Chapter 8: Chemical Equations

8.1 The Chemical Equation

- A chemical equation represents a chemical reaction. A balanced equation:
  - o Summarizes the reaction,
  - o Displays the substances that are reacting,
  - o Shows the products, and
  - o Indicates the amounts of all substances in the reaction.

- Let's examine the structure & terminology of a chemical equation.

$$\underbrace{Al + Fe_2O_3}_{\text{reactants}} \rightarrow \underbrace{Fe + Al_2O_3}_{\text{products}}$$

$$2\ Al + Fe_2O_3 \rightarrow 2\ Fe + Al_2O_3$$

$$2\ Al + Fe_2O_3 \xrightarrow{\Delta} 2\ Fe + Al_2O_3$$

Symbol	Meaning
+	Plus or added to (placed between substances)
→	Yields; produces (points to products)
(*s*)	Solid state (written after a substance)
(*l*)	Liquid state (written after a substance)
(*g*)	Gaseous state (written after a substance)
(*aq*)	Aqueous solution (substance dissolved in water)
Δ	Heat is added (when written above or below arrow)

$$2\ Al\,(s) + Fe_2O_3\,(s) \xrightarrow{\Delta} Fe\,(l) + Al_2O_3\,(s)$$

- Law of Conservation of Mass: In a chemical reaction atoms are neither created nor destroyed. All atoms present in the reactants must also be presents in the products.
  - o In a chemical reaction mass of reactants = mass of products.

To get everyone on the same λ for the Conductivity Lab, let's detour to Ch 15…

15.3 Electrolytes and Nonelectrolytes

- An aqueous solution, state (aq), is a homogeneous mixture made by dissolving a soluble substance in water. For example,

$$NaCl(s) \xrightarrow{H_2O(\ell)} NaCl(aq)$$

The water is drawn over the arrow to signify that it is not reacting with the water but only mixing with it, or dissolving in the water.

- An electrolyte is a substance whose aqueous solution conducts electricity (the subject of our lab!). We divide soluble substances into three types of electrolytes based on how well their aqueous solutions conduct electricity:
    - o Nonelectrolyte: the aqueous solution does not conduct electricity.
    - o Weak electrolyte: the aqueous solution conducts a small amount of electricity because the concentration of ions in solution is low.
    - o Strong electrolyte: the aqueous solution conducts electricity well, indicating a large number of ions are in solution.


Pure Water


Nonelectrolyte


Weak electrolyte


Strong electrolyte

Writing Dissociation Equations for Strong Electrolytes

- Soluble ionic compounds are strong electrolytes, and 100% of the molecules dissociate (separate) into their ions when dissolved in water.
    - The large number of ions generated allows the solution to conduct electricity strongly. We can write dissociation equations to show the ions generated.

$$NaCl(s) \xrightarrow{H_2O(\ell)} Na^+(aq) + Cl^-(aq)$$

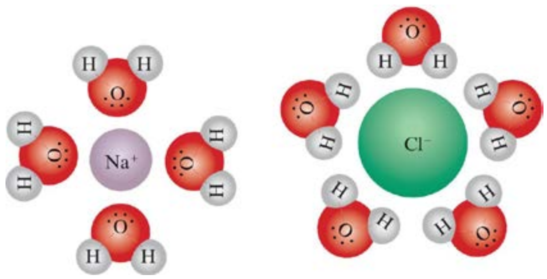
$$CaCl_2(s) \xrightarrow{H_2O(\ell)} Ca^{2+}(aq) + 2\ Cl^-(aq)$$

$$Al_2(SO_4)_3(s) \xrightarrow{H_2O(\ell)} 2\ Al^{3+}(aq) + 3\ SO_4^{2-}(aq)$$

$AgCl(s) \xrightarrow{H_2O(\ell)}$ no dissociation, no ions; this salt is insoluble in water

- We will shortly see 'Solubility Rules' which will allow us to predict which combinations of cation and anion will produce a soluble salt.

- The ions of soluble salts are surrounded by polar water molecules. This stabilizes the ions and keeps them in solution.



- The ions of insoluble salts are not sufficiently stabilized by this 'hydration' to remain in solution, so these salts do not dissolve.

What about nonelectrolytes and weak electrolytes?

