Unit II: **ACIDS & BASES**

A. **<u>Operational Definition:</u>**

- empirical definition ie. Based on operations or experiments that can be performed in the lab
- can be used to classify substances, but cannot be used to predict chemical formulas or explain the causes for their behavior

Characteristic	ACIDS	BASES
pH		
Effect on litmus		
Reaction with metals		
Reaction with carbonate compounds		
Reaction with each other		
Solution conductivity		
Taste		
Feel of solution		

B. **<u>Arrhenius Definition:</u>** **(a theoretical definition)**

Acid: a substance that forms an acidic solution by *ionizing* in water to form hydrogen ions (H^+).

Eg. $HCl_{(aq)}$ □ $H^+_{(aq)}$ + $Cl^-_{(aq)}$

Base: a substance that forms a basic solution by *dissociating* in water to form hydroxide ions (OH-).

Eg. $NaOH_{(aq)}$ □ $Na^+_{(aq)}$ + $OH^-_{(aq)}$

Practice Problems:

1. Write the equation for the formation of the following Arrhenius acids:

   a) hydroiodic acid

   b) sulfuric acid

2. Write the equation for the formation of the following Arrhenius bases:

   a) barium hydroxide

   b) strontium hydroxide

Neutral Compounds:

- neither acidic nor basic
- Do not change the color of litmus paper
- May be formed by reacting an acid with a base in a double replacement reaction called *Neutralization.*

Example: $HCl_{(aq)}$ + $NaOH_{(aq)}$ → $NaCl_{(aq)}$ + $HOH_{(l)}$

$HCl_{(aq)}$	+	$NaOH_{(aq)}$	→	$NaCl_{(aq)}$	+	$HOH_{(l)}$
Acid		*Base*		*Salt* (neutral ionic)		*Water* (neutral molecular)

INVESTIGATION: Testing Arrhenius's Acid-Base Definitions

Problem: Which of the substances tested may be classified as acidic, basic or neutral?

Procedure: Predict which of the substances below are acidic, which are basic and which are neutral (neither acidic nor basic).

Materials: Aqueous solutions of each compound, each at a concentration of 0.10 mol/L.

Evidence:

Table 1: Classification of different substances as acidic, basic or neutral: predictions and actual (based on the litmus test).

COMPOUND Name	Formula	PREDICTION	ACTUAL
Hydrogen chloride	HCl		
Sodium carbonate	Na_2CO_3		
Sodium hydrogen carbonate	$NaHCO_3$		
Sodium hydrogen sulfate	$NaHSO_4$		
Sodium hydroxide	$NaOH$		
Calcium hydroxide	$Ca(OH)_2$		
Sulfur dioxide	SO_2		
Magnesium oxide	MgO		
Ammonia	NH_3		
Hydrogen acetate	CH_3COOH		

Problems with Arrhenius Theory:

- Can only predict acidic properties of substances forming hydrogen ions in aqueous solution or basic properties of substances forming hydroxide ions in aqueous solution.

  Eg: HCl or NaOH **NOT** SO_2 or NH_3

C. **<u>Modern Arrhenius Definitions:</u> (a theoretical definition)**

- Takes into account the role of water

Acid: any substance that forms an acidic solution by reacting with water to form <u>hydronium ions</u>

Eg. $HCl_{(aq)}$ + $H_2O_{(l)}$ □ $H_3O^+_{(aq)}$ + $Cl^-_{(aq)}$

<u>The Hydronium Ion, $H_3O^+_{(aq)}$</u>

- Forms when a H^+ ion (proton) becomes "hydrated" by bonding with a water molecule
- A large proportion of aqueous H^+ ions are believed to exist in this form
- For the 6 strong acids, assume all H^+ ions are present as $\mathbf{H_3O^+_{(aq)}}$

Formation of $\mathbf{H_3O^+_{(aq)}}$:

Base: any substance that forms a basic solution by reacting with water to form <u>hydroxide ions</u>

