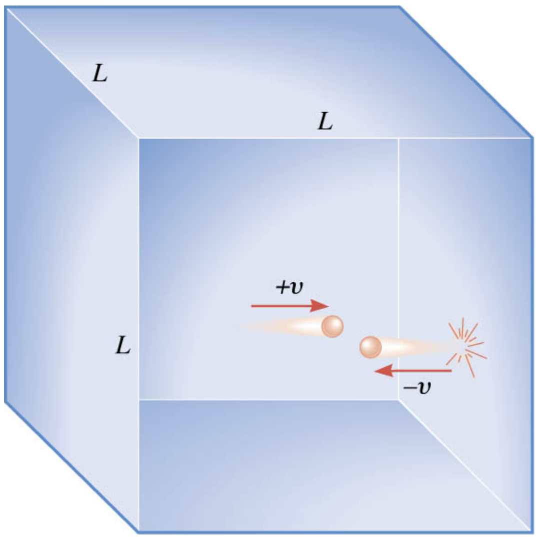


THE DISTRIBUTION OF MOLECULAR SPEEDS



12.4 Kinetic Theory of Gases

KINETIC THEORY



$$\sum F = ma = m\frac{\Delta v}{\Delta t} = \frac{\Delta(mv)}{\Delta t}$$

Average force on each gas molecule when hitting the wall

$$= \frac{\text{Final momentum-Initial momentum}}{\text{Time between successive collisions}}$$

$$= \frac{(-mv)-(+mv)}{2L/v} = \frac{-mv^2}{L}$$

$\boxed{\text{Average force on a wall}}$ $\quad \overline{F} = \left(\frac{N}{3}\right)\left(\frac{m\overline{v^2}}{L}\right) \Rightarrow P = \frac{\overline{F}}{A} = \frac{\overline{F}}{L^2} = \left(\frac{N}{3}\right)\left(\frac{m\overline{v^2}}{L^3}\right)$

$$PV = \left(\frac{N}{3}\right)m\overline{v^2} = \tfrac{2}{3}N\left(\tfrac{1}{2}m\overline{v^2}\right)$$

$\boxed{PV = NkT}$ $\quad \boxed{\overline{KE} = \tfrac{1}{2}m\overline{v^2}}$ $\quad \boxed{v_{rms} = \sqrt{\overline{v^2}}}$ root mean square speed

$\boxed{\text{Temperature reflects the }\underline{\text{average}}\text{ Kinetic Energy of the molecules}}$

$$\boxed{\tfrac{3}{2}kT = \tfrac{1}{2}mv_{rms}^2 = \overline{KE}} \qquad \boxed{k = 1.38\times10^{-23}\ \mathrm{J/K}}$$

Example: The Speed of Molecules in Air

Air is primarily a mixture of nitrogen N_2 molecules (molecular mass 28.0u) and oxygen O_2 molecules (molecular mass 32.0u). Assume that each behaves as an ideal gas and determine the rms speeds of the nitrogen and oxygen molecules when the temperature of the air is 293K.

$$\tfrac{1}{2} m v_{rms}^2 = \tfrac{3}{2} kT$$

$$\boxed{v_{rms} = \sqrt{\frac{3kT}{m}}}$$

T must be in Kelvin
$(\mathrm{K} = \mathrm{C}° + 273)$

$$\boxed{\begin{aligned} &\underline{\text{Nitrogen molecule}} \\ m &= \frac{28.0\,\mathrm{g/mol}}{6.022\times10^{23}\,\mathrm{mol^{-1}}} \\ &= \underline{4.65\times10^{-26}\,\mathrm{kg}} \end{aligned}}$$

$$v_{rms} = \sqrt{\frac{3kT}{m}}$$

$$= \sqrt{\frac{3\left(1.38\times10^{-23}\,\mathrm{J/K}\right)\left(293\,\mathrm{K}\right)}{4.65\times10^{-26}\,\mathrm{kg}}} = 511\,\mathrm{m/s}$$

Molecules are moving <u>really fast</u>
but do not go very far before hitting another molecule.

