Chapter 12

Kinetic Theory

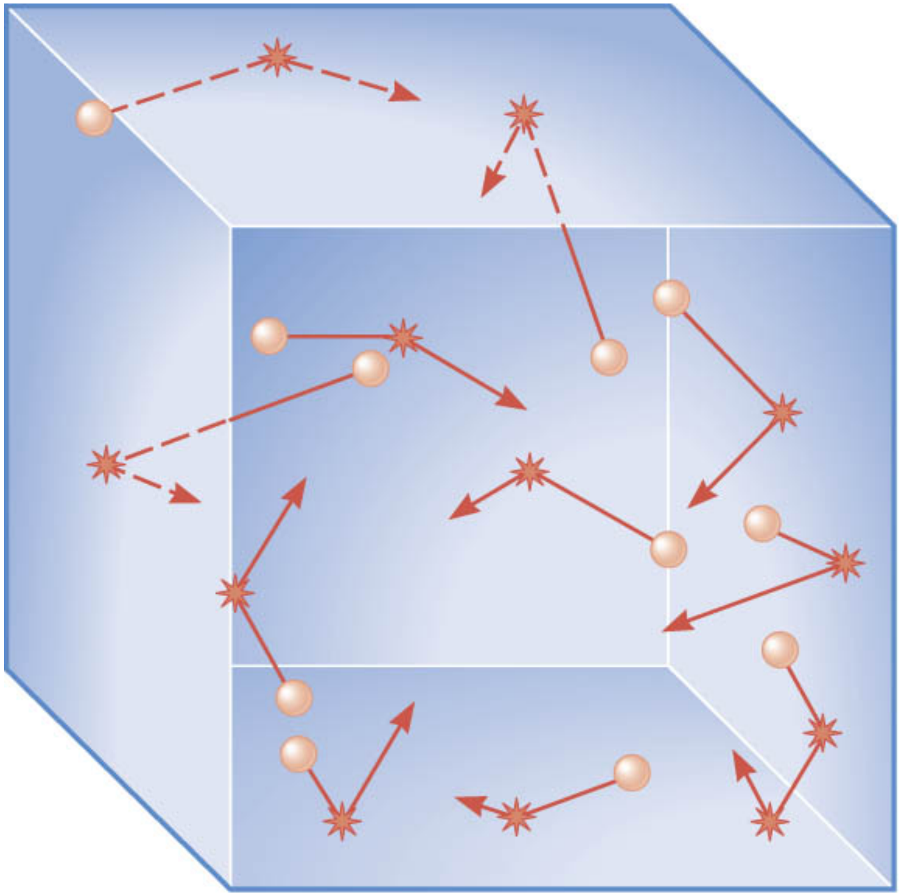
continued

12.4 Kinetic Theory of Gases

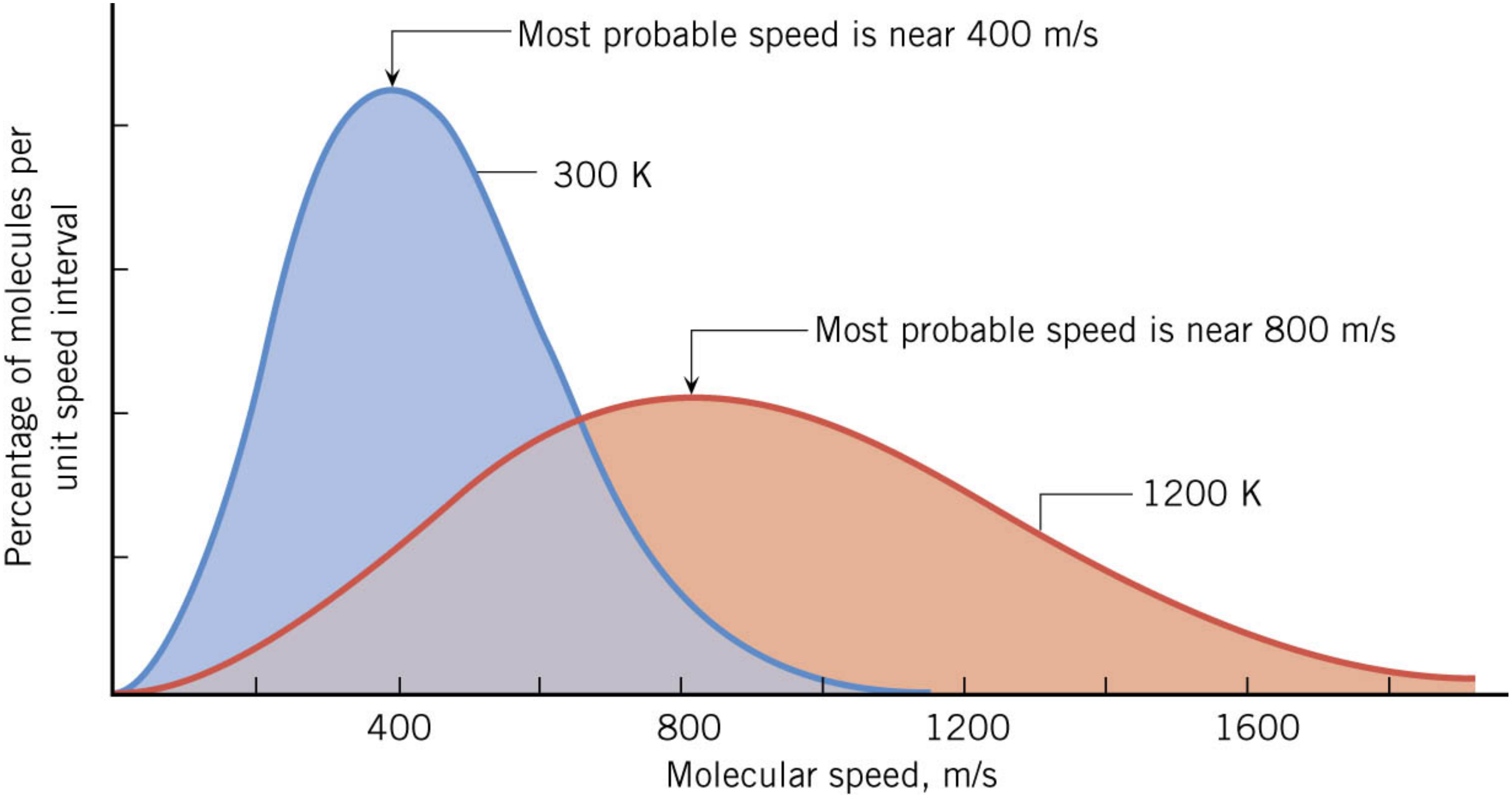
The particles are in constant, random motion, colliding with each other and with the walls of the container.

Each collision changes the particle's speed.

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

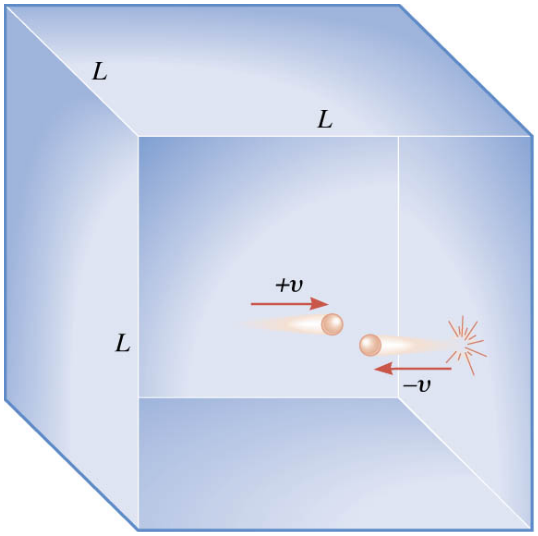


THE DISTRIBUTION OF MOLECULAR SPEEDS



12.4 Kinetic Theory of Gases

KINETIC THEORY



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

$$\text{Average force on each gas molecule when hitting the wall} = \frac{\text{Final momentum-Initial momentum}}{\text{Time between successive collisions}} = \frac{(-mv)-(+mv)}{2L/v} = \frac{-mv^2}{L}$$

$\boxed{\text{Average force on the wall}}$

$$\overline{F} = \left(\frac{N}{3}\right)\left(\frac{m\overline{v^2}}{L}\right) \Rightarrow P = \frac{\overline{F}}{A} = \frac{\overline{F}}{L^2} = \left(\frac{N}{3}\right)\left(\frac{m\overline{v^2}}{L^3}\right)$$

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

root mean square speed

$$\boxed{\overline{KE} = \tfrac{1}{2}m\overline{v^2}} \qquad \boxed{v_{rms} = \sqrt{\overline{v^2}}}$$

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

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

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

$(\mathrm{K} = \mathrm{C}° + 273)$

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

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

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

12.4 *Kinetic Theory of Gases*

THE INTERNAL ENERGY OF A MONATOMIC IDEAL GAS

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

Average KE per atom

$$\Big\Downarrow$$

multiply by the number of atoms

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

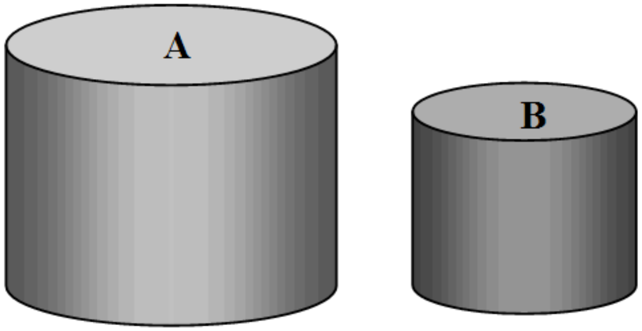
Total Internal Energy

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

H_2, N_2, H_2O, SO_2, CO_2, …(most gases except Nobel gases)

Clicker Question 12.3

Two sealed containers, labeled A and B as shown, are at the same temperature and each contain the same number of moles of an ideal monatomic gas. Which one of the following statements concerning these containers is true?



a) The rms speed of the atoms in the gas is greater in B than in A

b) The frequency of collisions of the atoms with the walls of container B are greater than that for container A

c) The kinetic energy of the atoms in the gas is greater in B than in A.

d) The pressure within container B is less than the pressure inside container A.

e) The force that the atoms exert on the walls of container B are greater than in for those in container A.

