

Solubility Rules, Types of Reactions and Net Ionic Equations

Objectives:

- To observe reactions involving some common ionic compounds, acids and bases.
- To learn how to classify reactions in aqueous solution.
- To become proficient at writing NET IONIC EQUATIONS.
- To discover some rules of solubility for ionic compounds in water.

Pre-laboratory Reading:

**Brown, LeMay
& Bursten**

Chapter 4: pages 115-119, Ionic Equations pages 122-124 and sections 3 and 4

Background:

Chemistry involves the study of matter, its composition and properties, and the changes (physical and chemical) that matter undergoes. In this experiment we will focus on types of chemical changes (reactions) in aqueous solution, observations that help us to determine if a reaction takes place and writing balanced net ionic chemical equations for reactions. Our observations will enable us to develop some rules of solubility for ionic compounds in water.

Part A: How do we know that a reaction has occurred?

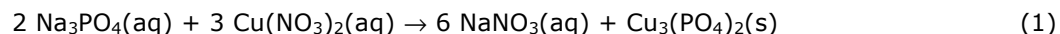
Indications that a chemical reaction has taken place include:

- Formation of a precipitate when two solutions are mixed.
- A color change. (Note: A lightening of a colored solution upon dilution is not a color change.)
- Formation of a gas, often observed as bubbles forming in a solution.
- A change in temperature of the reaction mixture: either cooling (endothermic reaction) or warming (exothermic reaction).
- Dissolving of a water insoluble substance upon addition of an acid or a base to the water.

Part B: Types of Reactions

In order to become proficient in predicting products for and writing balanced chemical equations for reactions, it is helpful to be able to classify reactions. Most chemical reactions can be classified as one of the following four types of reactions:

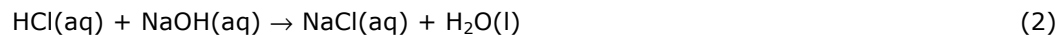
1. **A precipitation reaction involves the formation of an insoluble product, a precipitate.** Many (but not all) precipitation reactions are double-replacement reactions. (These are also called exchange or metathesis reactions.) In a double-replacement reaction the cations from two reactants swap anions with each other. Precipitation reactions that are double-replacement occur when aqueous solutions of soluble ionic compounds are mixed. If upon mixing an insoluble ionic compound forms, then a precipitation reaction occurs. An example is the reaction that occurs when aqueous solutions of sodium phosphate, $\text{Na}_3\text{PO}_4(\text{aq})$, and copper (II) nitrate, $\text{Cu}(\text{NO}_3)_2(\text{aq})$, are mixed.



Initially when the $\text{Na}_3\text{PO}_4(\text{aq})$ and $\text{Cu}(\text{NO}_3)_2(\text{aq})$ are mixed, the mixture contains dissolved Na^+ , PO_4^{3-} , Cu^{2+} , and NO_3^- ions. However, since copper (II) phosphate, $\text{Cu}_3(\text{PO}_4)_2$, is insoluble it quickly precipitates out. In this case, the sodium and copper (II) cations swap anions with each other.

Some precipitation reactions do not produce a solid that settles out of solution readily. In some cases a cloudy solution results instead and in other cases a gel-like precipitate that stays suspended in the mixture forms.

2. **An acid-Base (neutralization) reaction involves an acid reacting with a base.** The reactions that we classify as neutralization reactions in Chemistry 1A involve the transfer of a proton (H^+) from the acid to the base. For example, in the reaction between hydrochloric acid, $\text{HCl}(\text{aq})$, and aqueous sodium hydroxide, $\text{NaOH}(\text{aq})$, the acid (HCl) transfers an H^+ to the base (OH^-) forming water as one product and an ionic compound (a salt) as a second product. This reaction can also be called a double-replacement reaction.

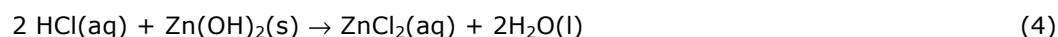


Note that this definition of an acid-base reaction does not limit us to reactions that take place in aqueous solution. For example, hydrogen chloride gas, $\text{HCl}(\text{g})$, will donate a proton to gaseous ammonia, $\text{NH}_3(\text{g})$, forming solid ammonium chloride, $\text{NH}_4\text{Cl}(\text{s})$, in an acid-base reaction.

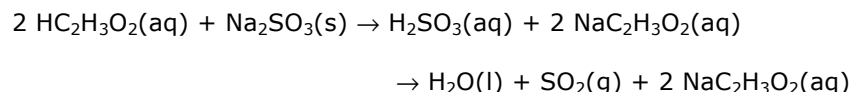


Notice that in this reaction water is not formed, but a salt (NH_4Cl) is formed and the reaction is not a double-replacement.

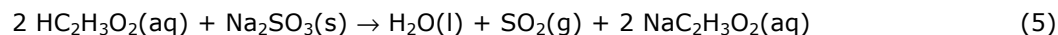
Acid-base reactions also occur between insoluble hydroxides and acids. These reactions cause the hydroxide to dissolve. The reaction between zinc hydroxide and hydrochloric acid is one example.



