

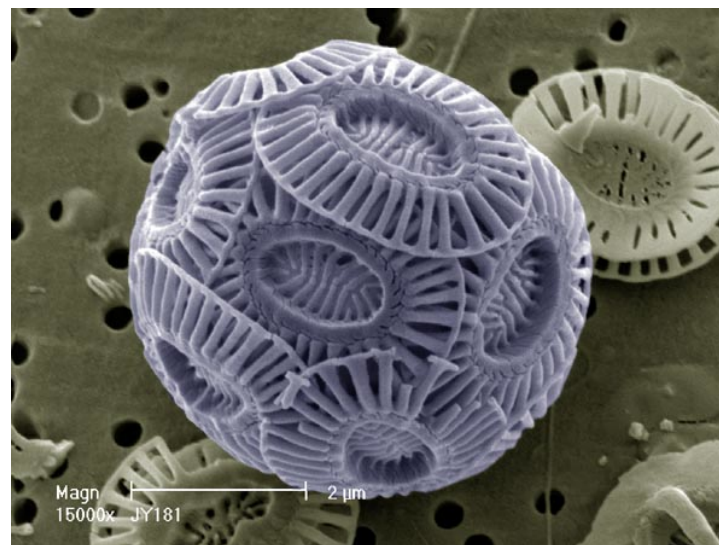
Chapter 4: Reactions in Aqueous Solutions

How do living organisms make bones, teeth, shells or exoskeletons?

They do this through a process called **biomineralization** which involves the formation of insoluble ionic compounds by living organisms.

Reactions with acid can dissolve these bones, shells and exoskeletons etc.

In this group of lectures and activities, we will try to understand reactions between ionic compounds, reactions between acids and bases as well as a new kind of reaction involving the transfer of electrons.



<http://oceanworld.tamu.edu/resources/oceanography-book/Images/emiliana-huxleyi.jp>

General Properties of Aqueous Solutions

- Lets find out how to predict how many ions are in the solution of a compound.

Below is a list of compounds that have been dissolved in water to make a solution.

Predict whether each solution will conduct electricity by completing the table below.

- All soluble ionic compounds and all strong acids conduct electricity strongly
- ✓ All weak acids and bases conduct electricity weakly
- ✓ All molecules that are not acids or bases do not conduct electricity at all
- Assume that all molecules in Chapter 4 are soluble.

a) Determine if each substance is molecular or ionic, an acid or a base or neither, or soluble or insoluble in water.

b) Using this information predict whether the solution will be a strong conductor of electricity (lots of ions in solution), a weak conductor of electricity (some ions in solution) or a nonconductor of electricity (no ions in solution).

Solution	Molecular (M) or Ionic (I)	Acid (A), or Base (B), or Neither (N)	Soluble (S) or Insoluble (I)	Strong (S), or Weak (W), or Nonconductor (NC)
Pure H ₂ O	M	N	NOT APPLICABLE	NC
NaCl	I	N	S	S
C ₁₂ H ₂₂ O ₁₁ (sugar)	M	N	S	NC
CH ₃ COOH (vinegar)	M	A	S	W
HCl	M	A	S	S
NaOH	I	B	S	S
CH ₃ OH (methanol)	M	N	S	NC
BaSO ₄	I	N	I	NC

Solubility rules to know:

If an ionic compound **contains** one of the following ions, it is **soluble** in water. If an ionic compound **does not contain** one of these ions, it is **insoluble** and releases no ions in water.

- Cations: NH₄⁺
Group I cations (Li⁺, Na⁺, K⁺, Rb⁺ and Cs⁺)
- Anions: nitrates (NO₃⁻)
acetates (CH₃COO⁻)
chlorates (ClO₃⁻)

Acids to know:

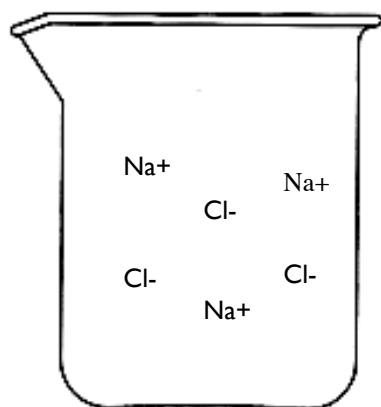
Strong Acids: HCl, HI, HBr, HNO₃, H₂SO₄
Weak : HF, H₂CO₃, CH₃COOH, H₃PO₄

Bases to know:

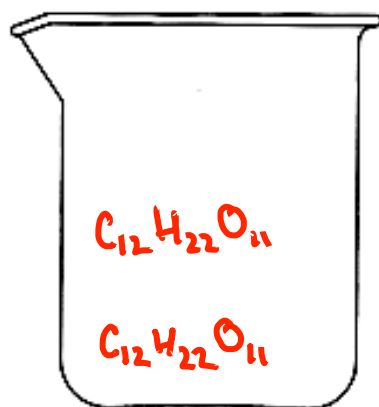
Strong: NaOH, KOH, Ba(OH)₂
Weak: NH₃

General Properties of Aqueous Solutions

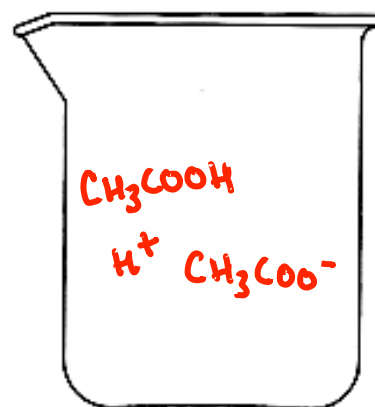
- c) Create a representative drawing of each solution from the previous page would look like in the beakers below.
For example, the NaCl solution has been drawn for you.