Chapter 13

Heat

13.1 *Heat and Internal Energy*

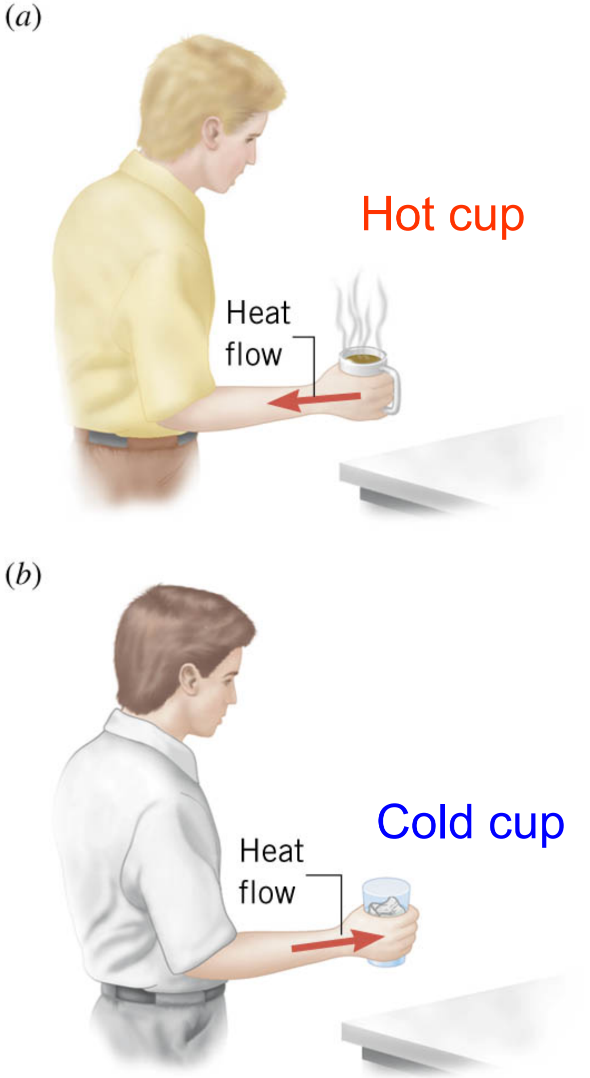
DEFINITION OF HEAT

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)

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.

13.2 Heat and Temperature Change: Specific Heat Capacity

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?

$$Q = mc\Delta T$$

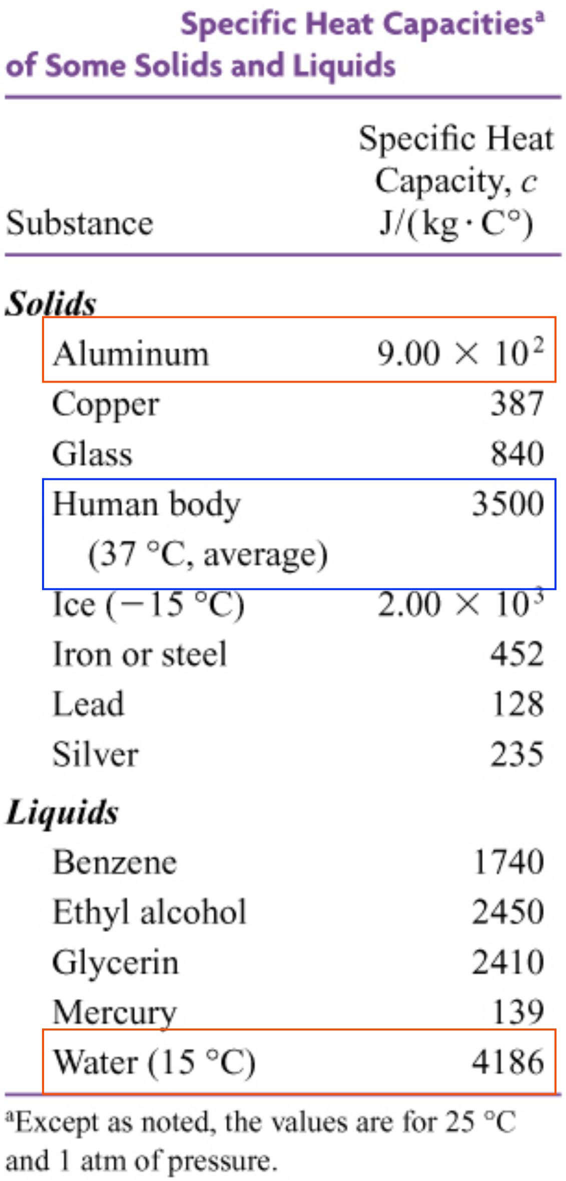
$$\Delta T = \frac{Q}{mc} = \frac{8.0\times10^5\,\mathrm{J}}{(65\ \mathrm{kg})\left[3500\,\mathrm{J}/(\mathrm{kg}\cdot\mathrm{C}^\circ)\right]} = 3.5\ \mathrm{C}^\circ$$

OTHER UNITS for heat production

1 cal = 4.186 joules (calorie)

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

Specific means per unit mass



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.

Clicker Question 13.1

Four 1-kg cylinders are heated to 100 C° and placed on top of a block of paraffin wax, which melts at 63 C°. There is one cylinder made from lead, one of copper, one of aluminum, and one of iron. After a few minutes, it is observed that the cylinders have sunk into the paraffin to differing depths. Rank the depths of the cylinders from deepest to shallowest..

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

a) lead > iron > copper > aluminum

b) aluminum > copper > lead > iron

c) aluminum > iron > copper > lead

d) copper > aluminum > iron > lead

e) iron > copper > lead > aluminum

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

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

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

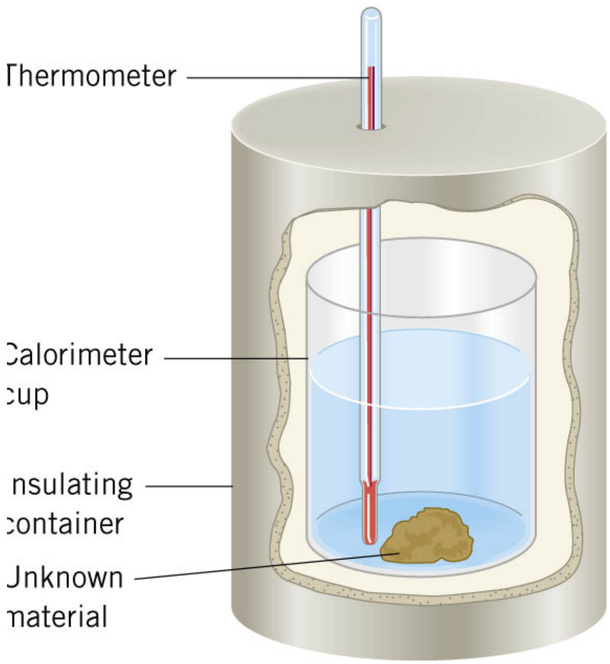
Constant volume
for a monatomic ideal gas

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

any ideal gas

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

13.2 *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. 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 ($\Delta T < 0$)

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

$\mathrm{Al} \equiv \mathrm{Aluminum},\ \mathrm{W} \equiv \mathrm{water},\ \mathrm{Unk} \equiv \mathrm{unknown}$

$$c_{\mathrm{Al}} = 900\ \mathrm{J/kg \cdot C°}$$

$$c_{\mathrm{W}} = 4190\ \mathrm{J/kg \cdot C°}$$

Net heat change equals zero.