THE INTERNAL ENERGY OF A MONO-ATOMIC IDEAL GAS

$$\overline{\mathrm{KE}} = \tfrac{1}{2} m v_{rms}^2 = \tfrac{3}{2} kT$$

Average KE per atom

$$\Big\Downarrow \text{ multiply by the number of atoms}$$

$$U = N \tfrac{3}{2} kT = \tfrac{3}{2} nRT$$

Total Internal Energy

THE INTERNAL ENERGY OF A MOLECULAR GAS MUST INCLUDE MOLECULAR VIBRATIONS!

$$\mathrm{H_2, N_2, H_2O, SO_2, CO_2,}\ \ldots\text{(most gases except Nobel gases)}$$

Chapter 13

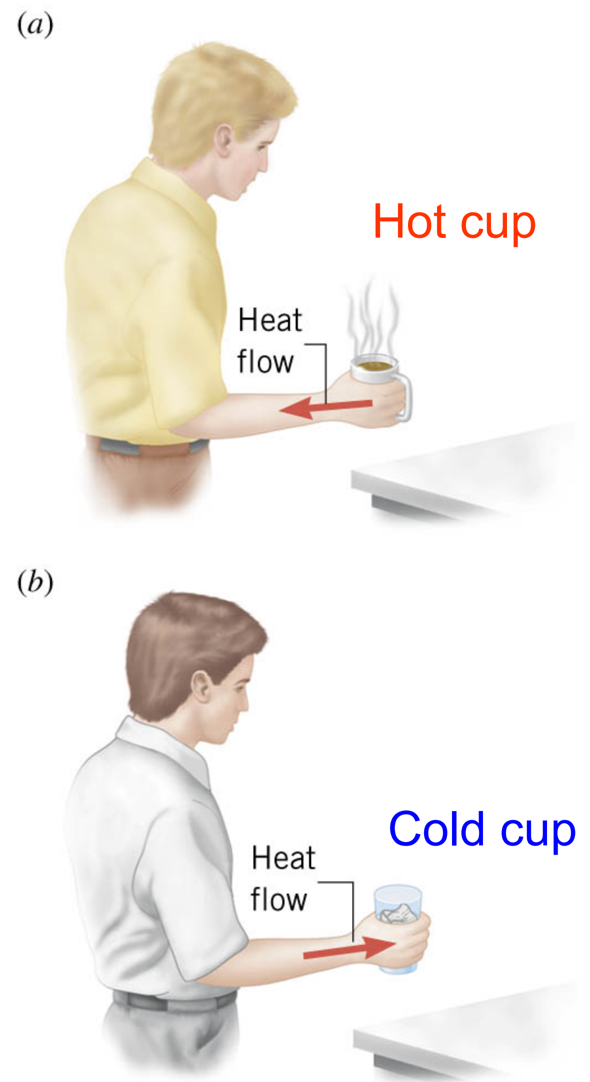
Heat

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)

> 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. You must use the word energy or internal energy.



13.2 Heat and Temperature Change: Specific Heat Capacity

Temperature of an object reflects the amount of internal energy within it. But objects with the same temperature and mass can have DIFFERENT amounts of internal energy!

SOLIDS AND LIQUIDS (GASES ARE DIFFERENT)

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

$$\boxed{Q = mc\Delta T}$$

c, is the specific heat capacity of the substance

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

$$\boxed{\Delta T > 0, \text{ Heat added}} \qquad \boxed{\Delta T < 0, \text{ Heat removed}}$$

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.

Specific means per unit mass

Example: A Hot Jogger

In a half-hour, a 65-kg jogger produces 8.0×10^5 J of heat. This heat is removed from the body by a variety of means, including sweating, one of the body's own temperature-regulating mechanisms. If the heat were not removed, how much would the body temperature increase?

$$Q = mc\Delta T$$

$$\Delta T = \frac{Q}{mc} = \frac{8.0\times10^5\,\text{J}}{(65\text{ kg})\left[3500\,\text{J}/(\text{kg}\cdot\text{C}^\circ)\right]} = 3.5\text{ C}^\circ$$

OTHER UNITS for heat production

1 cal = 4.186 joules (calorie)

1 kcal = 4186 joules ([kilo]calories for food)

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.

