CHEM 103
Temperature and Heat Energy

Lecture Notes
March 9, 2006
Prof. Sevian

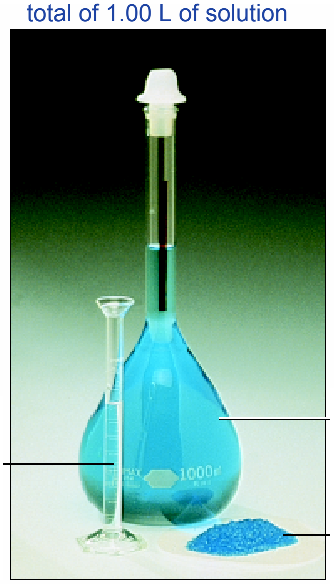
Agenda

- Recap solution concentration
- Recap titration as a way to do stoichiometry
- Energy in chemistry
  - Heat vs. temperature
  - Kinetic vs. potential energy
  - Kinetic and potential energy changes as heat energy is added to a pure substance
  - Transfer of energy and the Law of Conservation of Energy

Solution Concentration

- Many reactions of interest occur in aqueous solution
- To be able to quantify how much of a chemical reacts, and how much product is made, it is necessary to know quantities in moles
- In pure materials, the concentration of particles can be presented as density
- In mixtures that are aqueous solutions, the concentration of the particles of interest (solute) is usually presented as molarity
- Concentration just means how many particles (of interest) are present in a given amount of space
- Since Molarity = moles solute / Liter of solution, if you know the molarity and the volume of solution, you can find the moles of solute

Copper (II) sulfate solution has 25.0 g of $CuSO_4 \bullet 5H_2O$ (FW 250. g/mol) included in a total of 1.00 L of solution



How to Calculate Concentration of a Solution

Need to know:

- Amount of solute (in mol)
- Amount of solution (in L)

$$\text{Molarity} = \frac{mol \text{ of solute}}{L \text{ of solution}}$$

$$= \frac{\left(25.0\, g \times \frac{1\, mol}{250.\, g}\right)}{1.00\, L}$$

$$= 0.100 \frac{mol}{L} = 0.100\, M$$

Variations on the Theme

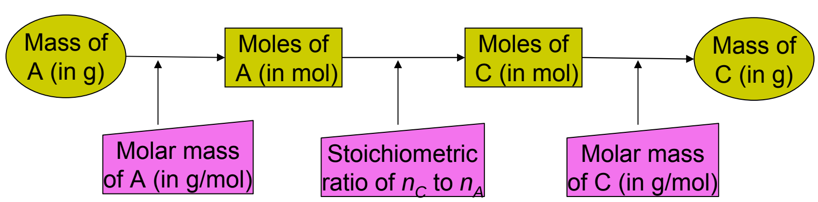
- Three variables:
  - Concentration of solution (molarity)
  - Amount of solute (moles or grams)
  - Volume of solution (liters)
- Given any two, you can always calculate the third
  - What is the concentration of a solution made by mixing ... (solute amount) into water to make a (certain number of liters) of solution?
  - How much solute (grams?) would be required to make (certain number of liters) of a (specify concentration) molar solution?
  - What volume of a (specify concentration) molar solution must be used to obtain (solute amount)?

Reminder: Stoichiometry

$$n_A\, \mathrm{A} + n_B\, \mathrm{B} \rightarrow n_C\, \mathrm{C} + n_D\, \mathrm{D}$$

<u>A typical scenario</u>

Given mass of chemical A, find mass that could be produced of chemical C.



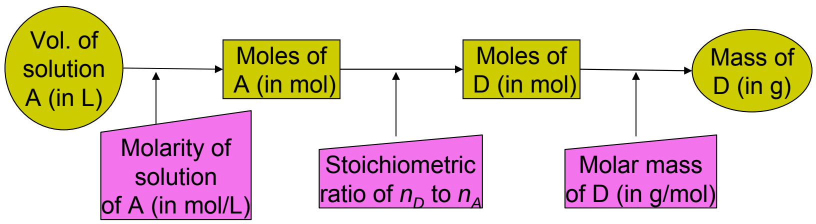
$$\text{mass of A (in } g) \times \frac{1\, mol \text{ A}}{\text{molar mass of A } (g)} \times \frac{n_C\, mol \text{ C}}{n_A\, mol \text{ A}} \times \frac{\text{molar mass of C } (g)}{1\, mol \text{ C}} = \text{mass of C (in } g)$$

Solution Stoichiometry

n_A A (*aq*) + n_B B (*aq*) → n_C C (*aq*) + n_D D (*s*)

A typical scenario

Given volume of a certain molar solution of chemical A, find mass that could be produced of chemical D.