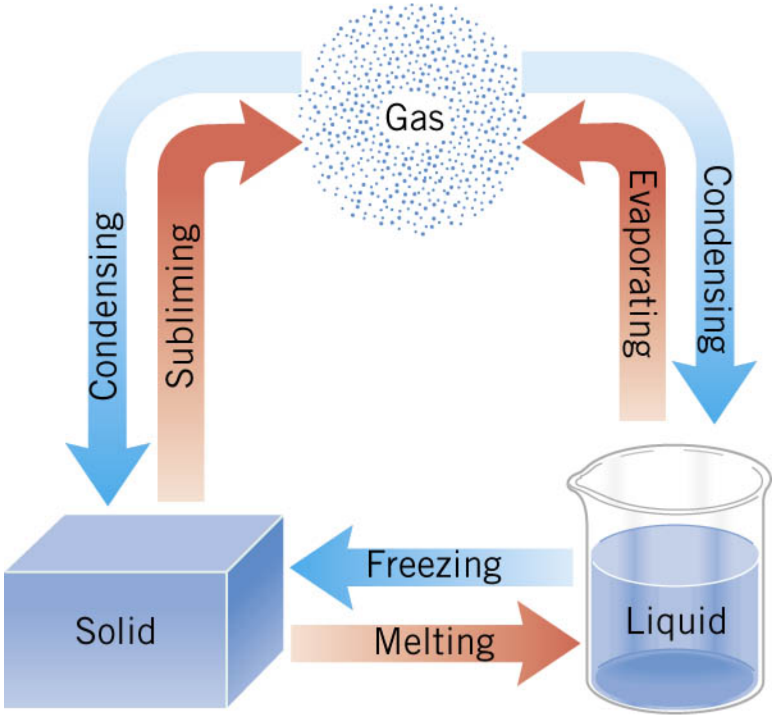
$$\sum Q = m_{\mathrm{Al}} c_{\mathrm{Al}} \Delta T_{\mathrm{Al}} + m_{\mathrm{W}} c_{\mathrm{W}} \Delta T_{\mathrm{W}} + m_{\mathrm{Unk}} c_{\mathrm{Unk}} \Delta T_{\mathrm{Unk}} = 0$$

Three heat changes must sum to zero

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

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.

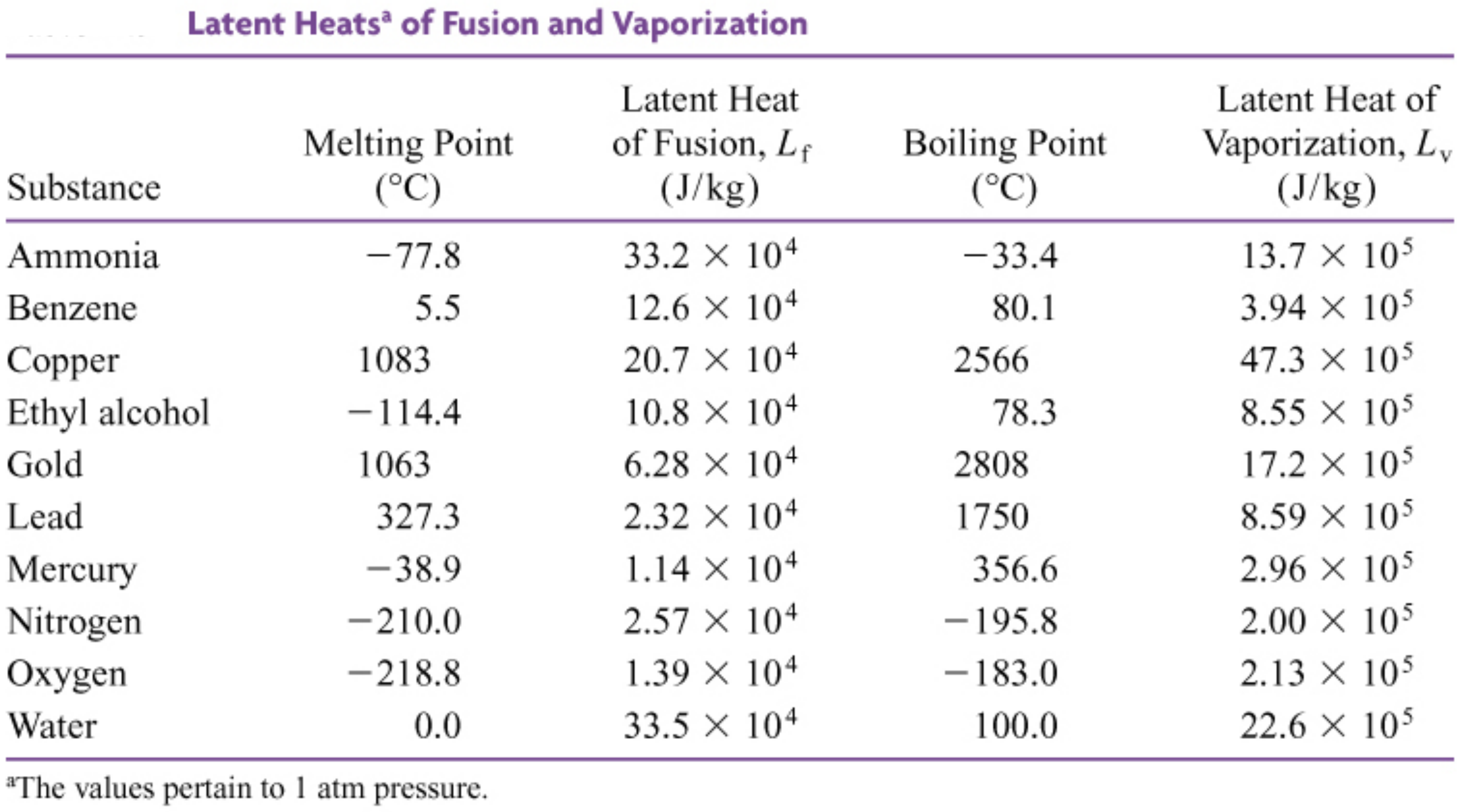
HEAT ADDED OR REMOVED IN CHANGING THE PHASE OF A SUBSTANCE

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 → Water $L_f > 0$

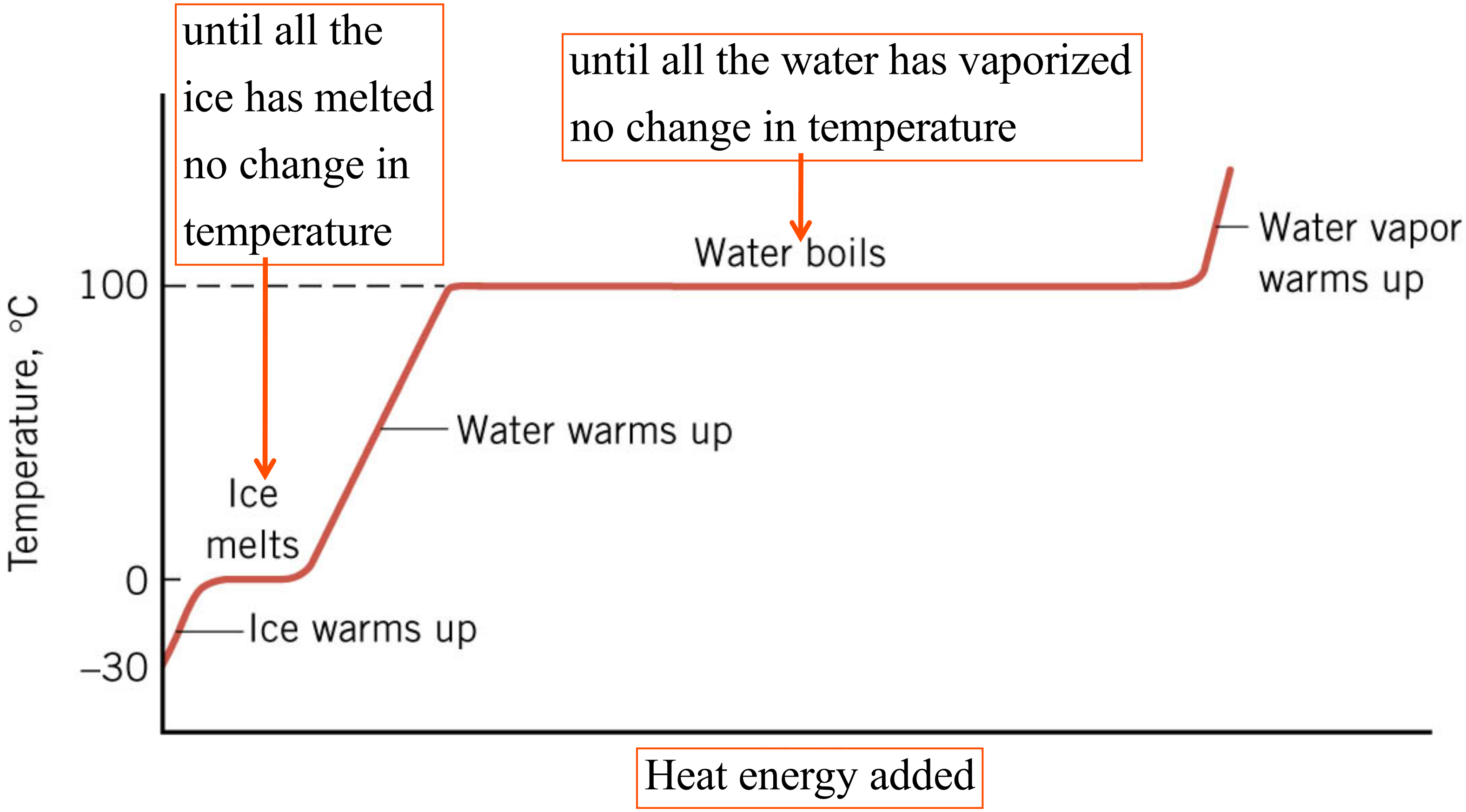
Remove heat: Water → Ice $L_f < 0$

Add heat: Water → Vapor $L_v > 0$

Remove heat: Vapor → Water $L_v < 0$

13.3 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).



until all the ice has melted no change in temperature

until all the water has vaporized no change in temperature

Heat energy added

13.3 Heat and Phase Change: Latent Heat

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.