13.2 Specific Heat Capacities (Gases)

To relate heat and temperature change in solids and liquids (mass in kg), use:

$$\boxed{Q = mc\Delta T} \qquad \text{specific heat capacity, } c \quad \left[\mathrm{J}/\left(\mathrm{kg}\cdot{}^\circ\mathrm{C}\right)\right]$$

For gases, the amount of gas is given in moles, use molar heat capacities:

$$\boxed{Q = nC\Delta T} \qquad \text{molar heat capacity, } C \quad \left[\mathrm{J}/\left(\mathrm{mole}\cdot{}^\circ\mathrm{C}\right)\right]$$

$$\boxed{C = \left(m/n\right)c = m_u c; \quad m_u = \text{mass/mole (kg)}}$$

ALSO, for gases it is necessary to distinguish between the molar specific heat capacities at constant pressure and at constant volume:

$$C_P, C_V$$

Constant pressure for a monatomic ideal gas

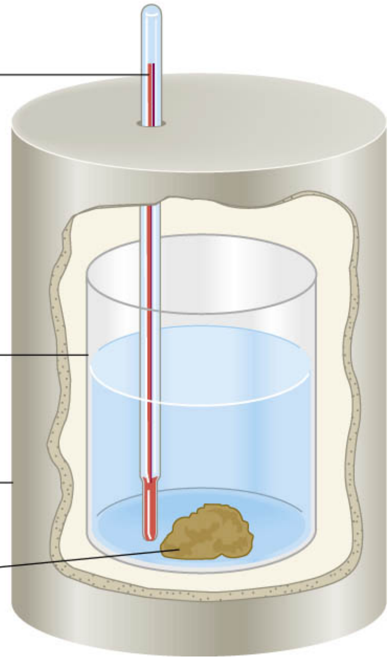
$$\boxed{\begin{aligned} Q_P &= nC_P\Delta T \\ C_P &= \tfrac{5}{2}R \end{aligned}}$$

Constant volume for a monatomic ideal gas

$$\boxed{\begin{aligned} Q_V &= nC_V\Delta T \\ C_V &= \tfrac{3}{2}R \end{aligned}}$$

any ideal gas

$$\boxed{C_P - C_V = R}$$



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. Net heat change equals zero.

A calorimeter is made of 0.15 kg of aluminum and contains 0.20 kg of water, both at 18.0 C°. A mass, 0.040 kg at 97.0 C° is added to the water, causing the water temperature to rise to 22.0 C°. What is the specific heat capacity of the mass?

Water and Al rise in temperature ($\Delta T > 0$)

Unknown stuff drops in temperature ($\Delta T < 0$)

$$\Delta T_{\mathrm{w}} = \Delta T_{\mathrm{Al}} = +4\,^\circ\mathrm{C}; \quad \Delta T_{\mathrm{Unk}} = -75\,^\circ\mathrm{C}$$

Al ≡ Aluminum, W ≡ water, Unk ≡ unknown

$$c_{\mathrm{Al}} = 900\ \mathrm{J/kg\cdot C^\circ}$$
$$c_{\mathrm{W}} = 4190\ \mathrm{J/kg\cdot C^\circ}$$

Net heat change equals zero.

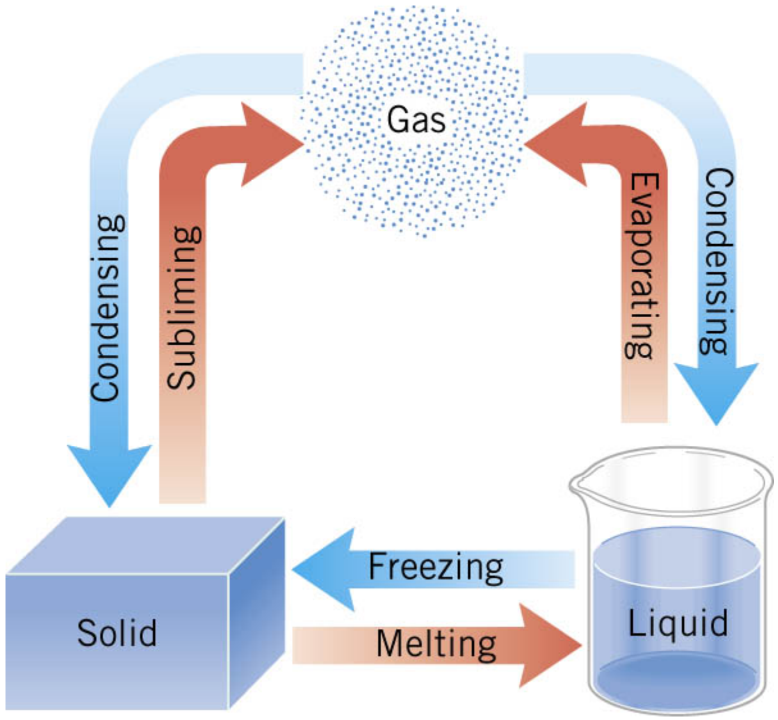
$$\sum Q = m_{\mathrm{Al}} c_{\mathrm{Al}} \Delta T_{\mathrm{Al}} + m_{\mathrm{W}} c_{\mathrm{W}} \Delta T_{\mathrm{W}} + m_{\mathrm{Unk}} c_{\mathrm{Unk}} \Delta T_{\mathrm{Unk}} = 0$$