Eg. $NH_{3(g)}$ + $HOH_{(l)}$ □ $NH_4OH_{(aq)}$

$NH_4OH_{(aq)}$ □ $NH_4^+_{(aq)}$ + $OH^-_{(aq)}$

Problems with this theory:

1. No experimental evidence that $NH_4OH_{(aq)}$ exists.

2. It cannot predict, in many cases, whether an acidic or basic solution will form.

Eg; $HCO_3^-_{(aq)}$ + $H_2O_{(l)}$ □ $CO_3^{2-}_{(aq)}$ + $H_3O^+_{(aq)}$

$HCO_3^-_{(aq)}$ + $HOH_{(l)}$ □ $H_2CO_3^-_{(aq)}$ + $OH^-_{(aq)}$

Question: What did the experimental evidence reveal?

D. **Bronsted-Lowry Definition:** **(a theoretical definition)**

Acid: donates a hydrogen ion (proton) ie. B-L acid is a *proton donor*

Base: accepts a hydrogen ion (proton) ie. B-L base is a *proton acceptor*

Eg. $HCl_{(aq)}$ + $H_2O_{(l)}$ □ $H_3O^+_{(aq)}$ + $Cl^-_{(aq)}$
Acid **Base**

Eg. $NH_{3(g)}$ + $HOH_{(l)}$ □ $NH_4^+_{(aq)}$ + $OH^-_{(aq)}$
Base **Acid**

***Note**:* In an acid-base reaction for a system at equilibrium, both forward and reverse reactions contain Bronsted-Lowry acids and bases.

- Conjugate Acid-base Pairs:
  - 2 substances that differ only by a single proton (H^+)

Examples:

- Amphoteric Species:
  - A substance that can act as a B-L Acid is some reactions, but in a B-L base in other reactions.
  - Includes water, as well as all hydrogen polyatomic ions

Examples:

Advantages over Arrhenius:

- Bronsted-Lowry focuses on the role of an acid and a base in an acid-base reaction, rather than on the acidic or basic properties of their aqueous solutions
- Water does not always have to be one of the primary reactants

Eg: $H_3O^+_{(aq)}$ + $NH_{3(g)}$ □ $H_2O_{(l)}$ + $NH_4^+_{(aq)}$

- In some rare cases, water does not even have to be present.

Eg: $HCl_{(g)}$ + $NH_{3(g)}$ □ $NH_4Cl_{(s)}$

ACIDS & BASES WORKSHEET #1

1. Which of the following are Arrhenius bases?

   a. KOH b. SO_2 c. $Ba(OH)_2$ d. Cl^-

2. Which of the following are Arrhenius acids?

   a. HCl b. $AlCl_3$ c. CH_4 d. HSO_4^-

3. Which of the following are Brønsted-Lowry bases?

   a. OH^- b. H_2O c. Cl^- d. NH_3

4. Which of the following substances is/are amphoteric?

   a. OH^- b. C_2H_6 c. HS^- d. $H_2PO_4^-$

5. Write equations for the reactions of the following amphoteric species with HCl and with NaOH:

   a. HCO_3^- b. HPO_4^{2-} c. HS^-

6. Identify the acid-base and conjugate acid-base pairs in the following:

   a. $NH_{3\,(g)} + HCO_3^-{}_{(aq)} \rightleftharpoons NH_4^+{}_{(aq)} + CO_3^{2-}{}_{(aq)}$
   b. $CH_3NH_{2\,(aq)} + HCl_{(aq)} \rightleftharpoons CH_3NH_3^+{}_{(aq)} + Cl^-{}_{(aq)}$
   c. $H_3O^+{}_{(aq)} + OH^-{}_{(aq)} \rightleftharpoons H_2O_{(l)} + H_2O_{(l)}$
   d. $H^-{}_{(aq)} + H_2O_{(l)} \rightleftharpoons H_{2\,(g)} + OH^-{}_{(aq)}$