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

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

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

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

$$= \frac{-(0.32\text{kg})(4.19\times10^3\text{J/kg}\cdot\text{C}^\circ)(-27\text{C}^\circ)}{33.5\times10^4\text{J/kg}} = 0.011\ \text{kg}$$

In C&J, you must use $\Delta T_{\text{lemonade}} > 0$ & $\left(mL_f\right)_{\text{gained}} = \left(cm\Delta T\right)_{\text{lost}}$

Clicker Question 13.2

A 10.0 kg block of ice has a temperature of 0 C°. How much heat must be added to melt half the ice? Latent heat of fusion for water is 33.5 x 10^4 J/kg .

$$\boxed{Q = mL_f}$$

a) 167 J

b) 1.67×10^6 J

c) 33.5×10^5 J

d) 33.5×10^3 J

e) 33.5 J

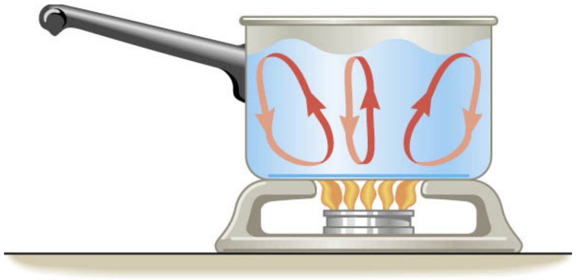
Chapter 13

The Transfer of Heat

CONVECTION, CONDUCTION, RADIATION

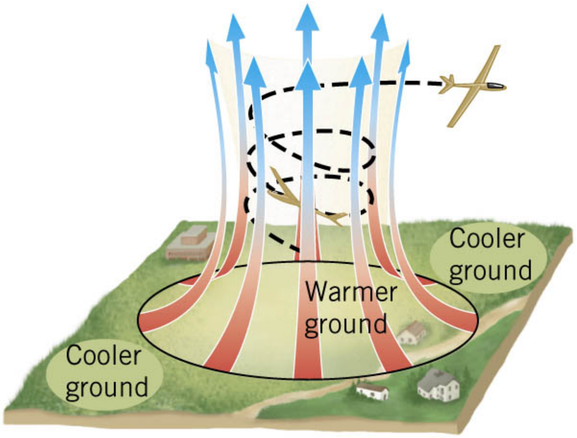
CONVECTION

Heat carried by the bulk movement of a fluid.

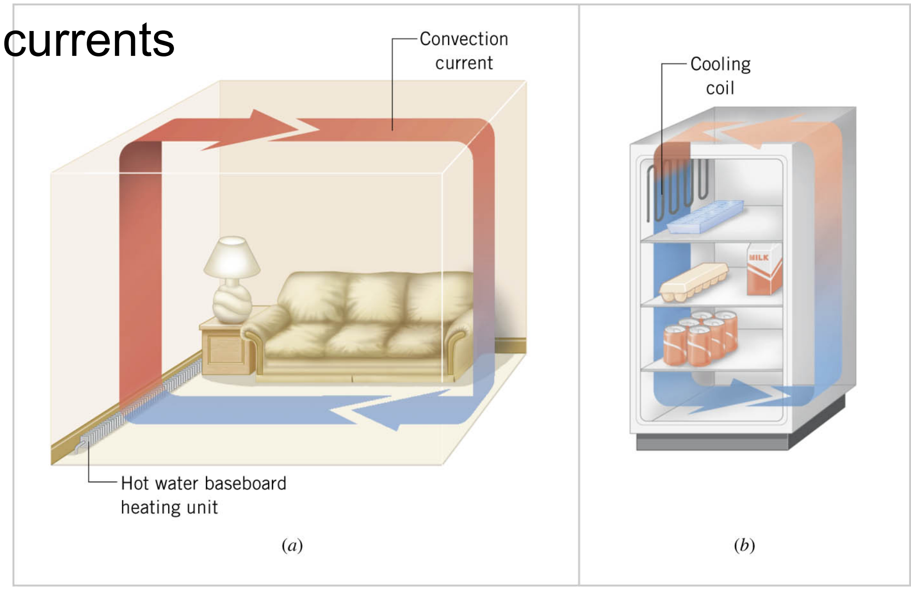


Convection
fluid currents

Convection
air currents



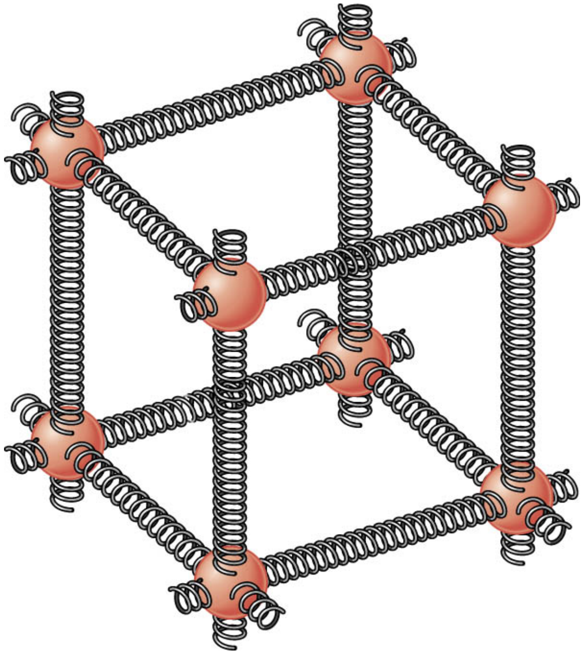
Convection
air currents



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.

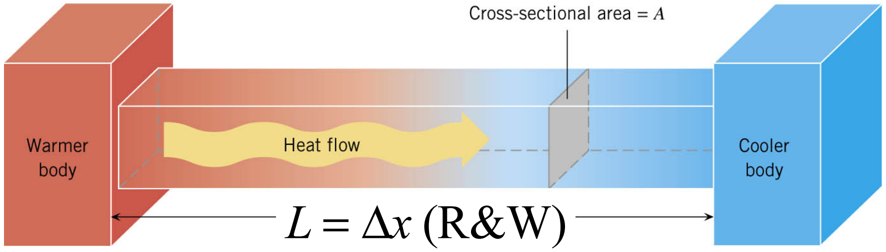


Model of solid materials.
Atoms connected by atomic spring-like forces.

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

13.4 ***Conduction***

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

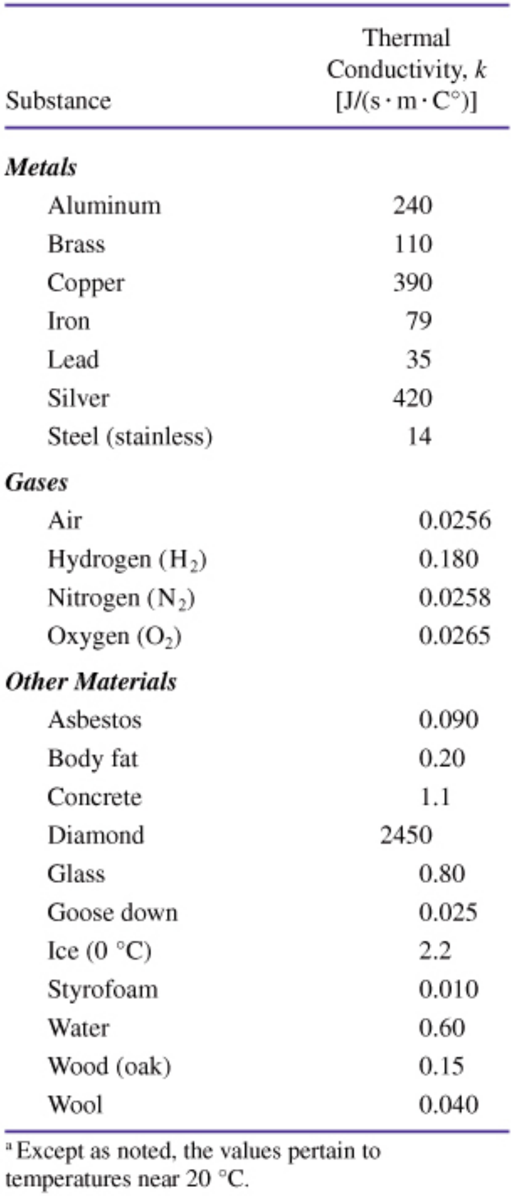
$$\boxed{Q = \frac{\left(kA\Delta T\right)t}{L}}$$

k, is the thermal conductivity

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

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

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

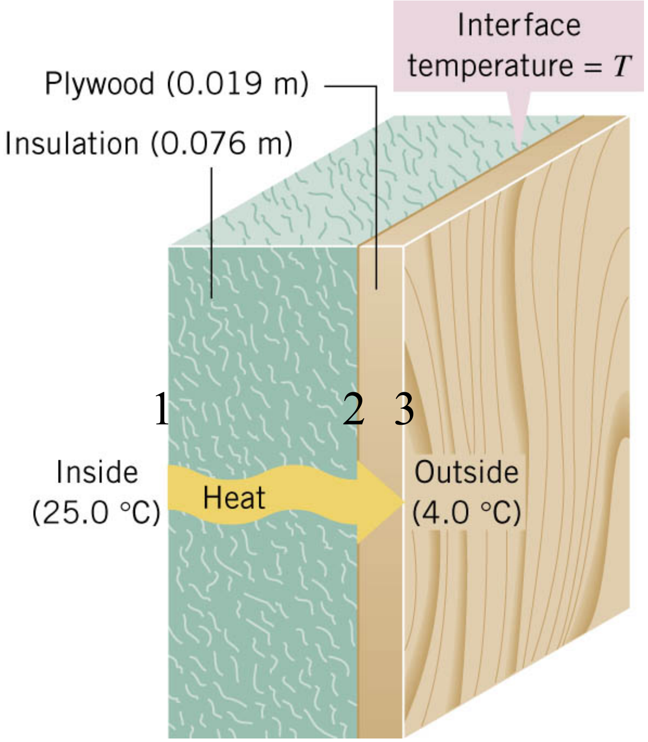
[a] Except as noted, the values pertain to temperatures near 20 °C.