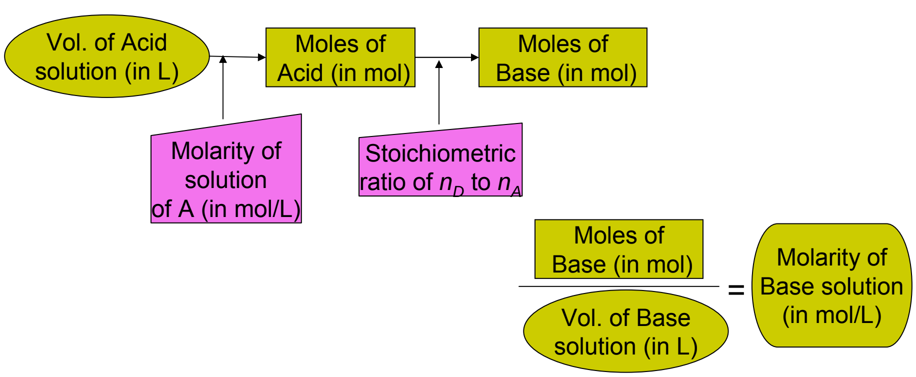
$$\text{volume of solution of A (in } L) \times \frac{\text{molarity of solution A } (mol)}{1\,L} \times \frac{n_D\ mol\ \text{D}}{n_A\ mol\ \text{A}} \times \frac{\text{molar mass of D } (g)}{1\,mol\ \text{D}} = \text{mass of D (in } g)$$

Acid-Base Titration

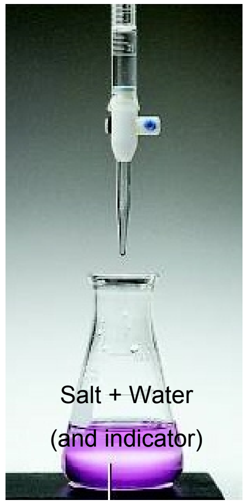
n_A Acid (*aq*) + n_B Base (*aq*) → n_S Salt (*aq*) + n_W H_2O (*l*)

A typical scenario

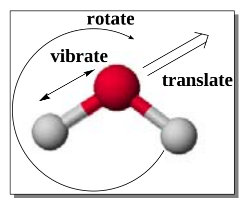
Given volume of a certain molar solution of Acid, find concentration of the Base solution if certain volume of Base used.



Example problem



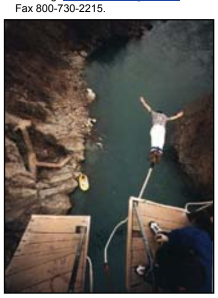
Solid sodium hydroxide absorbs moisture from the air, so it is difficult to weigh accurately to make a solution of known concentration. Potassium hydrogen phthalate, or KHP (m.w. 204.23), is monoprotic, can be weighed accurately, and is often used to standardize solutions of bases. 0.05182 grams of KHP are placed in a flask beneath a buret filled with NaOH solution of unknown concentration. If 23.4 mL of NaOH solution are required to exactly neutralize the KHP solution, what is the concentration of the NaOH solution?



Energy

1. Kinetic energy $E = \frac{1}{2}mv^2$
   - Energy of motion, mechanical energy
   - The faster the velocity, the higher the kinetic energy
   - Particle level energy
     - Thermal energy*: particles in motion in a material
     - Electrical energy: electrons moving through a conductor
     - Sound energy: orchestrated vibration of particles in a material such that spaces between the particles compress and expand
     - Light energy: photons of various energies
   - Macroscopic level mechanical energy
     - Moving objects

*Thermal energy and "heat" are synonyms



Energy

2. Potential energy
   - Energy of relative separation (because there are forces of attraction/repulsion between objects)
   - "Chemical" potential energy and electrostatic energy are associated with the arrangements of charged particles within and between atoms, according to predictions of Coulomb force

$$F = \frac{k\ Q_1\ Q_2}{r^2} \quad \text{and} \quad P.E. = -\int F\ dr$$

   - Gravitational potential energy is associated with arrangements of objects with mass, according to predictions of gravitational force

$$F = \frac{G\ m_1\ m_2}{R^2} \quad \text{which simplifies to } F = mg$$

$$\text{and} \quad P.E. = -\int F\ dr$$

Energy

- Energy can be converted from one form to another
- Energy transfer occurs in such a way that the total energy of the universe remains constant
  (First Law of Thermodynamics)
- Energy transfer occurs in such a way that matter and energy become more dispersed, that is, more spread out
  (Second Law of Thermodynamics)
- Let's consider how energy transfer happens when we are concerned only with thermal energy (a.k.a., heat)