7. Write the formula of the conjugate acid of each of the following:

   a. SO_4^{2-} b. H_2O c. Cl^- d. NH_3

8. Write the formula of the conjugate base of each of the following:

   a. HBr b. H_2SO_4 c. $CH_3NH_3^+$ d. $HClO_3$

9. Write a balanced equation of the reaction of each of the following bases with water:

10. Write a balanced equation for the reaction of each of the following acids with water:

    a. HBr b. H_2SO_4 c. CH_3COOH

11. Write acid-base reactions for the following systems at equilibrium. Identify the conjugate acid-base pairs in each system.

    a. $NH_{3\,(aq)} + H_2O \rightleftharpoons$
    b. $HCl_{(aq)} + H_2O \rightleftharpoons$
    c. $CH_3COO^- + H_2O \rightleftharpoons$
    d. $HSO_3^- + S^{2-} \rightleftharpoons$

STRONG AND WEAK ACIDS AND BASES

Terminology:

Irreversible reaction	Reversible reaction
"goes to completion"	Does not go to completion
Quantitative	nonquantitative
Stoichiometric	nonstoichiometric

STRONG ACID:

- An acid that ionizes completely in water (100% reaction for the 6 strong acids)
    - When added to water a strong acid will react with water to produce a stoichiometric equivalent amount of hydronium ion

Eg: $HCl_{(aq)} + H_2O_{(l)} \rightarrow H_3O^+_{(aq)} + Cl^-_{(aq)}$

WEAK ACID:

- An acid that ionizes partially in water
    - When added to water it does not completely react (less than 50% reaction for most weak acids), therefore it does not produce a stoichiometric equivalent amount of hydronium ion

Eg: $CH_3COOH_{(aq)} + H_2O_{(l)} \rightleftharpoons H_3O^+_{(aq)} + CH_3COO^-_{(aq)}$

1.3 % reaction: in a 0.10 mol/L solution of acetic acid only 13 molecules in 1000 will ionize. (reactants are favored)

STRONG BASES:

- A base that dissociates completely when dissolved in water to produce a stoichiometric equivalent amount of hydroxide ions
- Includes ionic hydroxides, which have varying solubilities in water

Eg: NaOH, KOH. LiOH, $Ba(OH)_2$, $Sr(OH)_2$ all have ***high solubility***

$Ca(OH)_2$ and $Mg(OH)_2$ have ***low solubility***

WEAK BASES:

- A base that does not react completely in water so doesn't produce stoichiometric equivalent amounts of hydroxide ion

Eg: $NH_{3(g)} + HOH_{(l)} \rightleftharpoons NH_4^+{}_{(aq)} + OH^-_{(aq)}$ ***0.12% reaction*** (in a 0.10 mol/L solution)

ACID-BASE REACTIONS

Consider nonionic, total ionic and net ionic equations studied in Chemistry 2202:

Nonionic: $NaOH_{(aq)} + HCl_{(aq)} \rightarrow NaCl_{(aq)} + HOH_{(l)}$

Total Ionic: $Na^{+}_{(aq)} + OH^{-}_{(aq)} + H^{+}_{(aq)} + Cl^{-}_{(aq)} \rightarrow Na^{+}_{(aq)} + Cl^{-}_{(aq)} + HOH_{(l)}$

Net Ionic: $OH^{-}_{(aq)} + H^{+}_{(aq)} \rightarrow HOH_{(l)}$

Spectator ions: $Na^{+}_{(aq)}$ and $Cl^{-}_{(aq)}$ (not involved in the reaction)

<u>Predicting Products from Bronsted-Lowry Acid/Base Reactions</u>

Determine the acid-base neutralization that occurs between aqueous solutions of sodium hydrogen sulfate and ammonium bicarbonate.

$$NaHSO_{3\,(aq)} + NH_4HCO_{3\,(aq)}$$

Step 1: Write all species as they exist in an aqueous environment

$Na^{+}_{(aq)}$, $HSO_3^{-}{}_{(aq)}$, $NH_4^{+}{}_{(aq)}$, $HCO_3^{-}{}_{(aq)}$

Step 2: Identify possible acids and bases according to the B-L definition

~~$Na^{+}_{(aq)}$ a metal, forget metals~~

$HSO_3^{-}{}_{(aq)}$ can act as an **acid or a base**

$NH_4^{+}{}_{(aq)}$ can act as an **acid**

$HCO_3^{-}{}_{(aq)}$ can act as an **acid or a base**

Step 3: Identify the strongest acid

* If one of the acids is one of the 6 strong acids it is always the acid

If a strong acid is not present determine the strongest acid from the acid-base table. ***The strongest acid is the one that is highest in the acid-base table.***