13.2 Conduction

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.

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

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

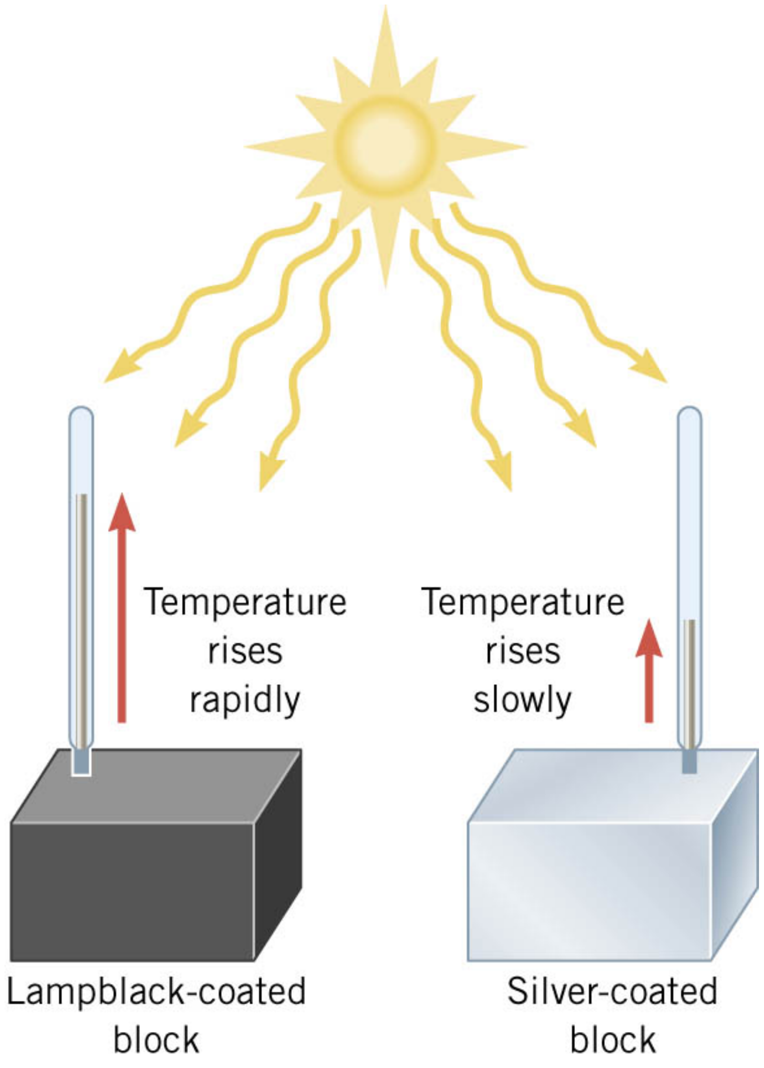
First solve for the interface temperature using:

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

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

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

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

emissivity $e =$ constant between 0 to 1

$e = 1$ (perfect black body emitter)

Stefan-Boltzmann constant

$\sigma = 5.67\times10^{-8}\,\mathrm{J}/\left(\mathrm{s}\cdot\mathrm{m}^2\cdot\mathrm{K}^4\right)$

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.

power, $P = \dfrac{Q}{t}$

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

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

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

Chapter 14

Thermodynamics

THE FIRST LAW OF THERMODYNAMICS

The internal energy of a system changes due to heat and work:

$$\boxed{\Delta U = U_f - U_i = Q + W}$$

$Q > 0$ system gains heat

$W > 0$ if work done on the system

The internal energy (U) of an Ideal Gas depends only on the temperature:

$$\boxed{\text{Ideal Gas (only):} \quad U = \tfrac{3}{2} nRT \text{ or } U = \tfrac{3}{2} Nk_B T}$$

$$\boxed{\begin{aligned} \Delta U &= U_f - U_i \\ &= \tfrac{3}{2} nR(T_f - T_i) \end{aligned}}$$

Otherwise, values for both Q and W are needed to determine ΔU

Clicker Question 14.1

An insulated container is filled with a mixture of water and ice at zero °C. An electric heating element inside the container is used to add 1680 J of heat to the system while a paddle does 450 J of work by stirring. What is the increase in the internal energy of the ice-water system?

$$\boxed{\Delta U = Q + W}$$

a) 450 J
b) 1230 J
c) 1680 J
d) 2130 J
e) zero J

14.1 Thermal Processes

Work done on a gas

$(\Delta P = 0)$ ***isobaric:*** constant pressure: $W = -P\Delta V$

$(\Delta V = 0)$ ***isochoric:*** constant volume: $W = -P\Delta V = 0$

For an Ideal Gas only

$(\Delta T = 0)$ ***isothermal:*** constant temperature: $W = nRT\ln\left(V_i / V_f\right)$

$(Q = 0)$ ***adiabatic:*** no transfer of heat: $W = \tfrac{3}{2}nR\left(T_f - T_i\right)$

14.2 Thermal Processes

An ***isobaric*** process is one that occurs slowly at constant pressure.

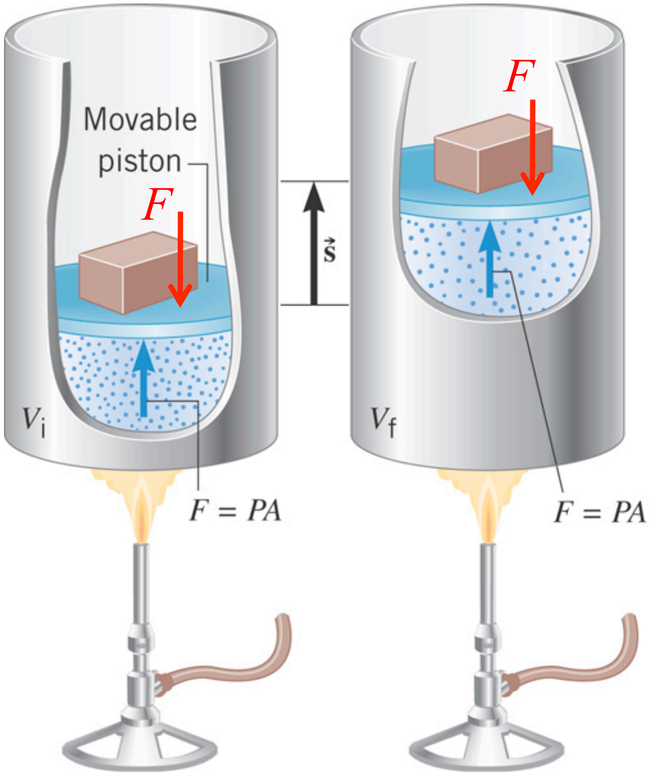
$$\boxed{\begin{array}{l}\cos\theta = +1 \\ \cos\theta = -1\end{array}}$$

$$\boxed{\begin{array}{l}\text{If piston is pushed down by mass, } W_{\text{on gas}} > 0. \\ \text{If piston is pushed upward by pressure, } W_{\text{on gas}} < 0\end{array}}$$

$$W = Fs\cos\theta = -P\left(As\right)$$

$$= -P\Delta V$$

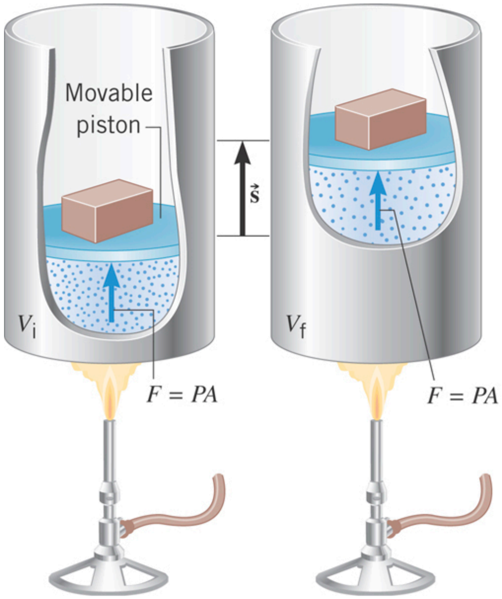
$$= -P\left(V_f - V_i\right)$$



Example Isobaric Expansion of Water (Liquid)

One gram of water is placed in the cylinder and the pressure is maintained at 2.0×10^{5} Pa. The temperature of the water is raised by 31°C. The water is in the liquid phase and expands by a very small amount, 1.0×10^{-8} m^{3}.