Heat Transfer

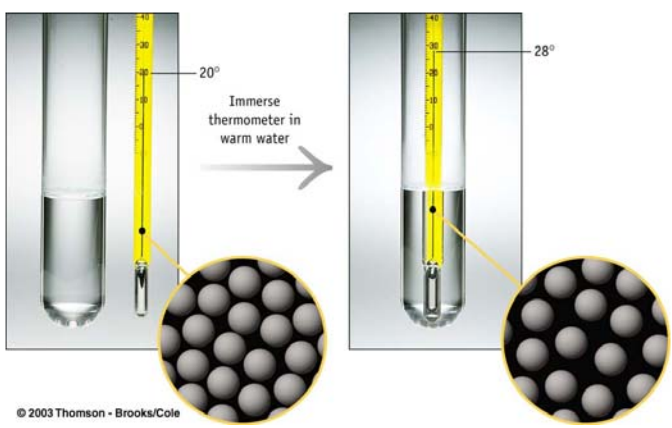
- Thermal energy
  http://www.colorado.edu/physics/2000/bec/temperature.html
- Transfer of thermal energy from one location to another
  http://jersey.uoregon.edu/vlab/Thermodynamics/therm1a.html

  When thermal energy is transferred, it always transfers from a location with more thermal energy to a location with less thermal energy. Energy continues to transfer until thermal equilibrium is established. (Energy gets more spread out.) Simply: hot to cold.

- To understand more about thermodynamic equilibrium, try all 7 "experiments" at
  http://jersey.uoregon.edu/vlab/Thermodynamics/index.html

Temperature

- A measurement made using an instrument called a thermometer
- How it works:



- So, what does temperature measure?

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Relative vs. Absolute Temperature Scales

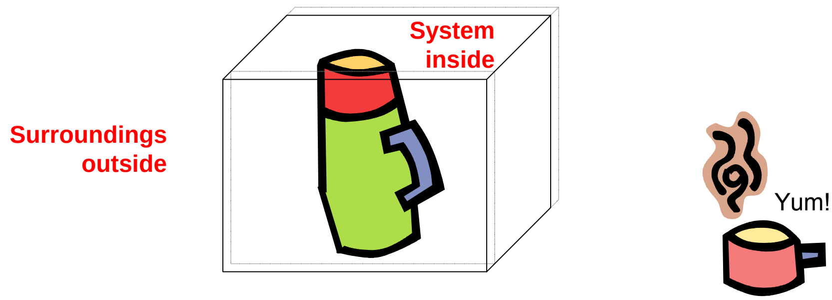
- Relative temperature (linear) scale measures temperature of an object relative to two points
  - Coldest and warmest temperatures at which humans can typically survive → Fahrenheit scale is relative
  - Freezing and boiling points of water → Celsius scale is relative
- Absolute temperature (linear) scale measures absolute motion of particles → Kelvin scale is absolute
  - Absolute zero temperature is a point of reference for disorder: there is no disorder at zero (Third Law of Thermodynamics)
  - Convenience: the size of 1 ºC is equal to the size of 1 K

Thermodynamics

- The study of heat (a.k.a., thermal energy)
- Theoretical model is built on taking averages (using statistics) of multiple possible arrangements of particles
- The most important question:
  What could the particles do?
- If heat transfers, it must transfer *from* something *to* something else
- Involves being able to draw imaginary boundaries around a "system"

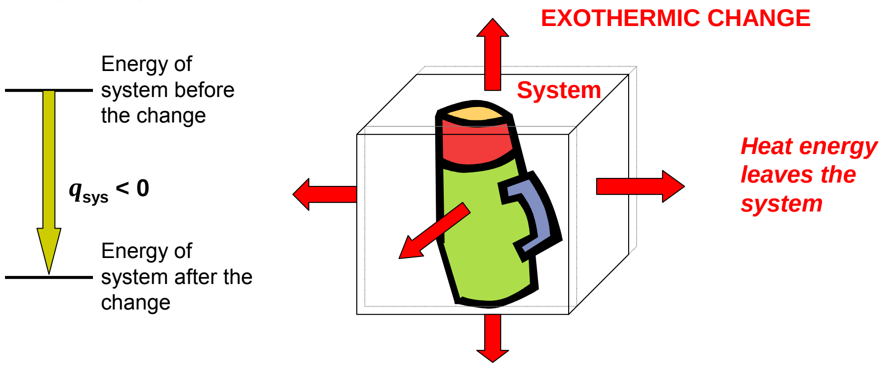
What is a System?