$HSO_3^{-}{}_{(aq)}$ is the highest on the acid-base table and therefore the strongest acid (SA) ***This is the proton donor!***

Step 4: Identify the strongest base

** If one of the bases is a strong base (OH^{-}) it is always the base.

If a strong base is not present determine the strongest base from the acid-base table. ***The strongest base is the one that is the lowest in the acid-base table.***

$HCO_3^-{}_{(aq)}$ is the lowest on the acid-base table and therefore the strongest base (SB) ***This is the proton acceptor!***

Step 5: Using only the (SA) and (SB) write the reactants and products. (Ignore everything else)

$HSO_3^-{}_{(aq)}$ + $HCO_3^-{}_{(aq)}$ *leave out the arrow for now* $SO_3^{2-}{}_{(aq)}$ + $H_2CO_{3(aq)}$
A B CB CA

Step 6: Decide on the type of arrow that should be drawn

a. A single arrow → if a strong acid (H_3O^+) is present

b. A single arrow → if a strong a base (OH^-) is present

c. An equilibrium arrow $\rightleftharpoons$ if both a weak acid and a weak base are present

d. A third arrow is used with the equilibrium arrow to indicate if reactants or products are favoured.

(i) Reactants are favoured at equilibrium $\overset{\longleftarrow}{\rightleftharpoons}$

- Look at the acid and the conjugate acid
- If the conjugate acid is above the acid on the acid-base table then the reactants are favoured.

$HSO_3^-{}_{(aq)}$ (A)

H_2CO_3 (CA) above the acid on the acid-base table, thus it will be the favoured proton donor and the reverse reaction will be favoured (higher

concentration of

reactants than products) $\overset{\longrightarrow}{\rightleftharpoons}$

$HSO_3^-{}_{(aq)}$ + $HCO_3^-{}_{(aq)}$ $\overset{\longleftarrow}{\rightleftharpoons}$ $H_2CO_3{}_{(aq)}$ + $SO_3^{2-}{}_{(aq)}$

(ii) Products are favoured at equilibrium

- Look at the acid and the conjugate acid
- If the acid is above the conjugate acid on the acid-base table then the products are favoured.

Note:

1. For acids with H in the chemical formula:
- If a strong acid, write the H^+ ion as H_3O^+ eg: HNO_3 becomes H_3O^+ & NO_3^-
- If a weak acid, write the formula as given eg: HF remains HF

2. If a strong base, drop the metal ion eg: NaOH becomes OH^-

Example: Perchloric acid is mixed with sodium hydroxide

ACIDS & BASES WORKSHEET #2

For each of the following, write the reaction equation, label each species as a Bronsted-Lowry acid or base and indicate (with the appropriate type of arrow) whether the reaction goes to completion or is at equilibrium. If at equilibrium also indicate whether the forward or reverse reaction is favored. Assume only one proton is transferred in each reaction.

1. Solutions of sodium sulfate and hydrofluoric acid are mixed.

2. A solution of NH_4NO_3 fertilizer is mixed with a solution of $NaCH_3COOH$.

3. Solid $NaCH_3COO$ reacts with aqueous $NaHSO_4$.

4. A solution of household ammonia is mixed with nitrous acid.

5. Solid sodium sulfite is dissolved in a solution of sulfurous acid.

6. In solution, the poisonous gas H_2S is used to react with carbonate ions.

7. Vinegar, a dilute ethanoic acid solution, is used to react with sodium hydrxode solution.

8. Sodium bicarbonate, $NaHCO_3$, reacts with excess stomach acid.

9. Nitric acid and potassium hydroxide solutions are mixed.

10. Solutions of sodium hydrogen sulfite and potassium hydrogen phosphate are mixed.