Find the work done and the change in internal energy.



$$\boxed{\begin{aligned} W &= -P\Delta V \\ &= -\left(2.0\times10^{5}\,\mathrm{Pa}\right)\left(1.0\times10^{-8}\,\mathrm{m}^{3}\right) = -0.0020\,\mathrm{J} \end{aligned}}$$

$$\boxed{\text{Liquid water } \Delta V \sim 0}$$

$$Q = mc\Delta T$$

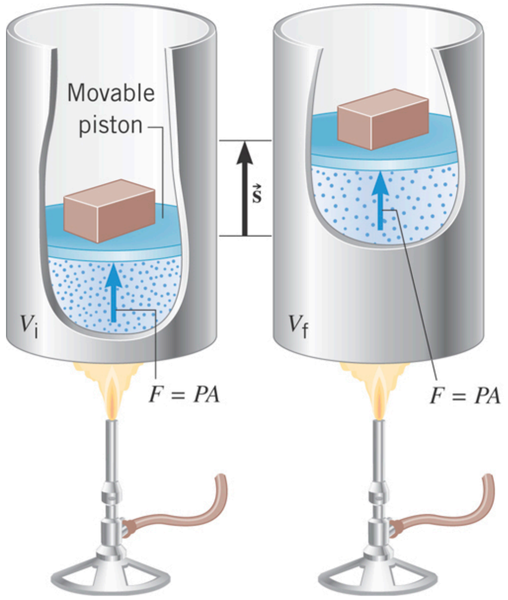
$$c_{\text{water}} = 4186\,\mathrm{J}/\left(\mathrm{kg}\cdot\mathrm{C}^{\circ}\right)$$

$$= \left(0.0010\ \mathrm{kg}\right)\left[4186\,\mathrm{J}/\left(\mathrm{kg}\cdot\mathrm{C}^{\circ}\right)\right]\left(31\ \mathrm{C}^{\circ}\right) = 130\ \mathrm{J}$$

$$\boxed{\Delta U = Q - W = 130\ \mathrm{J} - 0.0020\ \mathrm{J} = 130\ \mathrm{J}}$$

14.2 *Thermal Processes*

Example Isobaric Expansion of Water (Vapor)



One gram of water vapor is placed in the cylinder and the pressure is maintained at 2.0×10^5 Pa. The temperature of the vapor is raised by 31°C, and the gas expands by 7.1×10^{-5} m^3. Heat capacity of the gas is 2020 J/(kg-C°).

Find the work done and the change in internal energy.

$$\boxed{\begin{aligned} W &= -P\Delta V = -(2.0\times10^5\ \text{Pa})(7.1\times10^{-5}\text{m}^3) \\ &= -14.2\ \text{J} \end{aligned}}$$

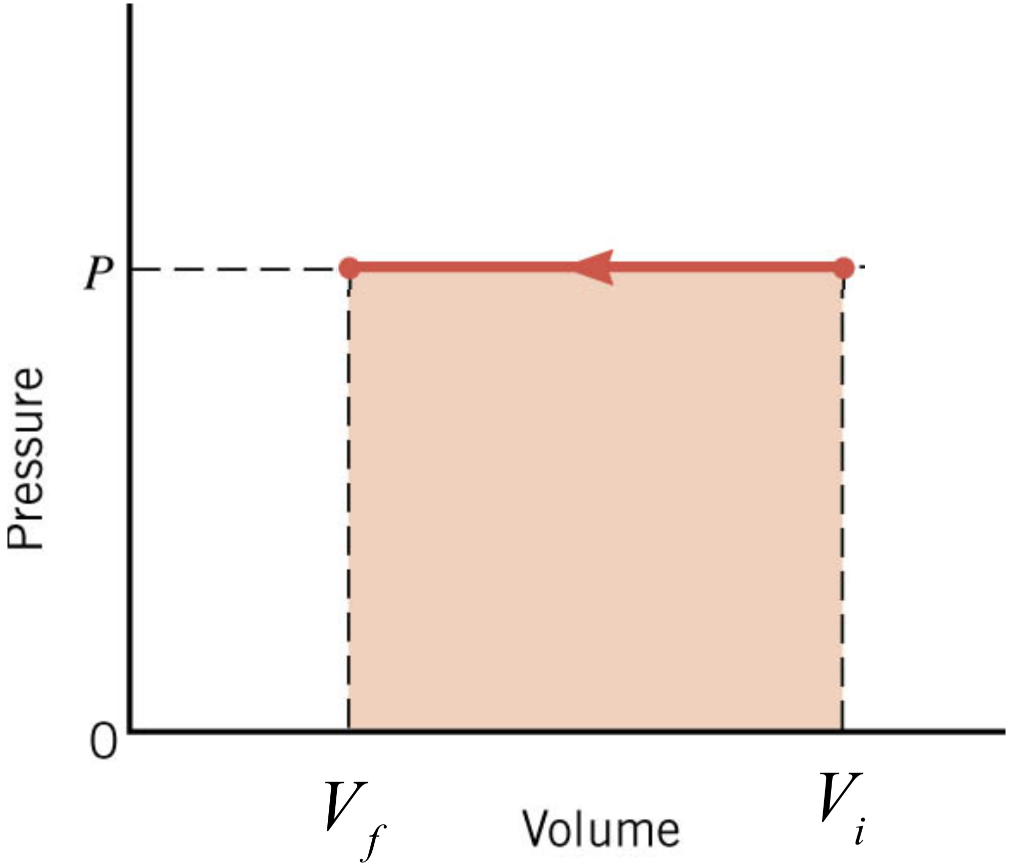
$$\begin{aligned} Q &= mc\Delta T \\ &= (0.0010\ \text{kg})\left[2020\,\text{J}/(\text{kg}\cdot\text{C}^\circ)\right](31\ \text{C}^\circ) = 63\ \text{J} \end{aligned}$$

$$\boxed{\Delta U = Q + W = 63\,\text{J} + (-14\,\text{J}) = 49\ \text{J}}$$

14.2 *Thermal Processes*

$$W = -P\Delta V = P\left(V_i - V_f\right)$$

The work done at constant pressure the work done is the area under a P-V diagram.



Clicker Question 14.2

An ideal gas at a constant pressure of 1×10^5 Pa is reduced in volume from 1.00 m^3 to 0.25 m^3. What work was done on the gas?

$$\boxed{W = -P\Delta V}$$

a) zero J

b) 0.25×10^5 J

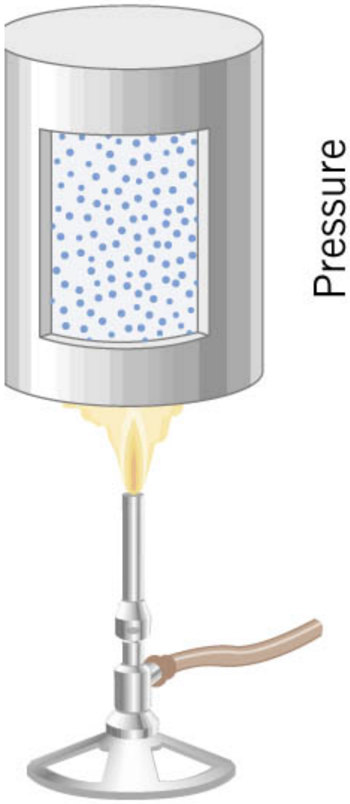
c) 0.50×10^5 J

d) 0.75×10^5 J

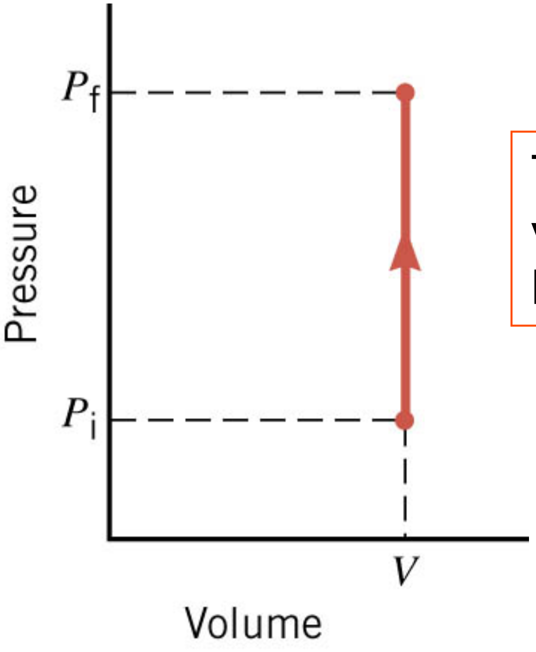
e) 4.00×10^5 J

14.2 Thermal Processes

isochoric: constant volume



(*a*)



(*b*)

The work done at constant volume is the area under a P-V diagram. The area is zero!

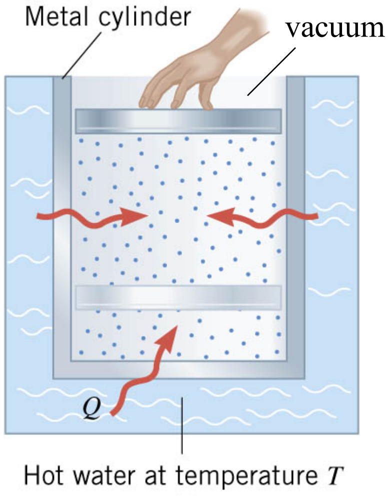
$$W = 0$$

$$\boxed{\Delta U = Q + W = Q}$$

Change in internal energy is equal to the heat added.