TABLE 15.2 | Representative Electrolytes and Nonelectrolytes

Electrolytes		Nonelectrolytes	
H_2SO_4	$HC_2H_3O_2$	$C_{12}H_{22}O_{11}$ (sugar)	CH_3OH (methyl alcohol)
HCl	NH_3	C_2H_5OH (ethyl alcohol)	$CO(NH_2)_2$ (urea)
HNO_3	K_2SO_4	$C_2H_4(OH)_2$ (ethylene glycol)	O_2
$NaOH$	$NaNO_3$	$C_3H_5(OH)_3$ (glycerol)	H_2O

- Nonelectrolytes do not generate any ions when they dissolve in water, and since there are no ions, no electricity is conducted. Since there are no ions to separate, we refer to the dissolving equation for a nonelectrolyte.

$$C_{12}H_{22}O_{11}(s) \xrightarrow{H_2O(\ell)} C_{12}H_{22}O_{11}(aq)$$

$$C_2H_5OH(\ell) \xrightarrow{H_2O(\ell)} C_2H_5OH\ (aq)$$

- Weak electrolytes are covalent (nonionic) compounds that react with water to generate a small number of ions resulting in weak conductivity.
  - o Weak acids and weak bases are weak electrolytes.
    - We say these substances ionize in water, creating ions where none existed before. Here are some ionization equations of weak electrolytes; note that water is a reactant in these equations.

Acetic acid, weak acid: $CH_3COOH(aq) + H_2O(\ell) \rightarrow H_3O^+(aq) + CH_3COO^-(aq)$

Ammonia, weak base: $NH_3(aq) + H_2O(\ell) \rightarrow NH_4^+(aq) + OH^-(aq)$

8.2 Writing and Balancing Chemical Equations

- A chemical equation is balanced consistent with the law of mass conservation so that we obtain the same number of each kind of atom on both sides of the equation.
  - Once all reactants and products have been specified, an equation is balanced only be adjusting coefficients.

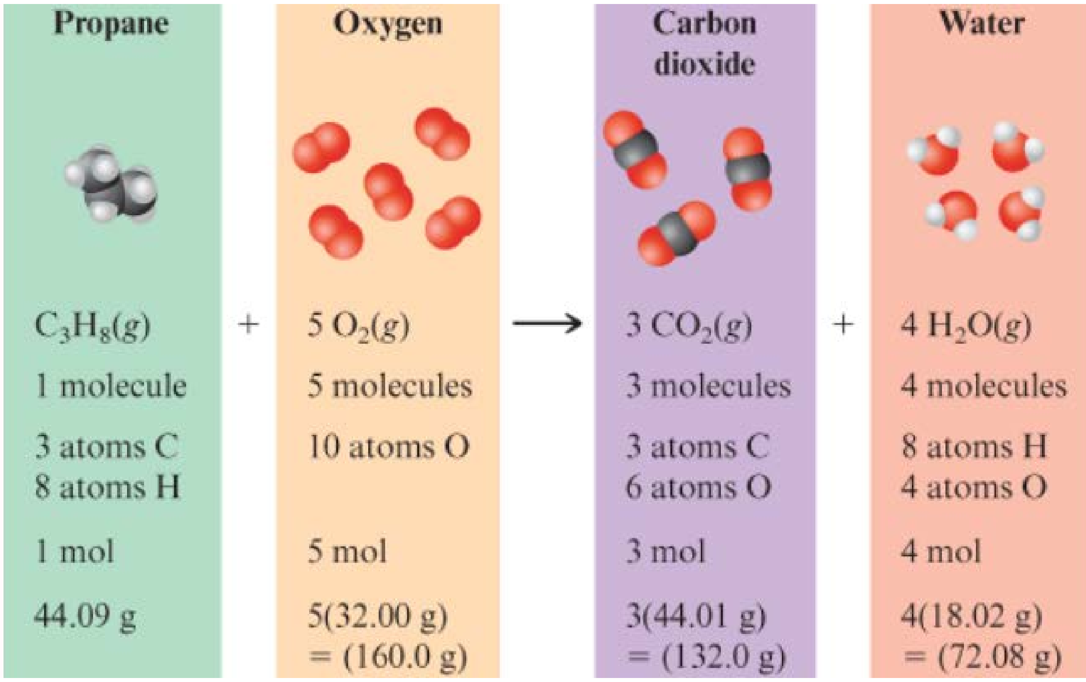
- There is no silver bullet for balancing the simple equations we will start with. At best, it is an iterative trial-and-error process.
  - My approach is to work from left to right, balancing each element one at a time. Often, you must start again at the left if one element was unbalanced by balancing another. But it goes fast!
  - You can also maintain a simple table of the numbers of each element on both sides of the equation to help you.