- A "system" is a 3-dimensional space, surrounded by an imaginary surface boundary, such that no <u>matter</u> passes through the boundary, but <u>heat energy</u> can transfer freely across the boundary



What happens to the SYSTEM when heat transfer occurs?

- As coffee eventually cools, heat energy is transferred to the air around the thermos and the counter beneath it.
- System: Particles in the coffee slow down their motion.
- Surroundings: Particles in the air, and particles in the counter, speed up their motion.

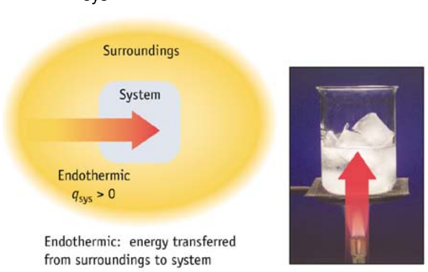


Conservation of Energy

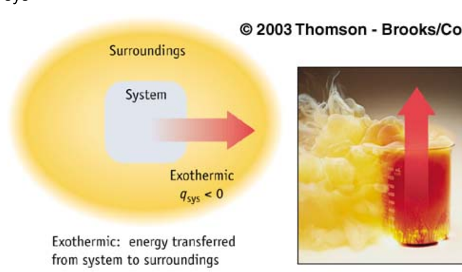
- When heat energy enters or leaves matter, energy is conserved.
- This means energy has to come from somewhere, and it has to go somewhere. It can be accounted for.
- Particle level: energy can go into or come out of the system, thereby increasing or decreasing the energy in the particles
  - Kinetic energy: motion of particles (translation, vibration, rotation) in solid, liquid and gas states
  - Potential energy: electron states in atoms or within bonds

Endothermic vs. Exothermic

Endothermic	Exothermic
Example: ice melting	Example: fire burning
Heat enters system	Heat exits system
System gains energy	System loses energy
$q_{sys} > 0$	$q_{sys} < 0$



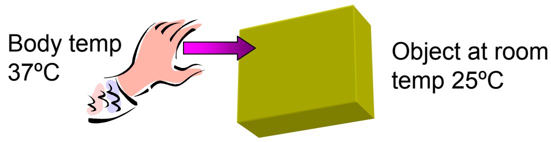
Endothermic: energy transferred from surroundings to system



Exothermic: energy transferred from system to surroundings

Quantitatively

- How do we measure heat lost or gained by a system?



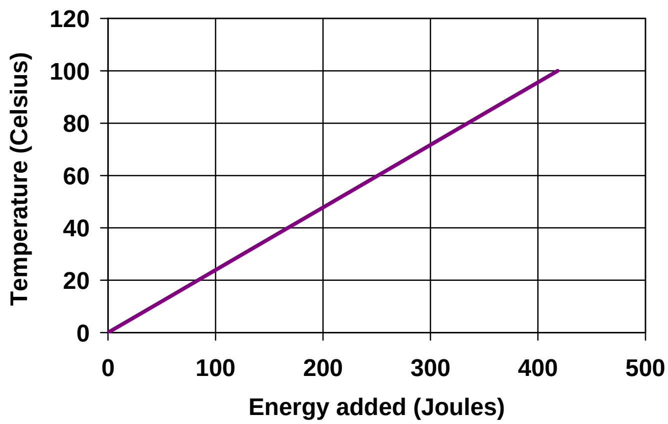
- What does the quantity of heat transferred depend on?
  - Quantity of material in the object
  - Size of temperature change
  - Identity of the material the object is made from

$$q = m\ C\ \Delta T$$

Water: A Useful Substance

- Liquid water's capacity to absorb heat (C) is enormous compared to most materials
- Heat capacity of water is very accurately known: 4.184 Joules per gram per degree Kelvin
- What this means:
  - If you have one gram of liquid water
  - To raise its temperature by 1 Kelvin (equal to 1ºC)
  - Takes 4.184 Joules of energy (equal to 1 calorie)
- Since $q = m\ C\ \Delta T$, if you are working with water then you know C. Therefore, if you have a specific quantity of water, and you measure the temperature it changes by, you can calculate the heat that transferred.