14.2 *Thermal Processes Using and Ideal Gas*

ISOTHERMAL EXPANSION OR COMPRESSION



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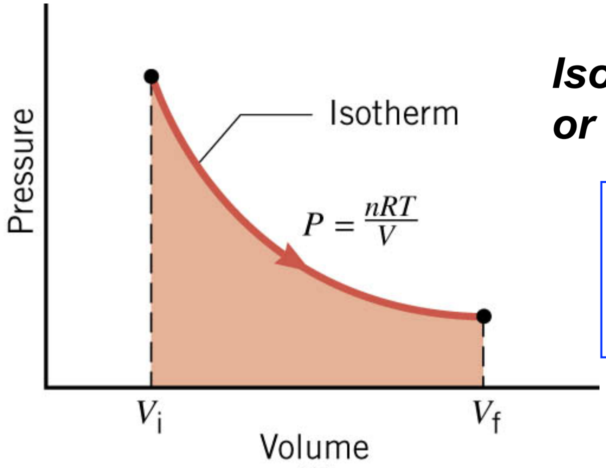


(*b*)

Isothermal expansion or compression of an ideal gas

$$\boxed{W_{\text{on gas}} = nRT\ln\left(\frac{V_i}{V_f}\right)}$$

Example 5 Isothermal Expansion of an Ideal Gas

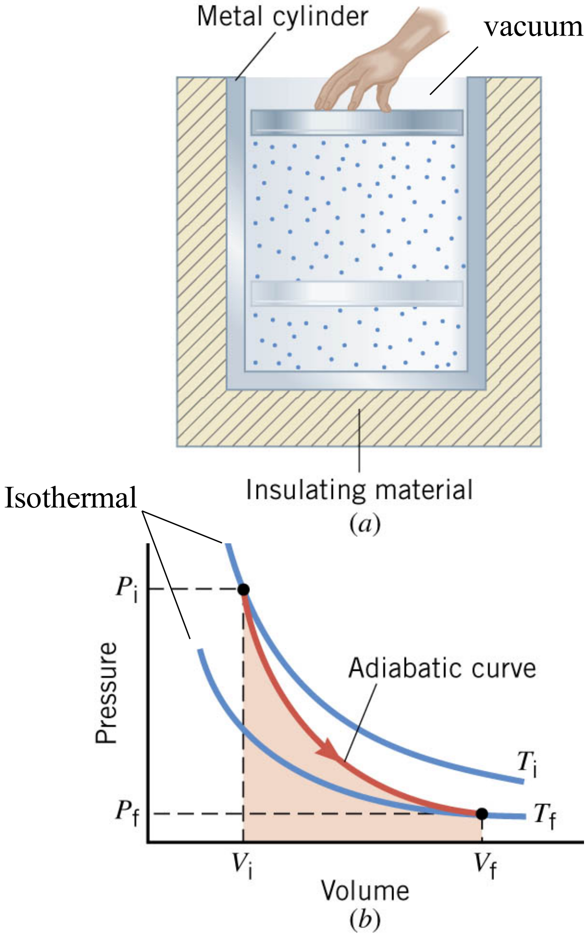
Two moles of argon (ideal gas) expand isothermally at 298K, from initial volume of 0.025m^3 to a final volume of 0.050m^3. Find (a) the work done by the gas, (b) change in gas internal energy, and (c) the heat supplied.

$$\begin{aligned}\text{a) } W_{\text{on gas}} &= nRT\ln\left(V_i/V_f\right)\\ &= (2.0\text{ mol})\left(8.31\text{J}/(\text{mol}\cdot\text{K})\right)(298\text{ K})\ln\left(\frac{0.025}{0.050}\right)\\ &= -3400\text{ J}\end{aligned}$$

$$\begin{aligned}\text{b) } \Delta U &= U_f - U_i = \tfrac{3}{2}nR\Delta T\\ \Delta T &= 0 \text{ therefore } \Delta U = 0\end{aligned}$$

$$\begin{aligned}\text{c) } \Delta U &= Q + W = 0\\ Q &= -W = 3400\text{J}\end{aligned}$$

14.2 Thermal Processes Using and Ideal Gas



ADIABATIC EXPANSION OR COMPRESSION

Adiabatic expansion or compression of a monatomic ideal gas

$$W = \tfrac{3}{2} nR\left(T_f - T_i\right)$$

Adiabatic expansion or compression of a monatomic ideal gas

$$P_i V_i^{\gamma} = P_f V_f^{\gamma}$$

$$\gamma = c_P / c_V$$

Ratio of heat capacity at constant P over heat capacity at constant V.

These are needed to understand basic operation of refrigerators and engines

ADIABATIC EXPANSION OR COMPRESSION

ISOTHERMAL EXPANSION OR COMPRESSION

14.2 Specific Heat Capacities

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

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

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

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

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

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

$$C_P, C_V$$

14.2 Specific Heat Capacities

Ideal Gas: $PV = nRT; \quad \Delta U = \frac{3}{2} nR\Delta T$

1st Law of Thermodynamics: $\Delta U = Q + W_{\text{on gas}}$

Constant pressure for a monatomic ideal gas

Constant Pressure ($\Delta P = 0$)

$$W_P = -P\Delta V = -nR\Delta T$$

$$Q_P = \Delta U - W = \tfrac{3}{2} nR\Delta T + nR\Delta T = \tfrac{5}{2} nR\Delta T$$

$$Q_P = nC_P\Delta T$$

$$C_P = \tfrac{5}{2} R$$

Constant volume for a monatomic ideal gas

Constant Volume ($\Delta V = 0$)

$$W_V = -P\Delta V = 0$$

$$Q_V = \Delta U - W = \tfrac{3}{2} nR\Delta T = \tfrac{3}{2} nR\Delta T$$

$$Q_V = nC_V\Delta T$$

$$C_V = \tfrac{3}{2} R$$

monatomic ideal gas

$$\gamma = C_P / C_V = \tfrac{5}{2} R / \tfrac{3}{2} R$$
$$= 5/3$$

any ideal gas

$$C_P - C_V = R$$

14.3 The Second Law of Thermodynamics

The second law is a statement about the natural tendency of heat to flow from hot to cold, whereas the first law deals with energy conservation and focuses on both heat and work.

THE SECOND LAW OF THERMODYNAMICS: THE HEAT FLOW STATEMENT

Heat flows spontaneously from a substance at a higher temperature to a substance at a lower temperature and does not flow spontaneously in the reverse direction.

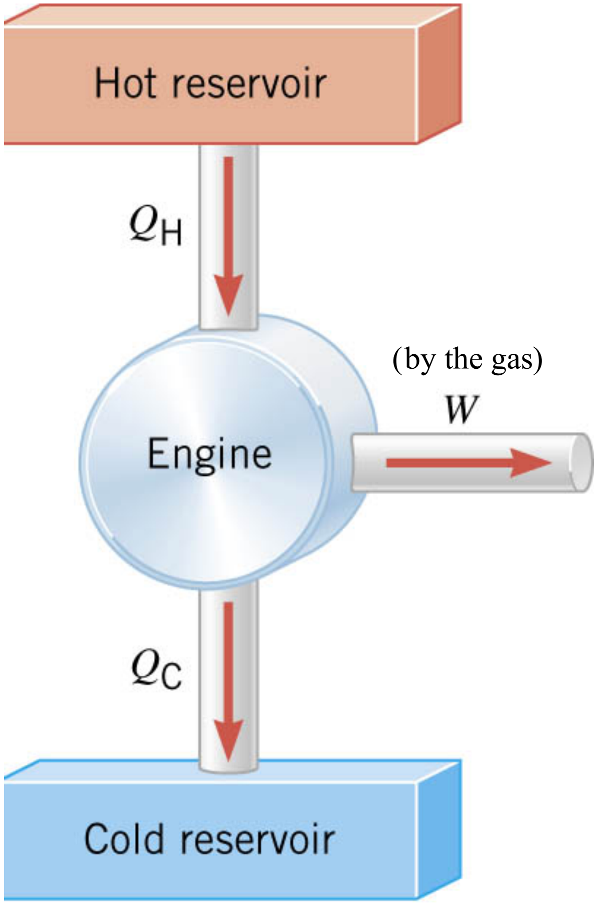
14.3 Heat Engines

A ***heat engine*** is any device that uses heat to perform work. It has three essential features.

1. Heat is supplied to the engine at a relatively high temperature from a place called the *hot reservoir.*

2. Part of the input heat is used to perform work by the *working substance* of the engine.

3. The remainder of the input heat is rejected to a place called the *cold reservoir.*



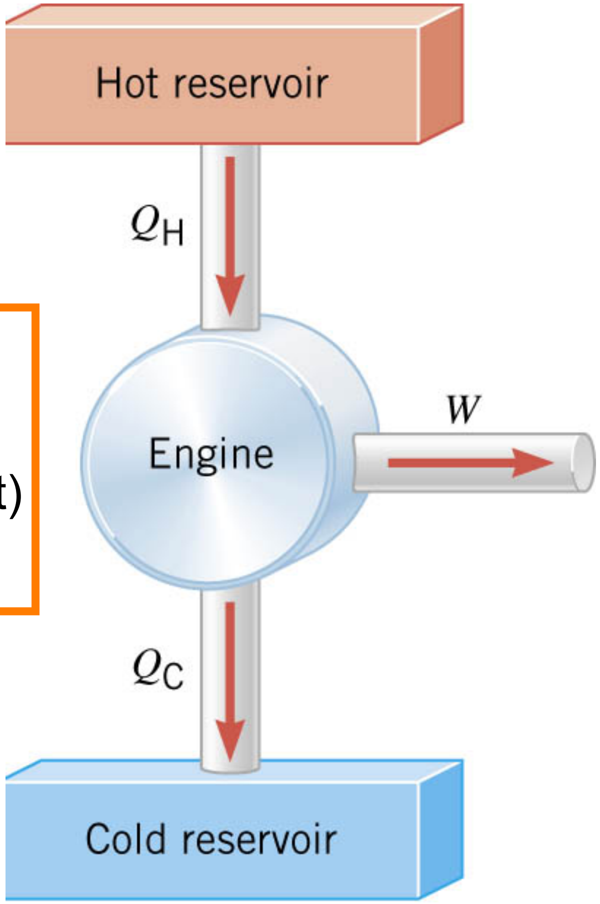
$$|Q_H| = \text{magnitude of input heat}$$