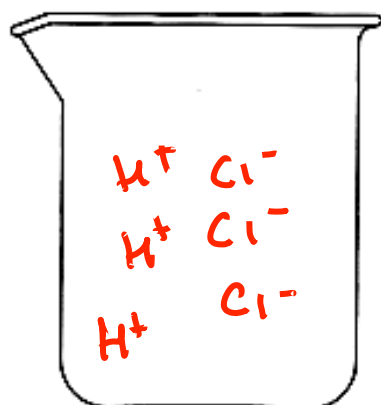
NaCl



$\text{C}_{12}\text{H}_{22}\text{O}_{11}$

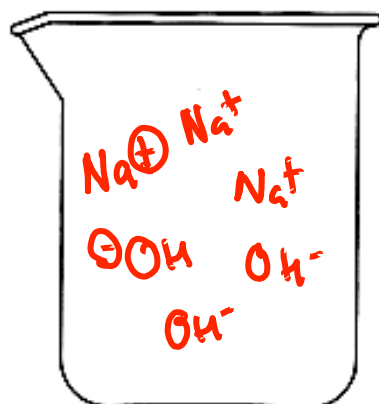


CH_3COOH
Weak

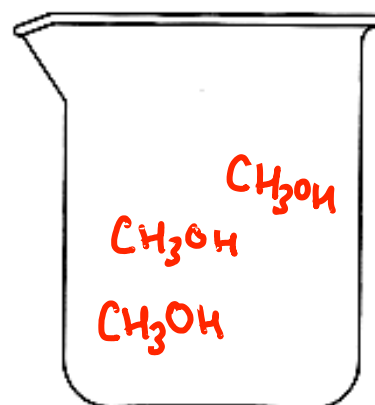


HCl

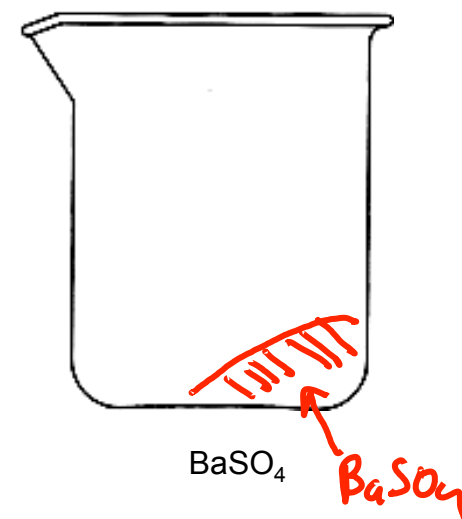
Strong



NaOH



CH_3OH



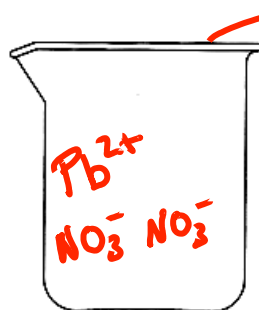
BaSO_4

BaSO_4

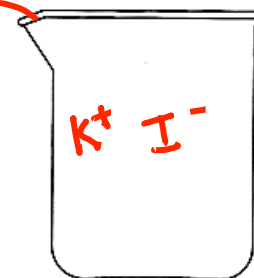
Precipitation Reactions

- All soluble ionic compounds break apart into separate ions when dissolved in water. The process of an ionic compound breaking apart in solution is called **dissociation**. When two ions come together in water to form an insoluble material that process is called **precipitation**.
- When an ionic compound is dissolved in water, we say that we have a **solution** of that compound, and this means we have a solution of ions dissolved in water.

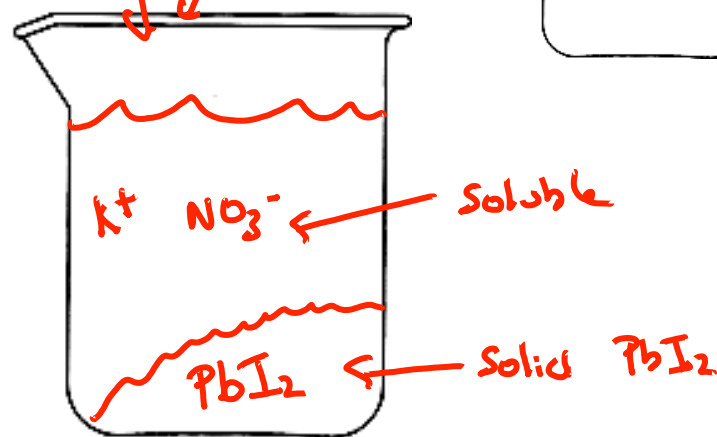
a. Draw a picture of a **Pb(NO₃)₂** solution



b. Draw a picture of a **KI** solution



c. Using the beaker at right, draw a picture of the resulting solution formed from **adding Pb(NO₃)₂ to KI**. See the note below to help with your drawing.



- ★NOTE: the presence of more than one soluble ionic compound in a solution is going to allow different pairs of ions to come in contact with each other. Some pairs of ions when they come in contact with each other form insoluble compounds. This is a property of the **pair of ions**, not of the individual ions.

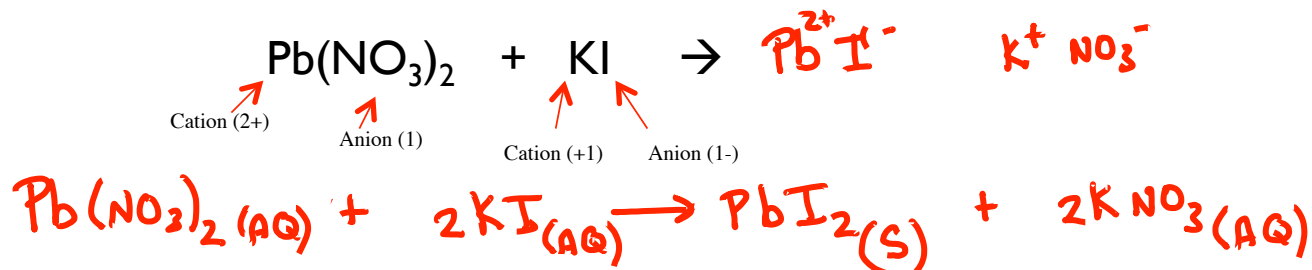
Examples:

Pb^{2+} and NO_3^-	lead ion and nitrate	is soluble
K^+ and I^-	potassium ion and iodide	is soluble
K^+ and NO_3^-	potassium ion and nitrate	is soluble
Pb^{2+} and I^-	lead ion and iodide	is insoluble

- Forming a solid from two dissolved ions is called a **precipitation reaction**

Writing Exchange Reactions

- When two soluble ionic compounds exist in the same container of water the compounds will undergo an **exchange reaction**. This is a type of chemical reaction is one where the reactants are composed of two different soluble ionic compounds and the cation-anion pair of one ionic compound is exchanged with the cation-anion of the other ionic compound in the container. Below is the exchange reaction from the previous page.