Three heat changes must sum to zero

$$c_{\mathrm{Unk}} = 1.3\times 10^{3}\ \mathrm{J/(kg\cdot C^\circ)}$$

13.3 ***Heat and Phase Change: Latent Heat***

THE PHASES OF MATTER



There is internal energy added or removed in a change of phase.

Typically, solid —> liquid (melt) or liquid —> gas (evaporate) requires heat energy to be ADDED.

Typically, gas—>liquid (condense), or liquid —> solid (freeze) requires heat energy to be REMOVED.

HEAT ADDED 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 the "latent heat", *L* :

$$\boxed{Q = mL}$$

SI Units of Latent Heat: J/kg

13.3 Heat and Phase Change: Latent Heat

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.

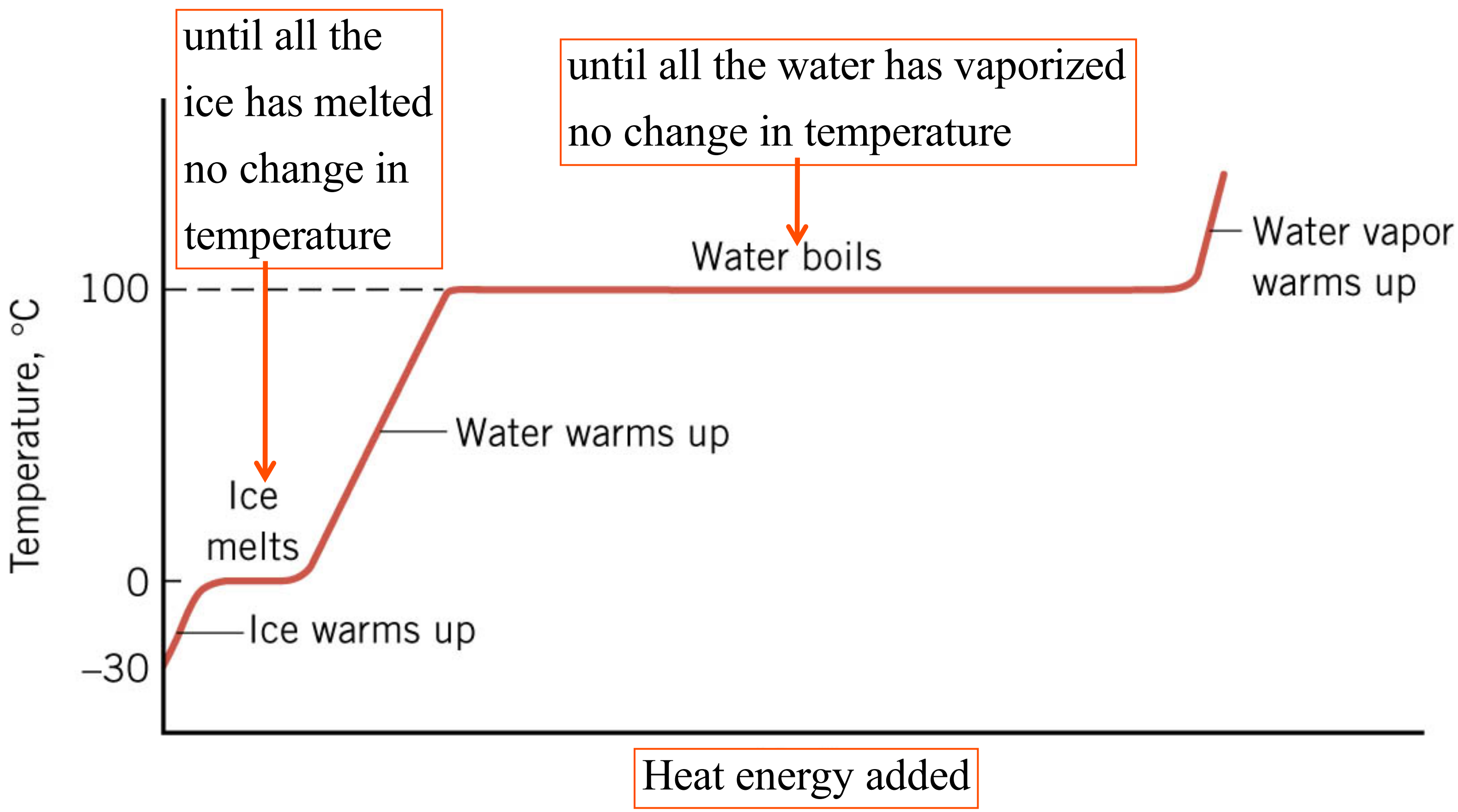
Add heat: Ice $\rightarrow$ Water $\quad L_f > 0$