Magnesium metal is placed into aqueous hydrobromic acid forming hydrogen gas and aqueous magnesium bromide.

Aqueous solutions of silver nitrate and aluminum iodide are mixed together forming solid silver iodide and aqueous aluminum nitrate.

Complete and balance the equation for the complete combustion of methanol, CH_3OH.

Information in a Chemical Equation



8.3 Why Do Chemical reactions Occur?

- Chemists have identified a number of "driving forces" which, when observed, tell us that the reactants are being converted to products. The reaction is being 'driven' forward.

  - Formation of a solid
  - Formation of a gas
  - Formation of water
  - Transfer of electrons

- We will consider these driving forces as we examine several types of chemical reactions in the next section.

8.4 Types of Chemical Equations

- Many chemical reactions can be classified as one or more of five principal reaction types.

- Synthesis (Combination) Reaction: Two reactants combine to give one product.

$$A + B \rightarrow AB$$

- Combustion Reaction: A substance reacts with oxygen to form oxides.

- Decomposition Reaction: A single reactant is decomposed (broken down) to give two or more products.

$$AB \rightarrow A + B$$

- Single-Displacement Reaction: An element reacts with a compound to replace one of the elements in the compound. The products are a different element and a different compound. (aka Single Replacement)

$$A + BC \rightarrow B + AC$$

- Double-Displacement Reaction: two reactant compounds exchange partners with each other and yield two different product compounds. (aka Double Replacement)

$$AB + CD \rightarrow AD + CB$$

8.5 Heat in Chemical Reactions

- Chemical reactions are either exothermic or endothermic:
  - Exothermic reactions liberate (release) heat.
  - Endothermic reactions absorb heat.

- We may write the amount of energy involved in-line with the reactants (endothermic rxn), or the products (exothermic rxn).

$$6\ CO_2(g) + 6\ H_2O(g) + 2519\ kJ \rightarrow C_6H_{12}O_6(s) + 6\ O_2(g)$$

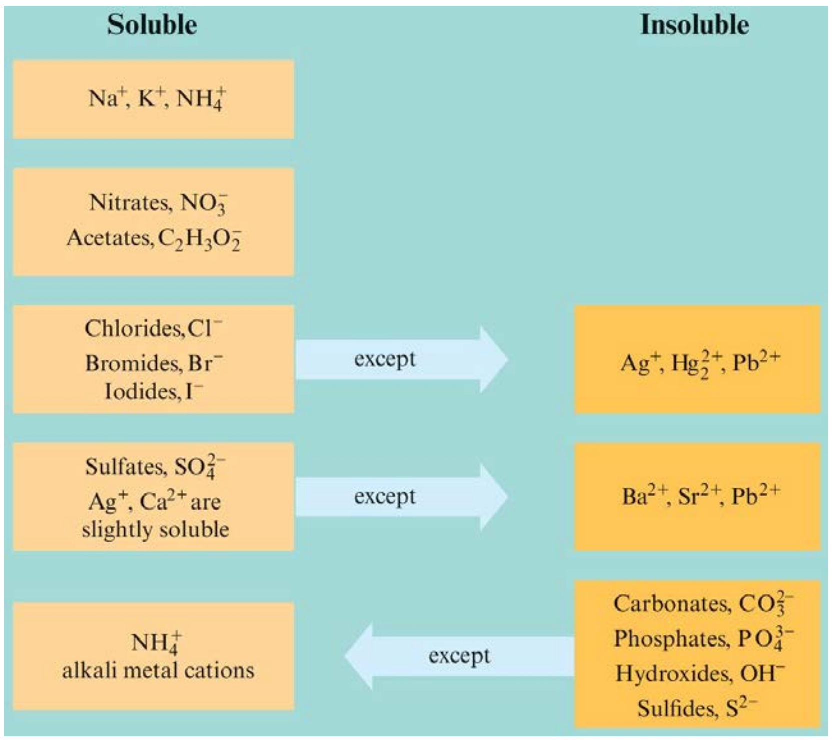
$$C_6H_{12}O_6(s) + 6\ O_2(g) \rightarrow 6\ CO_2(g) + 6\ H_2O(g) + 2519\ kJ$$

8.6 Climate Change: The Greenhouse Effect

- Suggested reading to better understand the role of $CO_2(g)$.