Below are the steps to write the balanced chemical equation for an exchange reaction between two ionic compounds.

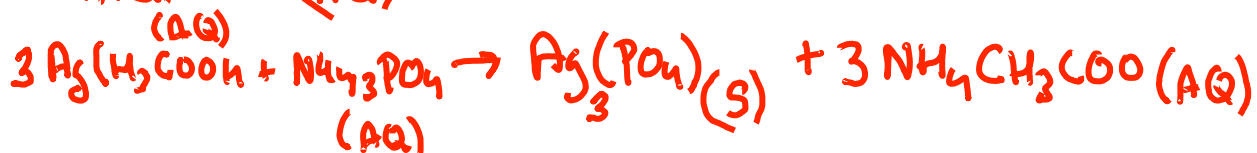
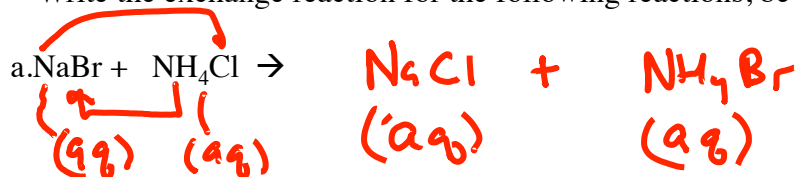
Step 1: Exchange cation –anion reacting pairs

Step 2: Write chemical formulas of products as neutral species

Step 3: Balance the overall reaction, both reactants and products

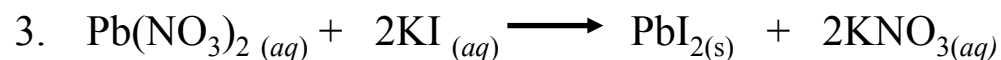
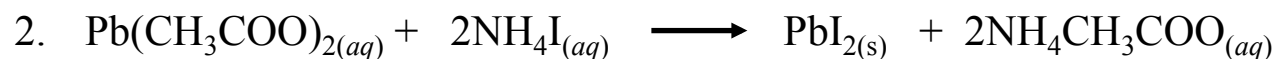
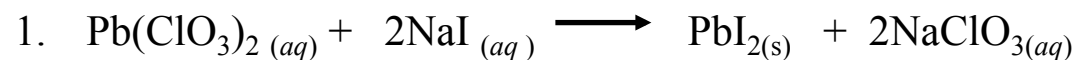
Step 4: Add phase labels: Look at each reactant and product. If it is soluble in water write an (aq) next to the formula, it is a solid in water write a (s), a gas in water a (g) and a liquid in water an (l). Note you will need to know the solubility rules to determine which reactants or products are soluble in water (aq) and which are insoluble (s).

- Write the exchange reaction for the following reactions, be sure to include the phase labels.



Comparing Exchange Reactions

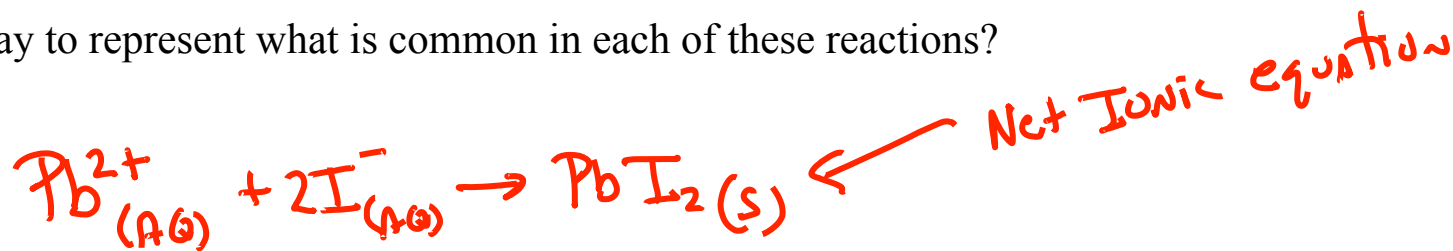
Below are the **balanced chemical equations** for three exchange reactions.



a. In the space below write down something each of these reactions has in common.

PbI_2 , all reactants soluble, Pb^{2+} , I^-

b. Is there a way to represent what is common in each of these reactions?



Writing Total Ionic and Net Ionic Equations

- For any reaction involving ions, we can write two kinds of equations. The first is known as an **ionic equation** and this equation contains all of the ions present during the reaction. We can also write a **net ionic equation**. The net ionic equation contains only the ions that react with each other.

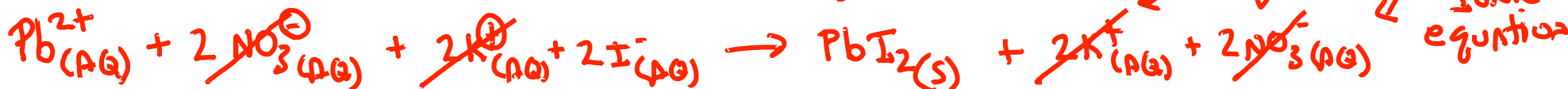
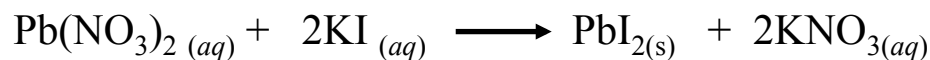
Steps for writing a total ionic equation and a net ionic equation:

✓ Step 1: Write down the balanced chemical equation with all reactants and products written as neutral compounds.