Remove heat: Water $\rightarrow$ Ice $\quad L_f < 0$

Add heat: Water $\rightarrow$ Vapor $\quad L_v > 0$

Remove heat: Vapor $\rightarrow$ Water $\quad L_v < 0$

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



Example Ice-cold Lemonade

Ice at 0°C is placed in a Styrofoam cup containing 0.32 kg of lemonade at 27°C. Assume that mass of the cup is very small and lemonade behaves like water.

After ice is added, the ice and lemonade reach an equilibrium temperature (*T* = 0 C°) with some ice remaining. How much ice melted?

Heat redistributes.

No heat added or lost.

$$\sum Q = \underbrace{m_I L_I}_{\text{Heat for Ice} \to \text{Water}} + \underbrace{m_W c_W \Delta T_W}_{\text{Heat change of lemondate}} = 0$$

$$\Delta T_W = -27\ \mathrm{C}^\circ$$

$$m_I L_I + m_W c_W \Delta T_W = 0$$

$$m_I = \frac{-m_W c_W \Delta T_W}{L_I}$$

$$= \frac{-(0.32\mathrm{kg})(4.19\times 10^3 \mathrm{J/kg\cdot C^\circ})(-27\mathrm{C}^\circ)}{33.5\times 10^4 \mathrm{J/kg}} = 0.110\ \mathrm{kg}$$

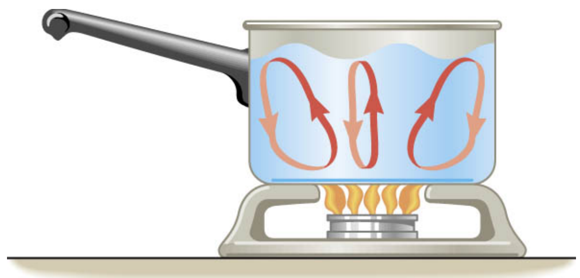
Chapter 13

The Transfer of Heat

CONVECTION, CONDUCTION, RADIATION

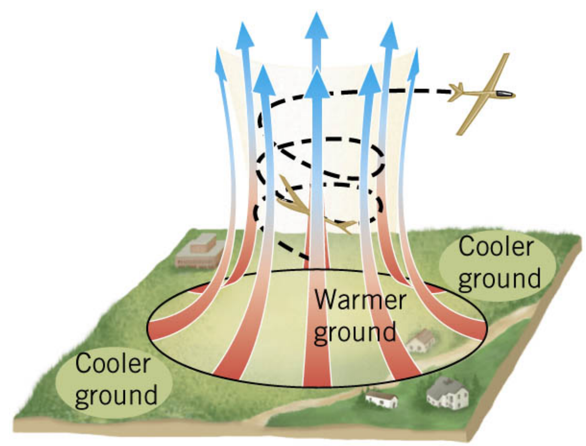
CONVECTION

Heat carried by the bulk movement of a fluid.