3. **Acid-Base reactions that result in the formation of a gas.** These are a special case of acid-base reactions. For example, the reaction between solid sodium sulfite, $\text{Na}_2\text{SO}_3(\text{s})$, and acetic acid, $\text{HC}_2\text{H}_3\text{O}_2(\text{aq})$, involves the transfer of protons from acetic acid to the sulfite ion, SO_3^{2-} , initially forming $\text{H}_2\text{SO}_3(\text{aq})$ which is unstable and decomposes to water, $\text{H}_2\text{O}(\text{l})$, and sulfur dioxide gas, $\text{SO}_2(\text{g})$.



The intermediate product (formation of H_2SO_3) is often omitted when writing the equation for this reaction giving the overall reaction:

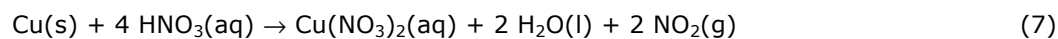


Notice, as in the other examples of acid-base reactions given, a salt ($\text{NaC}_2\text{H}_3\text{O}_2$) is formed. Compounds containing the carbonate (CO_3^{2-}) or hydrogen carbonate (HCO_3^-) ion react with acids similarly yielding water, $\text{CO}_2(\text{g})$ and a salt.

4. **Oxidation-Reduction reactions (redox reactions) involve a shift in electron distribution.** Redox reactions are an important class of reactions in everyday life. The reactions we use to generate much of our heat and power; combustion reactions to heat our homes and power our cars and the reactions that provide electricity from batteries are examples. Some redox reactions are not as easy. An example is the formation of sodium chloride, NaCl , from sodium metal, $\text{Na}(\text{s})$, and chlorine gas, $\text{Cl}_2(\text{g})$.



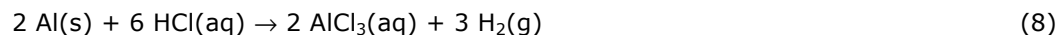
In this reaction, it is simple to determine that each sodium atom loses one electron (is oxidized) forming a sodium ion, Na^+ , while each chlorine atom gains one electron (is reduced) forming a chloride ion, Cl^- . In the balanced chemical equation for a redox reaction the total number of electrons lost must equal the number of electrons gained. Some redox reactions are more complicated, in that the electron transfer process is not as easily identified. One such reaction is that between copper and nitric acid:



In this reaction, it is simple to determine that the copper atom is oxidized, losing two electrons, since

solid copper is converted to Cu^{2+} . In order to determine which atom gains electrons, oxidation numbers must be assigned. Try to assign oxidation numbers. Do you find that it is two nitrate ions that are reduced to NO_2 ?

An important class of redox reactions is single-replacement reactions. (These are also called displacement reactions.) In these reactions, one component (cation or anion) of a reactant is replaced (or displaced), thus the term single-replacement (or displacement). Two examples involving cation replacement are given below:



In reaction (6), $\text{H}^+\text{(aq)}$ ions in the solution are replaced by $\text{Al}^{3+}\text{(aq)}$ ions. For each aluminum atom that loses three electrons three H^+ ions gain one electron. The H atoms combine to produce hydrogen gas, $\text{H}_2\text{(g)}$, and bubbles are observed. In reaction (8), $\text{Ni}^{2+}\text{(aq)}$ ions in the solution are replaced by $\text{Zn}^{2+}\text{(aq)}$ ions. Each zinc atom loses two electrons while each $\text{Ni}^{2+}\text{(aq)}$ ion gains two electrons. The Ni(s) formed coats the outer surface of the piece of solid zinc.

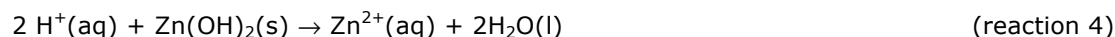
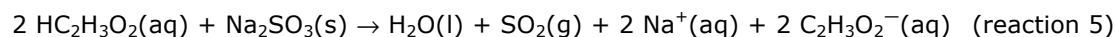
Precipitation reactions and acid-base reactions do not involve any shift in electron distribution therefore they are not classified as redox reactions.

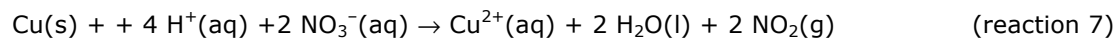
Part C: Net Ionic Equations

The complete balanced chemical equation for a reaction uses the full formulas of all of the reactants and products as shown previously in reactions 1 through 7. But, we often want to write chemical equations in net ionic form. This requires knowledge of the terms strong electrolyte, weak electrolyte and non-electrolyte as well as being able to recognize strong and weak acids and bases. Refer to the background reading in your textbook to review these. When writing a net ionic equation reactants and products are written in the form in which they predominantly exist and spectator ions are omitted. The following rules summarize the process.