Step 2: Identify all strong acids, strong bases, and soluble ionic compounds. Write them as their separate ions. Keep all weak acids and weak bases as molecules. The result of this step is the **total ionic equation**.

Step 3. Identify and cancel all ions that do not participate in the reaction. These are called *spectator ions* and appear the same on both sides of the reaction arrow. The result of this step is the **net ionic equation**.

What is the total ionic and net ionic equation for the balanced chemical equation below?

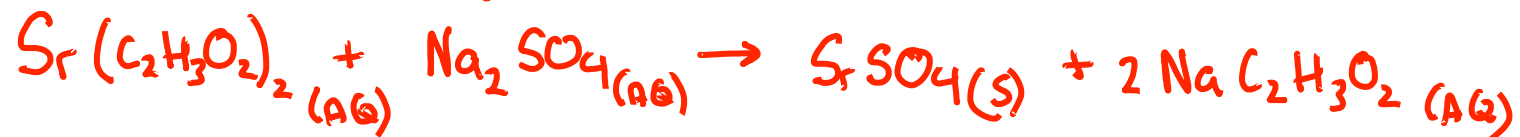


Writing Chemical Reactions from the Products of a Reaction

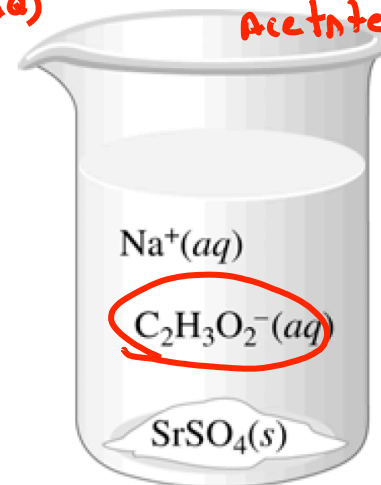
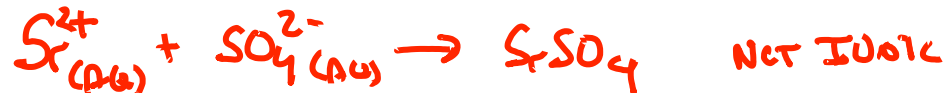
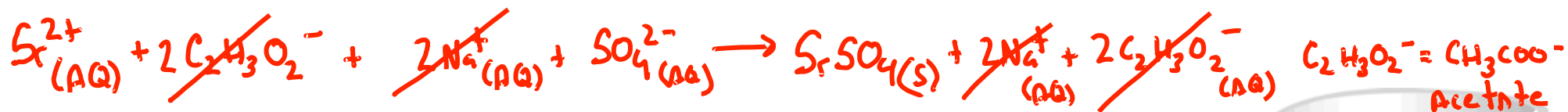
We have worked several problems where we knew something about the identity of the reactants. Now let's look at a problem where we only know something about the products.

- a) You find a beaker in a lab and determine it contains the ions and solid material as shown in the beaker below. Write the net ionic, total ionic and complete balanced equation that would produce these products.

Complete balanced equation



Total Ionic equation:



Concentrations of Solutions

- Let's define a new conversion factor to help us understand just how many ions or molecules we have dissolved in our solution. This conversion factor is called **molarity** and it is a way of expressing the concentration of an ion or molecule that is dissolved in some solution. Solutes are ionic compounds, or ions or molecules that are dissolved in a solution.

$$\text{Molarity (M)} = \text{moles of solute/liter of solution}$$

For example, a 3 M KI solution has 3.0 moles of KI/liter of solution.

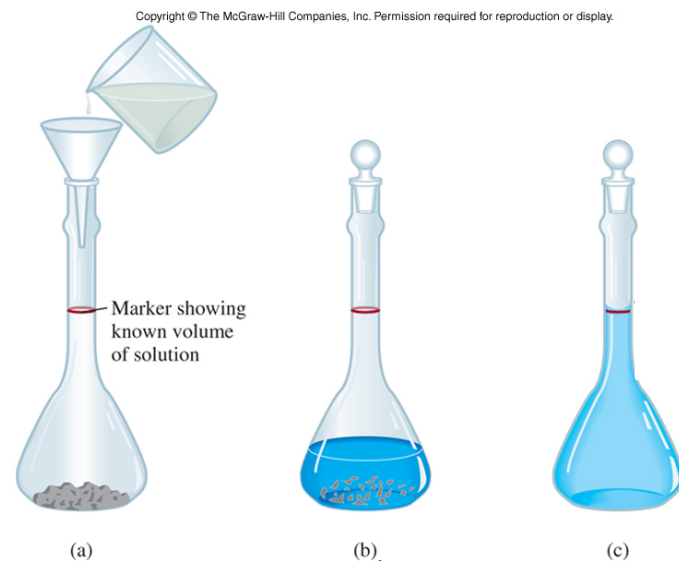
This conversion factor can be used just like all of the conversion factors that we have been using.

- a. Determine how many moles of Cu^{2+} ions exist in 10.00 mL of a 4.72 M CuSO_4 (aq) solution.

$$\cancel{10.00 \text{ mL}}_{\text{Solution}} \times \cancel{\frac{1 \text{ L sol'n}}{1000 \text{ mL sol'n}}} \times \frac{4.72 \text{ moles CuSO}_4}{\cancel{1 \text{ L sol'n}}} \times \frac{1 \text{ mole Cu}^{2+}}{1 \text{ mole CuSO}_4} = 0.0472 \text{ mole Cu}^{2+}$$

- Important note: Any time you are given a solution of anything you then know that those materials are soluble in solution. So a 0.1 M CaCl_2 solution means that CaCl_2 is a completely soluble ionic compound.

Aliquot is a small portion of a large solution



A Spreadsheet for Chemical Reactions: RICE Tables

- For many chemical reactions, we want to have a method of keeping track of how much of the reactants and products are present before and after the reaction. We can do this by using a spreadsheet called a **RICE table**.