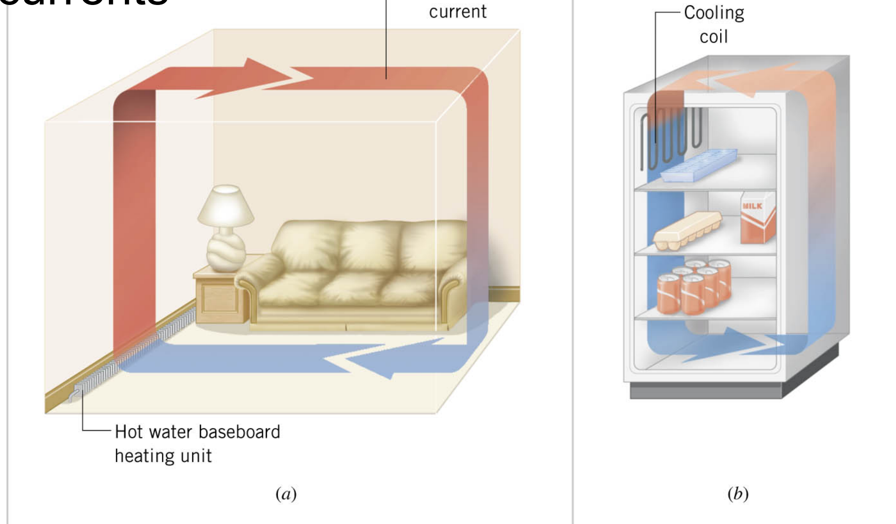


Convection
fluid currents

Convection
air currents



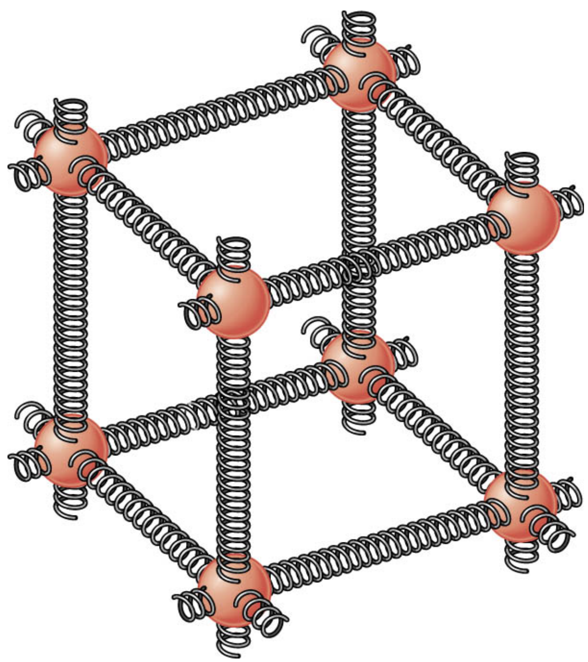
Convection
air currents



CONDUCTION

Heat transferred directly through a material, but not via bulk motion.

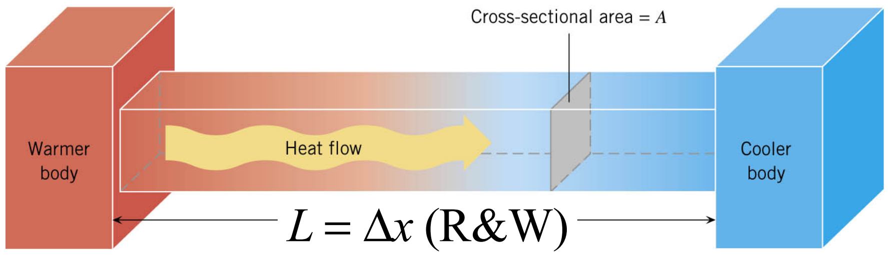
One mechanism for conduction occurs when the atoms or molecules in a hotter part of the material vibrate with greater energy than those in a cooler part. Though the atomic forces, the more energetic molecules pass on some of their energy to their less energetic neighbors.



Model of solid materials.
Atoms connected by atomic spring-like forces.