$$|Q_C| = \text{magnitude of rejected heat}$$

$$|W| = \text{magnitude of the work done}$$

Carnot Engine Working with an Ideal Gas

1. ISOTHERMAL EXPANSION ($Q_{in}=Q_H$, T_{Hot} constant)
2. ADIABATIC EXPANSION ($Q=0$, T drops to T_{Cold})
3. ISOTHERMAL COMPRESSION ($Q_{out}=Q_C$, T_{Cold} constant)
4. ADIABATIC COMPRESSION ($Q=0$, T rises to T_{Hot})



$$|Q_H| = \text{magnitude of input heat}$$

$$|Q_C| = \text{magnitude of rejected heat}$$

$$|W| = \text{magnitude of the work done}$$

14.3 Heat Engines

The ***efficiency*** of a heat engine is defined as the ratio of the work done to the input heat:

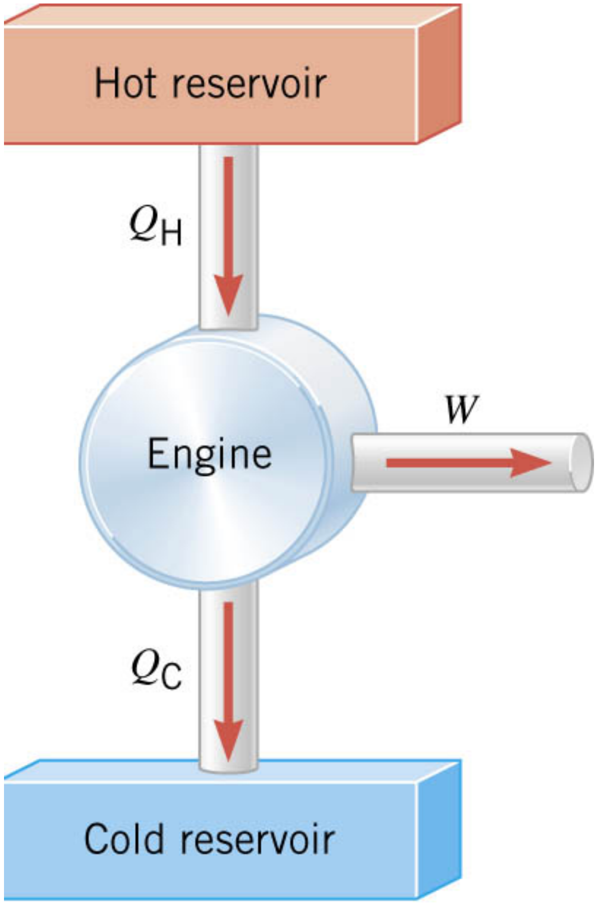
$$e = \frac{|W|}{|Q_H|}$$

If there are no other losses, then

$$|Q_H| = |W| + |Q_C|$$

$$\Downarrow$$

$$e = 1 - \frac{|Q_C|}{|Q_H|}$$



Example An Automobile Engine

An automobile engine has an efficiency of 22.0% and produces 2510 J of work. How much heat is rejected by the engine?

$$e = \frac{|W|}{|Q_H|}$$

$$= \frac{|W|}{|Q_C| + |W|} \quad \Rightarrow \quad e\left(|Q_C| + |W|\right) = |W|$$

$$|Q_C| = \frac{|W| - e|W|}{e} = |W|\left(\frac{1}{e} - 1\right) = 2510\,\text{J}\left(\frac{1}{0.22} - 1\right)$$

$$= 8900\ \text{J}$$

14.3 *Carnot's Principle and the Carnot Engine*

A reversible process is one in which both the system and the environment can be returned to exactly the states they were in before the process occurred.

CARNOT'S PRINCIPLE: AN ALTERNATIVE STATEMENT OF THE SECOND LAW OF THERMODYNAMICS

No irreversible engine operating between two reservoirs at constant temperatures can have a greater efficiency than a reversible engine operating between the same temperatures. Furthermore, all reversible engines operating between the same temperatures have the same efficiency.

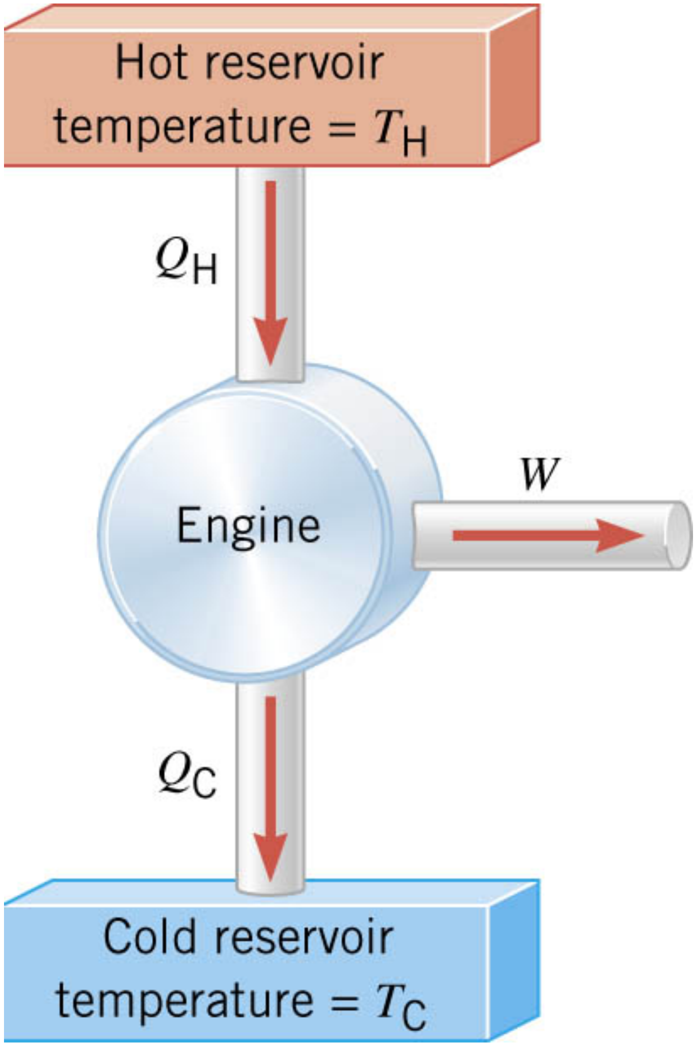
14.3 Carnot's Principle and the Carnot Engine

The ***Carnot engine*** is useful as an idealized model.

All of the heat input originates from a single temperature, and all the rejected heat goes into a cold reservoir at a single temperature.

Since the efficiency can only depend on the reservoir temperatures, the ratio of heats can only depend on those temperatures.

$$e = 1 - \frac{|Q_C|}{|Q_H|} = 1 - \frac{T_C}{T_H}$$



14.3 Carnot's Principle and the Carnot Engine

Example A Tropical Ocean as a Heat Engine

Surface temperature is 298.2 K, whereas 700 meters deep, the temperature is 280.2 K. Find the maximum efficiency for an engine operating between these two temperatures.

$$e_{\text{carnot}} = 1 - \frac{T_C}{T_H} = 1 - \frac{280.2\ \text{K}}{298.2\ \text{K}} = 0.060$$

Maximum of only 6% efficiency.
Real life will be worse.

Conceptual Example Natural Limits on the Efficiency of a Heat Engine

Consider a hypothetical engine that receives 1000 J of heat as input from a hot reservoir and delivers 1000J of work, rejecting no heat to a cold reservoir whose temperature is above 0 K. Decide whether this engine violates the first or second law of thermodynamics.

If $T_H > T_C > 0$

$$e_{\text{carnot}} = 1 - \frac{T_C}{T_H} \text{ must be less than 1}$$

$$e_{hypothetical} = \frac{|W|}{|Q_H|} = \frac{1000\,\text{J}}{1000\,\text{J}} = 1$$

Violates 2nd law of thermodynamics

14.3 Entropy

In general, irreversible processes cause us to lose some, but not necessarily all, of the ability to do work. This partial loss can be expressed in terms of a concept called ***entropy***.

Carnot engine

$$\frac{|Q_C|}{|Q_H|} = \frac{T_C}{T_H} \quad \Longrightarrow \quad \frac{|Q_C|}{T_C} = \frac{|Q_H|}{T_H}$$

entropy change

$$\Delta S = \left(\frac{Q}{T}\right)_{\mathrm{R}}$$

reversible

14.3 Entropy

Entropy, like internal energy, is a function of the state of the system.

$$\Delta S = \left(\frac{Q}{T}\right)_{\mathrm{R}}$$

Consider the entropy change of a Carnot engine. The entropy of the hot reservoir decreases and the entropy of the cold reservoir increases.

$$\Delta S = +\frac{|Q_C|}{T_C} - \frac{|Q_H|}{T_H} = 0$$

Reversible processes do not alter the entropy of the universe.