Steps involved in constructing a RICE table:

- Write down the **Reaction**.
- Below each reactant and product, write down the **Initial** amount of each present.
- Determine the **Change** in the amount of each reactant/product during the reaction and write this value below the initial amount of each reactant and product.
- Using the change values, add to or subtract from the initial amounts to determine the **Ending** amounts of each reactant/product.

Let's illustrate this with an example: $4 \text{ mole } A^+ \times \frac{1 \text{ mole } A_2B}{2 \text{ mole } A} = 2 \text{ mole } A_2B$ || $3 \text{ mole } B^{2-} \times \frac{1 \text{ mole } A_2B}{1 \text{ mole } B^{2-}} = 3 \text{ mole } A_2B$

Consider a reaction where two ions of A⁺ react with one ion of B²⁻ to give the ionic compound A₂B.

If four mole of A is added to three moles of B, how many moles of ionic compound A₂B are formed?

1. Reaction: write the reaction:



2. Initial: write the initial number of moles of each reactant and product under each letter.

I: 4 mole 3 mole 0 mole

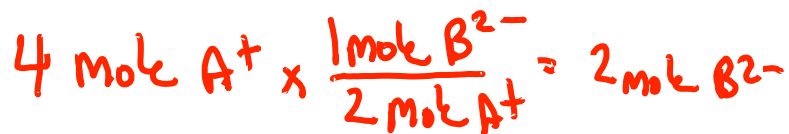
3. Change: write the number of moles of each reactant used and each product is formed under each letter in the reaction.

+ C: $- 4 \text{ mole}$ $- 2 \text{ mole}$ 2 mole

4. End: add or subtract the initial amounts to the changes.

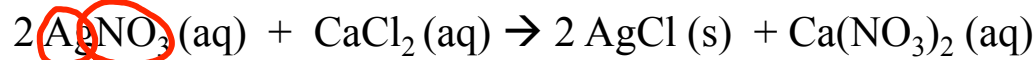
E: 0 mole 1 mole 2 mole

** Rice tables can be constructed using moles or molarity



Using RICE Tables for a Chemical Reaction

- Consider the reaction where 200.0 mL of a 0.1 M AgNO_3 solution is added to 150 mL of a 0.10 M CaCl_2 solution. Determine the concentration of the $[\text{Ag}^+]$ ion, $[\text{Cl}^-]$ ion, and $[\text{NO}_3^-]$ ion at the end of the reaction. The complete balanced equation is below.



Let's construct a RICE table to solve this problem, reacting to completion.

TOTAL volume: 200 mL + 150 mL = 350 mL
0.35L or

- a. Using the net ionic reaction that results from the addition of these two solutions to each other, complete the RICE table for the reaction above. b. Using the information in the RICE table calculate the concentration of the $[\text{Ag}^+]$ ion, the $[\text{Cl}^-]$ ion and the $[\text{NO}_3^-]$ ion at the end of the reaction. Don't forget to determine the new total volume at the end of the reaction.

R	$\text{Ag}^+(\text{aq})$	$+$	$\text{Cl}^-(\text{aq})$	\rightarrow	$\text{AgCl}(\text{s})$
I	0.02 mole		0.03 mole		0
$\pm \frac{C}{E}$	-0.02 mole		-0.02 mole		0.02 mole
	0		0.01		0.02

Bracket means concentration

$$[\text{Ag}^+] = \frac{\text{moles Ag}^+}{\text{Volume}} = \frac{0}{0.35} = 0 \text{ M}$$

$$[\text{Cl}^-] = \frac{0.01}{0.35\text{L}} = 0.0286 \text{ M}$$

$$[\text{NO}_3^-] = \frac{0.02 \text{ mole}}{0.35\text{L}} = 0.0571 \text{ M}$$

$$200 \text{ mL AgNO}_3 \times \frac{1\text{L}}{1000\text{mL}} \times \frac{0.1 \text{ moles AgNO}_3}{1 \text{ Liter}} \times \frac{1 \text{ mole Ag}^+}{1 \text{ mole AgNO}_3} = 0.02 \text{ moles Ag}^+ \times \frac{1 \text{ mole NO}_3^-}{1 \text{ mole Ag}^+} = 0.02 \text{ mole NO}_3^-$$

$$150 \text{ mL CaCl}_2 \times \frac{1\text{L}}{1000\text{mL}} \times \frac{0.1 \text{ mole CaCl}_2}{1 \text{ Liter Soln}} \times \frac{2 \text{ mole Cl}^-}{1 \text{ mole CaCl}_2} = 0.03 \text{ mole Cl}^-$$

Using RICE Tables for a Chemical Reaction (Space for Extra Work)

Understanding Acids

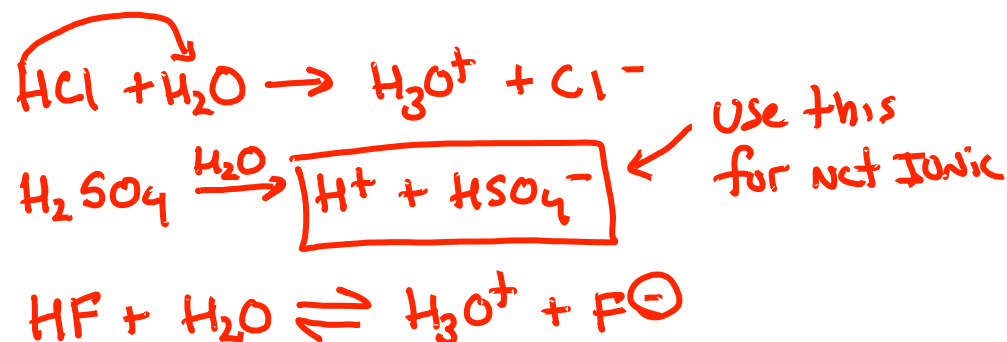
- So far, we have discussed reactions that occur between ions in a solution. These ions have been produced by ionic compounds. Reactions can of course also take place between two molecules or between a molecule and an ion! Let's look at how two molecules, hydrochloric acid and sulfuric acid, react with water:

- We define an acid as a substance that transfers a proton (H^+) to some other substance. In this case, the acid is transferring a proton to water, and we call this process the **ionization of the acid**.