Materials that conduct heat well are called ***thermal conductors***, and those that conduct heat poorly are called ***thermal insulators.***

CONDUCTION OF HEAT THROUGH A MATERIAL



The heat Q conducted during a time t through a bar of length L and cross-sectional area A is

$$\boxed{Q = \frac{(kA\Delta T)t}{L}}$$

k, is the thermal conductivity

SI Units of Thermal Conductivity:
J/(s·m·C°) (joule per second-meter-C°)

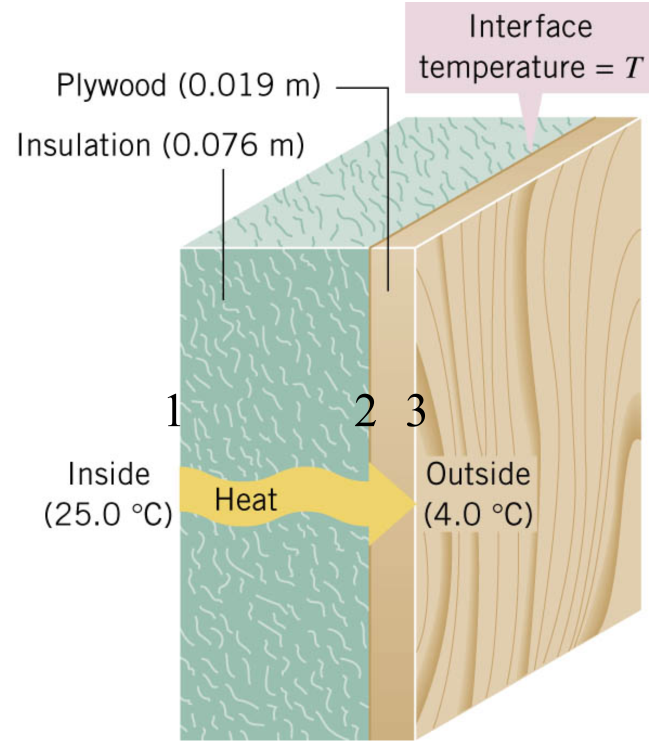
$$\boxed{H = \frac{Q}{t}}$$

Thermal Conductivities[a] of Selected Materials

Substance	Thermal Conductivity, k [J/(s·m·C°)]
Metals	
Aluminum	240
Brass	110
Copper	390
Iron	79
Lead	35
Silver	420
Steel (stainless)	14
Gases	
Air	0.0256
Hydrogen (H_2)	0.180
Nitrogen (N_2)	0.0258
Oxygen (O_2)	0.0265
Other Materials	
Asbestos	0.090
Body fat	0.20
Concrete	1.1
Diamond	2450
Glass	0.80
Goose down	0.025
Ice (0 °C)	2.2
Styrofoam	0.010
Water	0.60
Wood (oak)	0.15
Wool	0.040

[a] Except as noted, the values pertain to temperatures near 20 °C.

Example Layered insulation



One wall of a house consists of plywood backed by insulation. The thermal conductivities of the insulation and plywood are, respectively, 0.030 and 0.080 J/(s·m·C°), and the area of the wall is 35m^2.

Find the amount of heat conducted through the wall in one hour.

Note: Heat passing through insulation is the the same heat passing through plywood.

$$Q_{\text{insulation}} = Q_{12}; \quad Q_{\text{plywood}} = Q_{23}$$

$$T_1 = 25\text{C}°, T_3 = 4\text{C}°, T_2 \text{ is unknown}$$

First solve for the interface temperature using:

$$\boxed{\begin{aligned} Q_{12} &= Q_{23} \\ T_2 &= 5.8\text{C}° \\ \Delta T_{12} &= (25 - 5.8)\text{C}° = 19.2\text{ C}° \end{aligned}}$$