15.6 Writing Net Ionic Equations

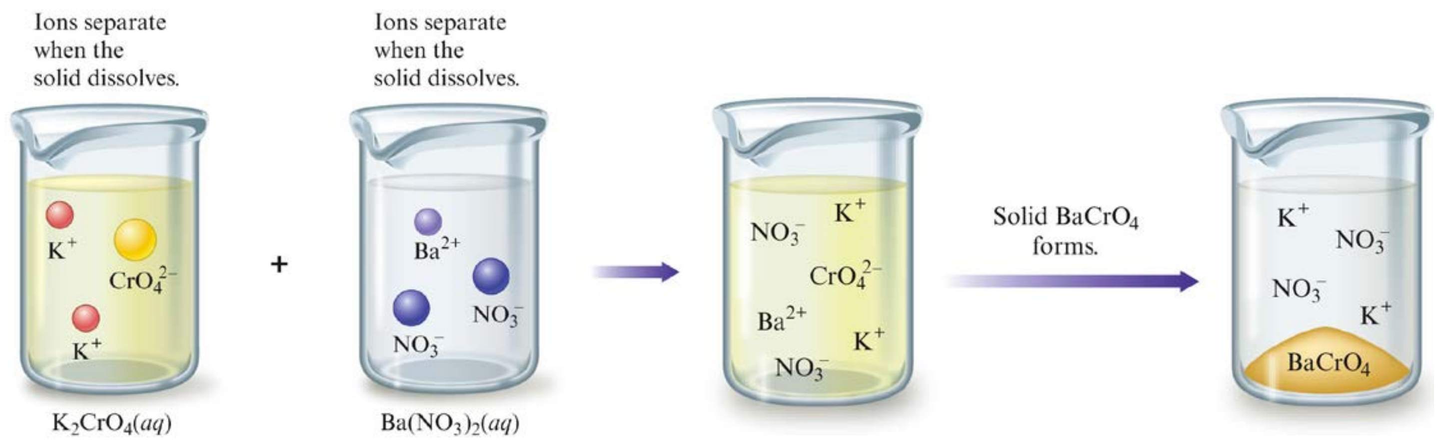
- Net Ionic Equations are written to include only those molecules or reactants that have reacted. They express the chemical change of a reaction.
  - For us, they are most often written for double displacement reactions which yield a solid product (Precipitation Reaction) or water (Neutralization Reaction).
  - The products of a Double Displacement reaction are predicted, and Solubility Rules are applied to determine their solubilities.



- Let us consider what happens when the solutions of two strong electrolytes are mixed; will products be formed?
  - Upon mixing these solutions, a yellow solid is formed. What is the identity of this solid product?

  - The mixed solution contains four types of ions: K^+, CrO_4^{2-}, Ba^{2+}, NO_3^-.

  - Determine the possible products from the ions in the reactants using Double Displacement and the Solubility Rules.



- How to Predict Precipitates When Solutions of Two Ionic Compounds Are Mixed

  1. Write the reactants as they actually exist before any reaction occurs. Recall that when a soluble salt dissolves, its ions separate (dissociate).

  2. Consider the various solids that could form. To do this, simply exchange the anions of the added salts (double displacement!).

  3. Use the solubility rules to decide whether a solid forms and, if so, to predict the identity of the solid.

Which of the following ions form compounds with Pb^{2+} that are generally soluble in water?

S^{2-} Cl^{-} NO_3^{-} SO_4^{2-} Na^{+}

A sodium phosphate solution reacts with a lead(II) nitrate solution. What precipitate, if any, will form?

$Pb_3(PO_4)_2$ $NaNO_3$ $Pb(NO_3)_2$ No ppt

Consider a solution with the following ions present:

NO_3^{-}, Pb^{2+}, K^{+}, Ag^{+}, Cl^{-}, SO_4^{2-}, PO_4^{3-}

When all are allowed to react (and there is plenty available of each), how many different solids will form? List them.

Complete and balance this chemical equation:

$AgNO_3(aq)$ + $KCl(aq)$ →

- We can write three different chemical equations to represent a precipitation reaction. We will write the three equations for this problem:

$K_2CrO_4(aq)$ + $Ba(NO_3)_2(aq)$ → ?

1. Formula (or Molecular) Equation: use Double Displacement to predict the products, and the Solubility Rules to predict the product states. Balance the equation. All formulas are neutral; no ions are shown.