- Acids** are characterized by how completely they ionize in water:

Strong Acids (HCl, HI, HBr, HNO₃, H₂SO₄) : Ionize completely in water

Weak Acids (HF, H₂CO₃, CH₃COOH, H₃PO₄) : Partially ionize in water



- We can also characterize acids by how many H^+ ions that they can donate to other substances. Some acids only have one H^+ to donate, while others have more.

Acids that have that one H^+ that they donate are called **monoprotic acids** (HCl, HI, HBr, HNO₃, HF, CH₃COOH) :

Acids that have more than two H^+ 's to donate are called **diprotic acids** (H₂CO₃, H₂SO₄)

Acids that have more than three H^+ 's to donate called **triprotic acids** (H₃PO₄)

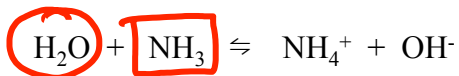
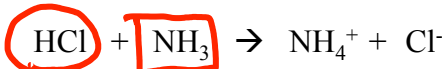
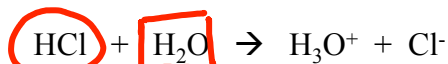
- NOTE that the number of H^+ 's an acid has has nothing to do with how strong the acid is!

What to know: Know the names and chemical formula of all of the acids on this page. Know which acids are strong and which are weak as well as which are monoprotic, diprotic or triprotic.

Understanding Bases

- Now let's look at bases. **Bases** accept a proton from an acid in an acid-base reaction.

a. Look at the acid-base reactions below. Circle the acid and put a box around the base:



What is different about the arrow in the last reaction? What do you think it is trying to tell the reader?

- Bases can also be characterized by how they ionize in water:

Strong Bases (NaOH, KOH, Ba(OH)₂): ionize completely in water



NOTE that some bases have two OH⁻ groups that can react.

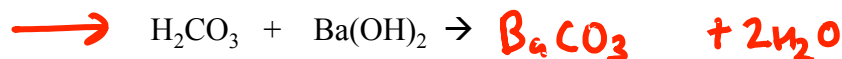
Weak Bases (NH₃): Partially ionize in water



Recall that we defined an **acid** as a substance that transfers a proton and a **base** as a substance that accepts that proton. An **acid-base reaction** always involves an acid transferring a proton to a base.

- Any time an acid and base are added together that reaction is not only an acid-base reaction but also a **neutralization** reaction.

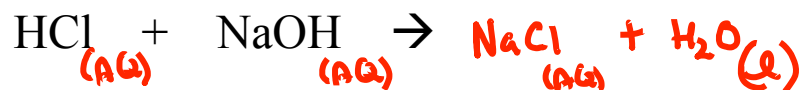
- Let's look at some examples below:



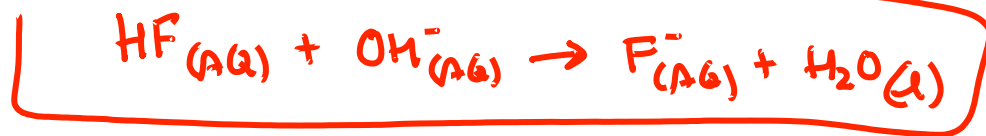
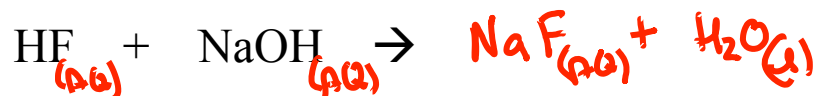
What to know: Know the names and chemical formula of all of the bases on this page. Know which bases are strong and which are weak.

Neutralization Reactions and Net Ionic Equations

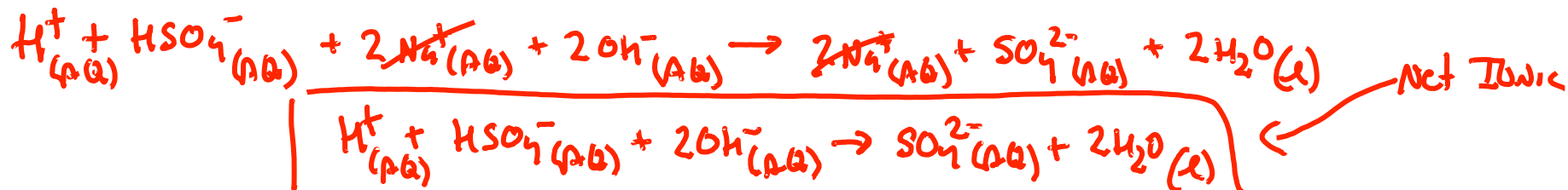
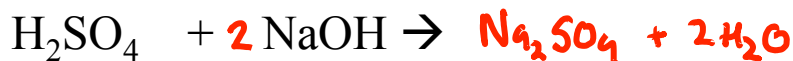
- a. Complete and balance the reaction below between a **strong monoprotic acid** and **strong base** then using the reaction write a new ionic equation.



- b. Complete and balance the reaction below between a **weak monoprotic acid** and a **strong base**, then using the reaction write a new ionic equation.



- c. Complete and balance the reaction below a **strong diprotic acid** and a **strong base** then using the reaction write a new ionic equation.

