Specific Heat/Heat Capacity

Different type of materials will need different amount of heat to raise its temp by 1°C (or 1K).

We can quantify this using *specific heat c*:

$$Q = mc \ \Delta T \qquad or \qquad dQ = mc \ dT$$

- $Q \rightarrow$ quantity of heat needed to raise T from T_1 to T_2 $(\Delta T = T_2 - T_1)$
- $m \rightarrow$ mass of the material
- $c \rightarrow$ "specific heat" is characteristic of the type of material [$J/kg \cdot K$]

Specific Heat Values

Table 17.3 Approximate Specific Heats and Molar Heat Capacities (Constant Pressure)

Substance	Specific Heat, <i>c</i> (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

Molar Specific Heat/Heat Capacity

□ One can also specify the amount of materials by the number of molecules (or mole n) instead of its mass (m in kg). With m=nM,

$$Q = mc \, \Delta T = (nM)c \, \Delta T = nC\Delta T \qquad (note: cM = C)$$

$n \rightarrow$ number of mole

- $M \rightarrow \text{molar mass (mass per mole)}$
- $C \rightarrow$ molar specific heat (note upper case)

 $(1 \text{ mole} = 6.022 \times 10^{23} \text{ particles})$

Specific Heat Values

 Table 17.3
 Approximate Specific Heats and Molar Heat Capacities (Constant Pressure)

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Molar Specific Heat

- Specific heat also depends on the *process* by which heat is being transferred into the system
- □ Two often used molar specific heats:
 - C_p : molar specific heat at *constant pressure*

(heating a liquid in an open container)

 C_v : molar specific heat at *constant volume*

(heating a gas in a closed container)

 \Box For most materials, $C_p > C_v$.





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Specific Heat (examples)

Physical intuition for *c*:

"For a given amount of heat flow *Q*, specific *heat c* is a measure of the *thermal sensitivity* of the material !"

- □ Hot food on metal/wood plate
- □ Colliding metal balls

Example (Iron vs. Wood Plate)

Metal PlateHot foodWood PlateImage: Weight of the second seco

m=0.25 kg $c_{iron}=470 \text{ J/kg K}$ $\Delta T = Q/mc$ m=0.25 kg $c_{wood}=2500 \text{ J/kg K}$

Putting the same amount of heat (hot food) on the plate, what is ΔT ?

hot to the touch!

$$\Delta T = \frac{2000J}{0.25kg \cdot 470J / kg \cdot K} = 17K \qquad \Delta T = \frac{2000J}{0.25kg \cdot 2500J / kg \cdot K} = 3.2K$$

much less temp increase !

Example (Colliding Balls)



$$M = 0.5kg$$

$$m = 10mg = 1 \times 10^{-5} kg$$

$$c_{wood} = 2500J / kg \cdot K$$

$$v = 5 m / s$$

KE delivered to the small piece of paper by the two balls:

$$KE = 2\left(\frac{1}{2}Mv^2\right) = Mv^2 = 0.5kg(5m/s)^2 = 12.5J$$

 $KE \rightarrow Q$, what is the temperature increase for the small piece of paper? Q = KE = 12.5J (starting @)room T)

$$\Delta T = Q / mc_{wood} = \frac{12.5J}{(1 \times 10^{-5} kg \cdot 2500J / kg \cdot K)} = 500K \to \frac{793.15K}{520^{\circ}C} \quad \text{paper will burn!}$$

.11

Extensive and Intensive Quantities

- Extensive quantities: depend on the amount of substance:
 - \rightarrow double the amount \Rightarrow double the quantity

e.g., volume *V* is an extensive quantity

Intensive quantities: not depend on amount of substance

- → units are typically per kg[\cdot/kg]or per mol[\cdot/mol] e.g. specific heat *c* and molar heat capacity *C*:
 - $\begin{bmatrix} J/kg \cdot K \end{bmatrix} \qquad \begin{bmatrix} J/m \ ol \cdot K \end{bmatrix}$

(Note: Typically, heat capacity is an extensive quality and specific heat is intensive but your book does not make this distinction.)