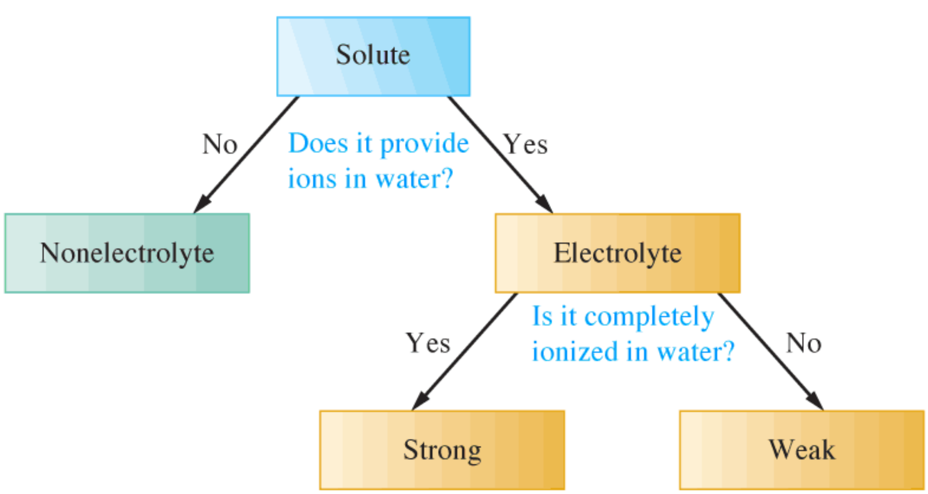
2. Complete (Total) Ionic Equation: all strong electrolytes in the Formula Equation are shown as their ions. Separate (*aq*) species in the Molecular Equation into their ions; be careful with coefficients and subscripts.

   Identify the spectator ions, those which do not change from the reactant side to the product side of the equation; they remain in solution.

3. **Net Ionic Equation (NIE)**: shows only those components of the solution that undergo a change. Simply re-write the Complete Ionic Equation, omitting the spectator ions.

Write the balanced Molecular, Complete Ionic, and Net Ionic equations for:

$FeSO_4(aq)$ + $K_3PO_4(aq)$ →



7.1 The Mole

- Atoms and molecules are incredibly small particles, yet we need a way to reliably measure out known quantities in the lab.

- Since chemical equations relate numbers of atoms and molecules, we need a way to count these in the lab.

- We have the following SI definitions to help us:

  - The mass of 1 atom of $^{12}_{6}\mathrm{C}$ = 12 u exactly.
  - The number of $^{12}_{6}\mathrm{C}$ atoms in exactly 12 g of $^{12}_{6}\mathrm{C}$ is exactly 1 mole.

    - mole is abbreviated mol
    - 1 mol of $^{12}_{6}\mathrm{C}$ contains 6.022:14 × 10^{23} $^{12}_{6}\mathrm{C}$ atoms.
    - 6.022 × 10^{23} is Avogadro's number.
    - A mole tells us how many, just like a dozen or a gross.

- Since all atomic weights in the periodic table are determined relative to C-12, we have the following perspectives:
  Mass of an atom of an element = atomic weight number + units 'u'
  Mass of 1 mole of an element = atomic weight number + units 'g'

Symbol name	C (carbon)	Al (aluminum)	Pb (lead)
Element	Richard Megna/Fundamental Photographs 	Richard Megna/Fundamental Photographs 	Richard Megna/Fundamental Photographs 
Average atomic mass	12.01 u	26.98 u	207.2 u
Mass of sample	12.01 g	26.98 g	207.2 g
Number of atoms in sample	6.022 × 10^{23} atoms	6.022 × 10^{23} atoms	6.022 × 10^{23} atoms

- We can convert among number, moles, and mass of an element by noting the following:

$$6.022 \times 10^{23} \text{ atoms} = 1 \text{ mole} = \text{molar mass (g)}$$

  - Many conversion factors may be created from these equivalences, but always include moles in your conversion factor.

What is the mass of 0.252 mol of copper?

How many atoms are present in 0.025 mol of iron?

How many magnesium atoms are contained in 5.00 g of Mg?

7.2 Molar Mass of Compounds

- One mole of a compound contains Avogadro's number of formula units ('molecules') of that compound.

- The molar mass of a compound can be calculated by adding the molar masses of all the atoms in the chemical formula.

  - Be careful counting the numbers of atoms in the formula!
  - Be careful when dealing with naturally-occurring diatomics!