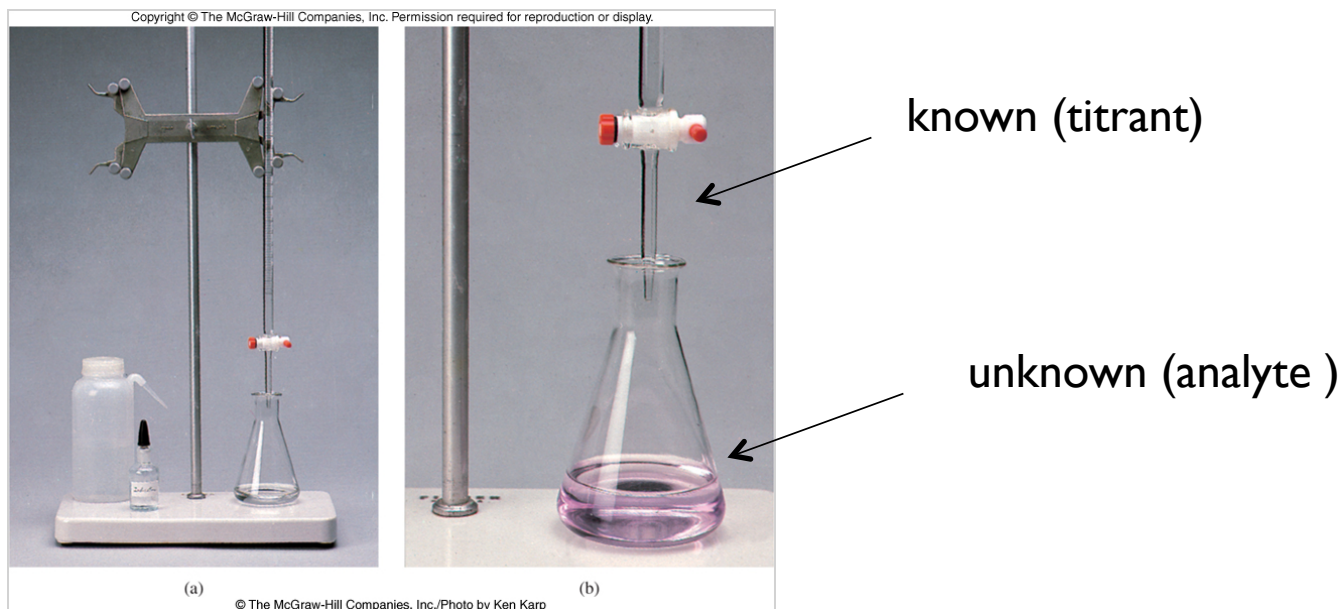


What are Titrations and How Do We Use Them?

A **titration** is a technique for determining the amount of one chemical present in a sample. It involves a reaction between two chemicals, this reaction can be any type of reaction like a neutralization reaction or a precipitation reaction.

In **acid-base titrations**, a solution of known concentration called a titrant (say, a base) is added gradually to a solution of unknown concentration called the analyte (say, an acid) with the goal of determining the analyte's unknown concentration.

The point at which the reaction conducted during the titration is complete is called the **equivalence point**. At this point, the number of moles of titrant added is equal to the number of moles of analyte in the original solution. We can then determine the concentration of the unknown analyte by using the stoichiometry from the balanced acid-base reaction, the concentration and volume of titrant added, and the volume of the analyte solution



Titration of an Acid by a Base

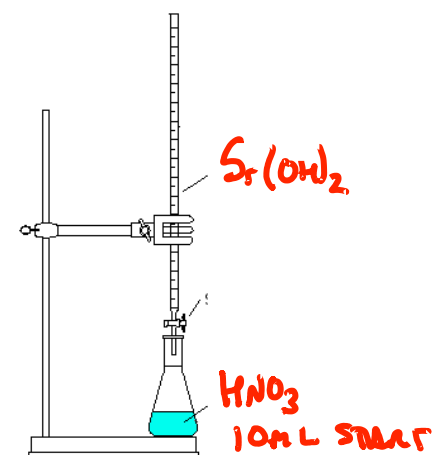
- Consider the following neutralization reaction:



Suppose it required 13.2 mL of 1.0 M Sr(OH)₂ to neutralize a 10 mL sample of HNO₃ of an unknown concentration in a titration experiment.

- a. How many moles of HNO₃ reacted with the Sr(OH)₂?

$$13.2 \text{ mL Sr}(\text{OH})_2 \times \frac{1 \text{ L}}{1000 \text{ mL}} \times \frac{1.0 \text{ mole Sr}(\text{OH})_2}{1 \text{ Liter Sol'n}} \times \frac{2 \text{ moles HNO}_3}{1 \text{ mole Sr}(\text{OH})_2} = 0.0264 \text{ mole HNO}_3$$



- b. What is the concentration of the nitric acid in original 10 mL sample?

$$[\text{HNO}_3] = \frac{0.0264 \text{ mole HNO}_3}{10 \times 10^{-3} \text{ L}} = 2.64 \text{ M HNO}_3$$

$$10 \text{ mL} = 10 \times 10^{-3} \text{ L}$$

Titrating a Mixture of Acids

Let's consider two new acids that you have never encountered before: benzoic acid and gallic acid.

Both are colorless white solids and monoprotic acids.

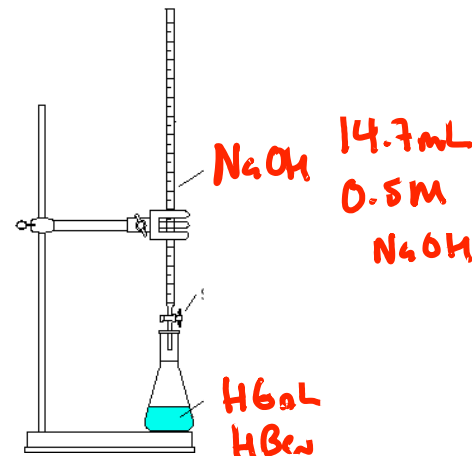


a. Let 'HBen' represent benzoic acid and 'HGal' represent gallic acid. Write a complete, balanced equation for the neutralization of HBen with NaOH and write the complete, balanced equation for the neutralization of HGal with NaOH.