Phases of Matters



 $T < T_{freezing}$

 $T_{freezing} < T < T_{boiling}$

 $T > T_{boiling}$

Heat Exchanges during Phase Changes

During **Phase Changes**, energy exchanged is used for *internal* structural changes (e.g., pulling molecules further apart) :

e.g. ice \rightarrow water or water \rightarrow steam

$$Q = m L$$

heat of fusion (water)heat of vaporization (water) $L_f = 3.34 \times 10^5 J/kg$ <</td> $L_v = 2.26 \times 10^6 J/kg$

Since all energy is used for internal structural change, heat exchanged by substances during **Phase Changes** does NOT produce ΔT .

Heats of Fusion & Heats of Vaporization

Substance	Norm	Normal Melting Point		Normal Boiling Point		Heat of Vanorization L
	K	°C	(J/kg)	K	°C	(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}

 Table 17.4
 Heats of Fusion and Vaporization

*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. Copyright © 2008 Pearson Education, Inc., publishing as Pearson Addison-Wesley.

Calorimetric Processes

Now we are ready to describe thermodynamic process such as the following:





Calorimetry: Problem Solving with Heat Exchanges (method 1)

- Main Concept: Conservation of Energy
 - $\sum \Sigma Q = 0 \text{ (sum of all heat flows into and out of system =0)}$
- Sign Convention: heat enters a system is + heat leaves a system is -

$$\Box \quad \varDelta T = T_f - T_i$$

Calorimetry: Problem Solving with Heat Exchanges (method 2)

□ Main Concept: Conservation of Energy

OR
$$\sum Q_{gain} = \sum Q_{loss}$$

□ Keep all heats as positive quantities

Calorimetry: Problem Solving with Heat Exchanges

Steps:

- 1. Identify all phase change pts
- 2. Apply (either $Q=mc\Delta T$ or Q=mL) for each processes separately. (don't apply $Q=mc\Delta T$ across ph. changes!)

3. Use

$$\sum_{ALL} Q = 0 \quad \text{and follow sign convention}$$

or just do
$$\sum Q_{gain} = \sum Q_{loss}$$

Calorimetry (example 17.8)



with a temperature of 0°C?

#1: Conduction

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

(+H is in the dir. of *decreasing T*)

- $H \rightarrow heat \ current \ [J/s]$ (heat flow rate)
- $k \rightarrow$ thermal conductivity $[W / m \cdot K]$ (characteristic of the material)
- $-R = L/k \rightarrow \text{thermal resistance}$ (larger is better)

(a) Heat current H



(b) Doubling the cross-sectional area of the conductor doubles the heat current (*H* is proportional to *A*).



(c) Doubling the length of the conductor halves the heat current (H is inversely proportional to L).



Thermal Resistivity (additive R values)

 $H(heat current) = kA(T_H - T_L) / L = A(T_H - T_L) / R$ where R = L / kFor a composite system, we have the following: H $H_{1} = \frac{A(T_{H} - T_{M})}{R_{1}} \qquad H_{2} = \frac{A(T_{M} - T_{L})}{R_{2}}$ Now, by conservation of energy, we need to have $H_{1} = H_{2} = H$ 2 1 Re-arranging and adding the two equations gives: $T_H - T_M = \frac{HR_1}{4}$ $\bigoplus \qquad \Rightarrow \quad T_H - T_L = \frac{H(R_1 + R_2)}{A} \quad \Rightarrow \quad H = \frac{A(T_H - T_L)}{R_1 + R_2}$ T_L T_{H} T_{M} $T_M - T_L = \frac{HR_2}{4}$ So, for composite system, *R* is additive.