What is the molar mass of water?

What is the molar mass of oxygen gas?

What is the molar mass of Na_2SO_4?

What is the mass of 0.150 mol of Na_2SO_4.

Chapter 9: Calculations from Chemical Equations

9.1 Introduction to Stoichiometry

- Stoichiometry is the art of calculating the amounts of products or reactants using a balanced chemical equation.

- At the heart of stoichiometry is using a ratio of coefficients from the balanced equation to convert the moles of one species into the moles of another.
  - o Dimensional analysis skills are used here!

- Consider the balanced equation for the combustion of propane:

$$1\ C_3H_8(g) \quad + \quad 5\ O_2(g) \quad \rightarrow \quad 3\ CO_2(g) \quad + \quad 4\ H_2O(g)$$

  Let's see how stoichiometry works!

When 0.5 mol of propane combusts, how many mol of H_2O are made?

How many mol of oxygen are need to combust 5.0 mol of propane?

How many mol of CO_2 are produced when 6.0 mol of water forms?

9.2 Mole–Mole Calculations

- Let's look at a couple more examples.

How many moles of aluminum oxide will be produced from 0.50 mol of oxygen? $4\ Al + 3\ O_2 \rightarrow 2\ Al_2O_3$

How many moles of aluminum hydroxide are required to produce 22.0 mol of water? $2\ Al(OH)_3 + 3\ H_2SO_4 \rightarrow Al_2(SO_4)_3 + 6\ H_2O$

9.3 Mole–Mass Calculations

- Sometimes you will be given an initial mass or be asked to determine your answer as a mass.
  - Use molar mass to convert mass to moles, or moles to mass.

How many moles of potassium chloride and oxygen can be produced from 100.0 g of potassium chlorate? $2\ KClO_3 \rightarrow 2\ KCl + 3\ O_2$

How many grams of silver nitrate are required to produce 0.25 mol of silver sulfide? $2\ AgNO_3 + H_2S \rightarrow Ag_2S + 2\ HNO_3$

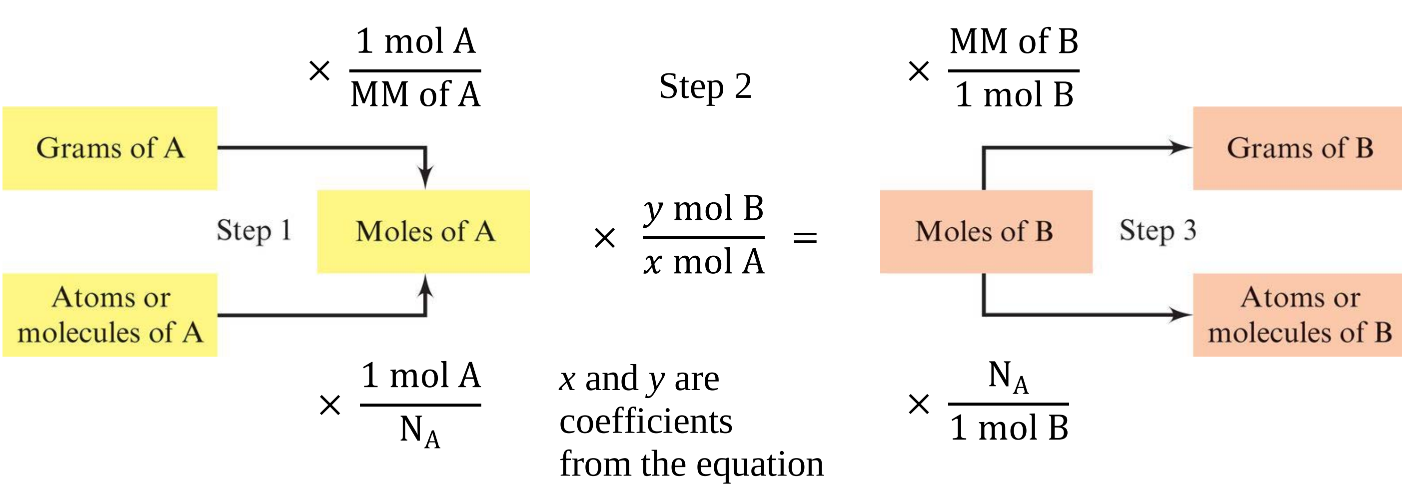
9.4 Mass–Mass Calculations

- Or you might be given mass and be asked to answer in mass!
  - Remember that moles are needed at the heart of stoichiometry.