• Here is some useful information about each acid:

Benzoic acid ("HBen") molar mass = 122 g/mol
Gallic acid ("HGal") molar mass = 170 g/mol



You have 1.00 gram of a mixture of these two acids. You titrate the mixture using 0.500 M NaOH, and find that it takes a total of 14.7 mL of base to completely neutralize *both* acids. Determine the mass of each acid present in the original mixture.

b. Assign variables to each of your acids in the unknown mixture. Write down which variables you assigned to which acid below.

let $x = \text{mass HBen}$ let $y = \text{mass HGal}$

c. Given that you have a 1.00 gram mixture of both of these acids and using the variables assigned above, write an equation that relates the masses of each acid to the total mass of the mixture.

$$x + y = 1.00$$

Titrating a Mixture of Acids (continued)

- d. Given that it requires 14.7 mL of 0.5 M NaOH to completely neutralize both acids, develop a second equation that equates the total number moles of NaOH required to neutralize each acid to the total number of moles of NaOH required to neutralize both acids.

Total number of moles of NaOH to neutralize HGal	+	Total number of moles of NaOH to neutralize HBen	=	Total number of moles of NaOH to neutralize HGal and HBen
$\frac{y}{170}$		$\frac{x}{122}$		7.35×10^{-3}

$$5.882 \times 10^{-3} y + 8.197 \times 10^{-3} x = 7.35 \times 10^{-3}$$

$$y (\text{g HGal}) \times \frac{1 \text{ mole HGal}}{170 \text{ g}} \times \frac{1 \text{ mole NaOH}}{1 \text{ mole HGal}} = \frac{y}{170}$$

$$x (\text{g HBen}) \times \frac{1 \text{ mole HBen}}{122 \text{ g}} \times \frac{1 \text{ mole NaOH}}{1 \text{ mole HBen}} = \frac{x}{122} \quad \leftarrow \text{moles NaOH to neutralize HBen}$$

TOTAL # moles of OH to neutr. HBen + HGal

$$14.7 \text{ mL NaOH} \times \frac{1 \text{ L}}{1000 \text{ mL}} \times \frac{0.500 \text{ moles NaOH}}{\text{L}} = 7.35 \times 10^{-3} \text{ moles of NaOH}$$

- e. In the space below, write both equations you found in parts c and d. Solve these equations simultaneously to find the masses of the benzoic acid (HBen) and the gallic acid (HGal).

$$5.882 \times 10^{-3} y + 8.197 \times 10^{-3} x = 7.35 \times 10^{-3}$$

$$x + y = 1.00 \quad \hookrightarrow y = 1.00 - x$$

$$5.882 \times 10^{-3} (1.00 - x) + 8.197 \times 10^{-3} x = 7.35 \times 10^{-3}$$

$$x = 0.634 \text{ (HBen)}$$

$$y = 1.00 - 0.634 = 0.366 \text{ (HGal)}$$

Titration of a Mixture (Space for Extra Work)

Oxidation-Reduction (Redox) Reactions and Oxidation Numbers

- The following reaction that you have seen before in class and the laboratory is neither a **precipitation reaction** nor an **acid-base reaction**.



The reaction above is one where electrons are transferred from one element to another during the reaction. This kind of reaction is called an **oxidation-reduction reaction**.

Oxidation Numbers are used to keep track of electron movement in chemical reactions. Each atom has an oxidation number; if that number changes during a reaction, then an **oxidation-reduction (redox) reaction** has occurred. Oxidation numbers can be positive, negative, integers, or fractions! **What to know: know the rules for assigning oxidation numbers and how to determine if a reaction is an oxidation-reduction reaction.**

To assign oxidation numbers to any substance, follow the following rules *in order*:

- Pure elements:** For any atom in its elemental form, the oxidation number is zero.

Examples: Na Hg O₂ H₂ In these compounds, each atom has an oxidation number of zero.

- Monatomic ions:** For monatomic ions in ionic compounds, the oxidation number equals the charge on the ion. All group I ions have an oxidation number of +1 and all group II ions have an oxidation number of +2.

Examples: In NaCl both Na⁺ and Cl⁻ are monatomic ions (not polyatomic ions). The oxidation of Na⁺ is +1 and the oxidation number of Cl⁻ is -1.
In K₂O the two monatomic K⁺ ions both have an oxidation number of +1, the O²⁻ ion has an oxidation number of -2

- Fluorine:** always -1

Example: In HF, the F has an oxidation number of -1.

- Hydrogen:** +1 unless violated by rules 2, 3

Example: In H₂O, H has an oxidation number of +1.

Violation example: In NaH, Na⁺ is +1 and H⁻ is -1

- Oxygen:** -2 unless when violated by rules 2, 3, 4

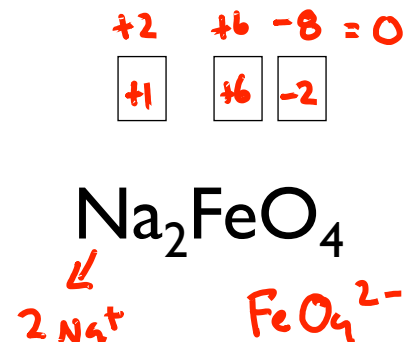
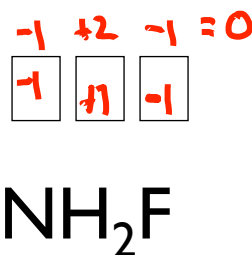
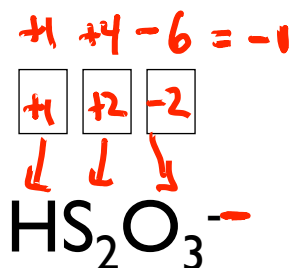
Example: In H₂O, O has an oxidation number of -2.

Violation example: In H₂O₂, H is +1 and O is -1

- "Oxidation State Rule":** For neutral species, oxidation numbers add to zero. For ions, they add to charge on ion (Examples above)

Activity 4.I 0: Determining Oxidation Numbers

a) Write the oxidation number of each element in the box above it.



- Let's look at two important oxidation reactions. This is the combustion of a hydrocarbon and hydrogen.

Hydrocarbons are molecules that contain hydrogen and carbon. When hydrocarbons are combusted they produce carbon dioxide and water as products. **Combustion reactions** always involve a reaction with oxygen. Hydrogen can also be combusted but the only product from this combustion is water. **Know combustion reactions of hydrocarbons and hydrogen.**