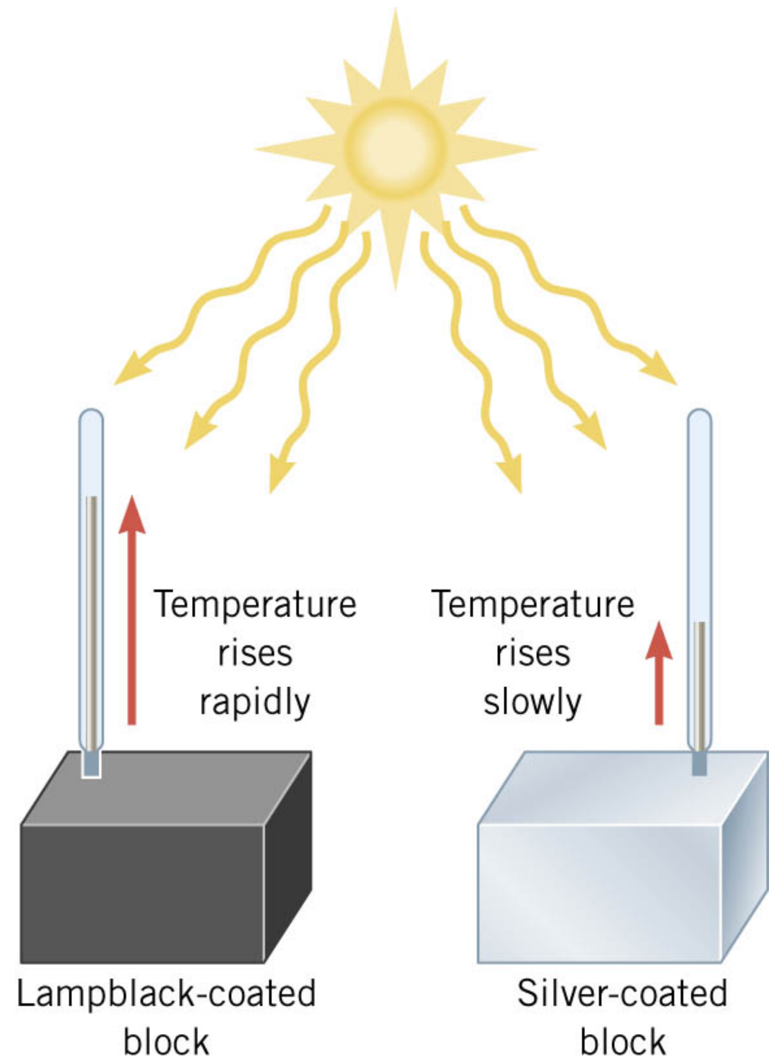
$$\boxed{\begin{aligned} Q_{12} &= \frac{(k_{12} A \Delta T_{12})t}{L_{12}} = \frac{.03(35)(19.2)3600}{.076}\text{J} \\ &= 9.5 \times 10^5\text{J} \end{aligned}}$$

RADIATION

Radiation is the process in which energy is transferred by means of electromagnetic waves.

A material that is a good absorber is also a good emitter.

A material that absorbs completely is called a ***perfect blackbody***.



THE STEFAN-BOLTZMANN LAW OF RADIATION

The radiant energy *Q*, emitted in a time *t* by an object that has a Kelvin temperature *T*, a surface area *A*, and an emissivity *e*, is given by

$$\boxed{Q = e\sigma T^4 At}$$

$$\boxed{\begin{array}{l}\text{emissivity } e = \text{constant between 0 to 1} \\ e = 1 \text{ (perfect black body emitter)}\end{array}}$$

$$\boxed{\begin{array}{l}\text{Stefan-Boltzmann constant} \\ \sigma = 5.67\times10^{-8}\ \mathrm{J}/\left(\mathrm{s}\cdot\mathrm{m}^2\cdot\mathrm{K}^4\right)\end{array}}$$

Example **A Supergiant Star**

The supergiant star Betelgeuse has a surface temperature of about 2900 K and emits a power of approximately 4x10^{30} W. Assuming Betelgeuse is a perfect emitter and spherical, find its radius.

$$\text{power, } P = \frac{Q}{t}$$

with $A = 4\pi r^2$ (surface area of sphere with radius r)

$$r = \sqrt{\frac{Q/t}{4\pi e\sigma T^4}} = \sqrt{\frac{4\times10^{30}\,\mathrm{W}}{4\pi(1)\left[5.67\times10^{-8}\ \mathrm{J}/\left(\mathrm{s}\cdot\mathrm{m}^2\cdot\mathrm{K}^4\right)\right](2900\ \mathrm{K})^4}}$$

$$= 3\times10^{11}\,\mathrm{m}$$