For a 1.00-gram sample of liquid water

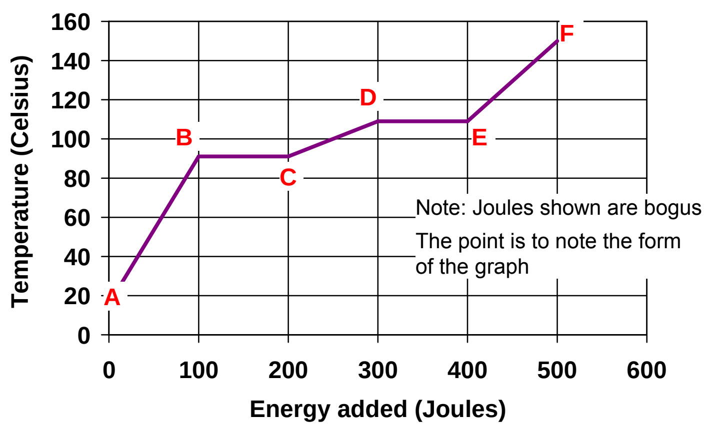


What happens if you add more heat energy to liquid water at 100ºC?

- It boils
- What is boiling?
  - There is a statistical range of kinetic energies (velocities) of particles in the liquid
  - Some particles will always have enough energy to break away from attractive forces that keep them in liquid → evaporation
  - As temperature rises, eventually it is high enough that so many particles can break away that their gas pressure (vapor pressure) equals the pressure of the surroundings → boiling
- Boiling continues with no change in temperature until all liquid particles have converted to gas phase

Heating Curve of 1.00-gram Sample of Methane (CH_4) at Standard Pressure

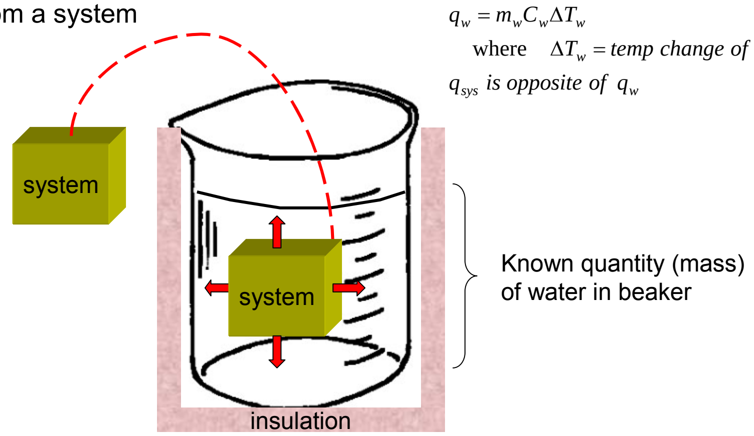
A = solid below melting*
B = solid has reached melting temperature, and is beginning to melt*
C = liquid at melting temperature, has just completed melting
D = liquid has reached boiling temperature, and is beginning to boil*
E = gas at boiling temperature, has just completed boiling*
F = gas above boiling temperature



See http://www.chemistry.wustl.edu/~gelb/gchem/materials/phases/

Back to Liquid Water's Capacity to Absorb Heat Energy

Measuring heat transferred from a system



<u>Problem Solving Strategy</u>

$q_w = m_w C_w \Delta T_w$

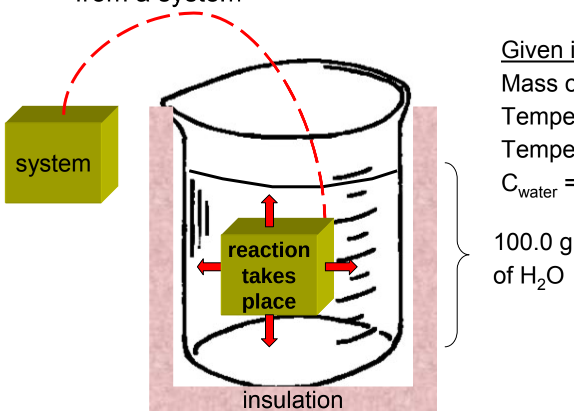
where $\Delta T_w = temp\ change\ of\ H_2O$

q_{sys} is opposite of q_w

Beaker image: core.ecu.edu/chem/chemlab/ equipment/ebeaker.htm

Calorimetry

Measuring heat transferred from a system



Problem Solving Strategy

$q_w = m_w C_w \Delta T_w$

where $\Delta T_w = \textit{temp change of } \mathrm{H_2O}$

q_{sys} *is opposite of* q_w

Given information

Mass of water = 100.0 g

Temperature of water before = 23.3ºC

Temperature of water after = 47.3ºC

C_{water} = 4.184 J/g·K

Beaker image: core.ecu.edu/chem/chemlab/ equipment/ebeaker.htm

Heat Changes More Generally