Table 17.5 Thermal Conductivities

Substance	$k(W/m \cdot K)$
Metals	
Aluminum	205.0
Brass	109.0
Copper	385.0
Lead	34.7
Mercury	8.3
Silver	406.0
Steel	50.2
Solids (representative values)	
Brick, insulating	0.15
Brick, red	0.6
Concret	0.8
Cork	0.04
Felt	0.04
Fiberglass	0.04
Glass	0.8
Ice	1.6
Rock wool	0.04
Styrofoam	0.01
Wood	0.12 - 0.04
Gases	
Air	0.024
Argon	0.016
Helium	0.14
Hydrogen	0.14



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Protective tile for the space shuttle has both low values of *k* and *c* !

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Oxygen

0.023

#2: Convection

 Heating by moving large amounts of hot fluid, usually water or air.

 Heating element in the tip warms surrounding water.
 Heat is transferred by convection of the warm water movement.



#3: Radiation

 Infrared lamps, hot objects, a fireplace, standing near a running furnace ... these are all objects heating others by "broadcasting" EM radiation.

 $H = Ae\sigma T^4$ (Stefan-Boltzmann Law)

 $A \rightarrow$ surface area of object at T

e → emissivity [0,1]
(effectiveness of surface in emitting EM radiation)

 $\sigma \rightarrow$ Stefan-Boltzmann constant (a fundamental physical constant)



Camera sensitive to these radiation can be used to take this picture.

□ Radiation and Absorption

- The *environment* around an object at a given *T* also radiates electromagnetic energy and the radiating object will *absorb* some of this energy.
- In general, the absorption will again depends on the surface properties of the object, i.e., the same A, e, and σ . Now, if the surrounding environment is at T_s , the *net* heat current radiated by the object will be,

$$H_{net} = Ae\sigma T^4 - Ae\sigma T_s^4 = Ae\sigma (T^4 - T_s^4)$$

(radiate) (absorb)

PHYS 262/266

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Chapter 18: Thermal Properties of Matter

Topics for Discussion

- Equations of State
- Ideal Gas Equation
- PV Diagrams
- Kinetic-Molecular Model of an Ideal Gas
- Heat Capacities
- Distribution of Molecular Speeds



Equations of State

- □ State Variables
 - \rightarrow physical variables describing the macroscopic state of the system:

P, *V*, *T*, *n* (or *m*)

□ Equation of State

 \rightarrow a mathematical relationship linking these variables

Ideal Gas – a Box of Dilute Gas

This discussion applies in general to all physical systems ... now we focus on a system of dilute gas



The Ideal Gas Equation

Properties of a gas is studied by varying the macroscopic variables:
 P, *V*, *T*, *n* and observing the result.

□ Observations:

- 1. $P \propto 1/V$ e.g. air pump
- 2. $V \propto T$ e.g. hot air balloon
- 3. $P \propto T$ e.g. hot closed spray can
- 4. $V \propto n$ e.g. birthday balloon



applet

http://phet.colorado.edu/en/simulation/gas-properties

Ideal Gas Law (summary)

□ By putting all these observations together, we have

PV = nRT

 $R \rightarrow$ Universal Gas Constant (R = 8.314 J/mol K)

(This is an important example of an **Equation of State** for a gas at *thermal equilibrium*.)

- \Box An Ideal Gas (dilute):
 - No molecular interactions besides elastic collisions
 - Molecular volume <<< volume of container</p>

Most everyday gases ~ Ideal!

The Ideal Gas Law

Important Notes:

- The relationship P vs. T (at cont V) & V vs. T (at cont P) are *linear* for all *diluted* gases.
 - \rightarrow diluted gas ~ Ideal
- They both extrapolate to a single *zero* point (absolute zero).
 - \rightarrow *T* has to be in K!



The Ideal Gas Law (alternative form)

Instead of the *number of moles* (*n*), one can specify the amount of gas by the actual *number of molecules* (*N*). $N = n N_A$ ($N_A = 6.02214 \times 10^{23} molecules/mole$) where N_A is the # of molecules in a *mole* of materials (Avogadro's number).

$$PV = nRT \rightarrow PV = \frac{N}{N_A}RT = NkT$$

where k is the Boltzmann constant,

$$k = \frac{R}{N_A} = 1.381 \times 10^{-23} J / molecule \cdot K$$