How many grams of chromium(III) chloride are required to produce 75.0 g of silver chloride? $CrCl_3$ + 3 $AgNO_3$ → $Cr(NO_3)_3$ + 3 AgCl

What mass of water is produced by the complete combustion of 225.0 g of butane (C_4H_{10})? 2 C_4H_{10} + 13 O_2 → 8 CO_2 + 10 H_2O

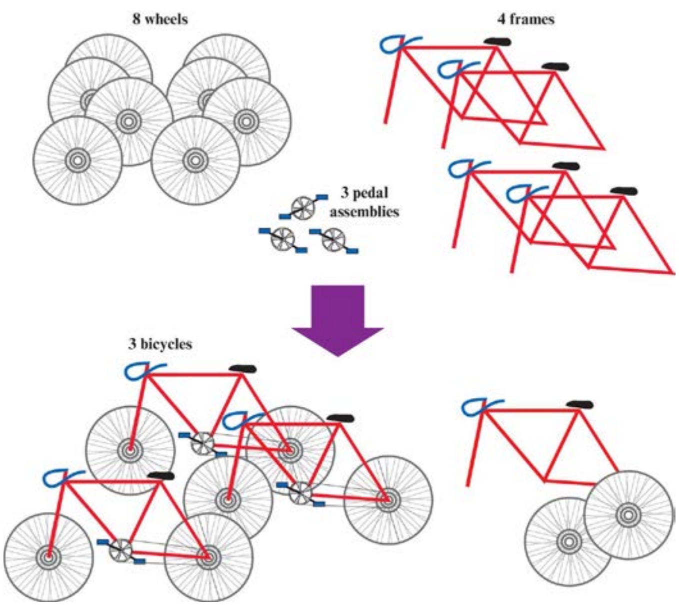
A Summary of the Calculations in Simple Stoichiometry



9.5 Limiting Reactant and Yield Calculations

- In the real world, we may have more of a reactant than needed, either by accident or by design.
  - o Consider this analogy in which we are assembling bicycles according to the 'equation:'

1 Frame + 2 Wheels + 1 Pedal Assembly → 1 Bicycle



  - o When we run out if pedal assemblies, we cannot produce more bicycles.
    - ▪ We refer to the pedal assembly as the 'limiting reactant.'
    - ▪ The frame & wheels are 'excess reactants' and are left over.

- Let us apply these concepts to balanced chemical equations.

PROBLEM-SOLVING STRATEGY For Limiting Reactant Problems

1. Calculate the amount of product (moles or grams, as needed) formed from each reactant.
2. Determine which reactant is limiting. (The reactant that gives the least amount of product is the limiting reactant; the other reactant is in excess.)
3. Once we know the limiting reactant, the amount of product formed can be determined. It is the amount determined by the limiting reactant.
4. If we need to know how much of the other reactant remains, we calculate the amount of the other reactant required to react with the limiting reactant, then subtract this amount from the starting quantity of the reactant. This gives the amount of that substance that remains unreacted.

- Yahoo! The book and I are on the same wavelength!

How many grams of hydrogen chloride can be produced from 0.490 g of hydrogen and 50.0 g of chlorine? $H_2(g) + Cl_2(g) \rightarrow 2\ HCl(g)$

How many grams of barium sulfate will be formed from 200.0 g of barium nitrate and 100.0 g of sodium sulfate? What mass of the excess reactant is left over?

$$Ba(NO_3)_2(aq) + Na_2SO_4(aq) \rightarrow BaSO_4(s) + 2\ NaNO_3(aq)$$

- Thus far, our calculations have assumed the maximum yield of product, or 100%.

- Product yield might be less than 100% for a variety of reasons:
  - Side reactions produce other, unwanted products.
  - Reversible reactions occur.
  - Some of the product is lost in handling and transfer.

- Percent yield is defined as the actual yield (observed/measured in the lab) divided by the theoretical yield (calculated by stoichiometry) times 100%.
  - Yields may all be expressed in grams, or all expressed in moles.

$$\text{Percent Yield} = \frac{\text{Actual Yield}}{\text{Theoretical Yield}} \times 100\%$$

If the theoretical yield for a reaction is 72.3 g of CCl_4, and 65.0 g of carbon tetrachloride was actually obtained, calculate the percent yield. (See example 9.13 on page 188 of your text for the complete calculation.)