- Strong electrolytes in aqueous solution are written as separated aqueous ions because this is their predominant form in water. Strong electrolytes include most soluble ionic compounds, strong acids and strong bases.
- Weak electrolytes are only partially ionized when dissolved in water. In water solution their predominant form is as molecules. Weak electrolytes are therefore written in molecular form, not as separated aqueous ions. Weak electrolytes include weak acids and weak bases.
- Non-electrolytes do not form ions when dissolved in water. They exist as molecules and must be written in molecular form. Common non-electrolytes include sugars (sucrose, glucose) and alcohols such as ethanol ($\text{CH}_3\text{CH}_2\text{OH}$).
- Gases, solids and liquids are written in molecular form, not as ions.
- Spectator ions are omitted. These are ions that do not undergo a chemical change during the reaction; they are the same before and after the reaction. Much like the "spectators" in a sporting event, these ions are present, but do not actually participate in the event.

Compare the net ionic equations given below for each reaction previously discussed. **Be sure that you understand why they are written as shown. Phase labels must be given when writing net-ionic reactions!**





Part D: Solubility Rules

In developing solubility rules, we will start with the knowledge that ionic compounds containing the following are always soluble:

- Those containing a Group 1A cation (Na^+ , K^+ , Li^+ , etc.). A few examples are NaCl , KOH , and Li_2CO_3 .
- Those containing the nitrate (NO_3^-) ion. For example $\text{Ba}(\text{NO}_3)_2$ and $\text{Fe}(\text{NO}_3)_3$.

We will develop additional solubility rules for some other cations and anions by observing various precipitation reactions.

Laboratory Exercise:

Safety:

Hydrochloric acid is hazardous with respect to contact with skin and clothing. If your skin or clothing should come into contact with this solution, rinse immediately with water. Safety glasses must be worn at all times. Report spills to your instructor for proper clean-up.

Use caution when handling the silver nitrate solution since it will cause darkening of skin that it contacts. Although the darkening is not harmful and will wear off, most people would prefer to avoid this.

Equipment and Reagents:

Spot Plate (located in the laboratory room)-The clear plastic spot plates work best since you can either place them on the black bench top or on a piece of white paper to view the reactions.

Toothpicks

Reagent Sets (all solutions will be in dropper bottles):

Reagent Set 1: 1 M NaOH
Dilute (less than 1 M) aqueous solutions of Na_2CO_3 , Na_2SO_4 , NaCl, $\text{NaC}_2\text{H}_3\text{O}_2$, $\text{Ba}(\text{NO}_3)_2$, $\text{Ca}(\text{NO}_3)_2$ and $\text{Mg}(\text{NO}_3)_2$, AgNO_3 , $\text{Co}(\text{NO}_3)_2$, $\text{Cu}(\text{NO}_3)_2$, $\text{Al}(\text{NO}_3)_3$ and NH_4NO_3

Reagent Set 2: 1 M NH_3
Dilute (less than 1 M) aqueous solutions of $\text{Mg}(\text{NO}_3)_2$, $\text{Co}(\text{NO}_3)_2$, $\text{Ba}(\text{NO}_3)_2$, and NaNO_3

Reagent Set 3: 6 M HCl
Solid samples of CaCO_3 , $\text{Mg}(\text{OH})_2$ and Zn
Dilute (less than 1 M) aqueous solutions of Na_2CO_3 , NaHCO_3 , AgNO_3 , NaNO_3 , and Na_2SO_4

Note: The NaOH(aq) solutions should be capped when not in use to avoid contamination of the NaOH(aq) with CO_2 from the air. If the NaOH(aq) becomes contaminated by exposure to air, unexpected side reactions that produce insoluble carbonates may occur.

Procedure:

Obtain a spot plate, wash it and rinse with deionized water. A variety of spot plates are available in the lab including colorless plates that you can see through (can be placed on the dark colored bench top or on white paper to change the background), white plates and black plates. You may find that each type of spot plate is useful for different types of observations.

To check for a temperature change when two reagents are mixed in a well on a spot plate, lift the plate and touch the underside of the well containing the reagents.

Each laboratory bench will be given three sets of reagents labeled Set 1, Set 2, and Set 3. Working with a partner, follow the directions given below for each set. The sets do not need to be done in numerical order.

You must carefully follow instructions, using the amounts of each reagent indicated. Using too much of a reagent can cause side reactions that are not included in our list of reaction types for Chemistry 1A. You will learn about these other reactions in the courses you take after 1A.

Your observations should be made within about 30 seconds of mixing reagents. After longer times, side reactions may begin to occur.

1. Set 1: Complete Table 1 in the Data and Results section by doing the following:

- Place **four drops** of the barium nitrate solution, $\text{Ba}(\text{NO}_3)_2$, into 5 separate wells on your spot plate.

- b. Into one of these five wells place **two to three drops** of the sodium carbonate solution, Na_2CO_3 , stir with a clean toothpick and observe. Record in Table 1 any changes that indicate if a reaction has taken place. **Be as specific as possible in your written observations!** If no reaction occurs indicate this in the table by writing NR. Repeat with the other four wells containing the barium nitrate solution by adding to one well the sodium sulfate solution, Na_2SO_4 , to another well the sodium hydroxide solution, NaOH, to another well the sodium chloride solution, NaCl, and to the last the sodium acetate solution, $\text{NaC}_2\text{H}_3\text{O}_2$.
 - c. **Rinse the spot plate using a wash bottle into a waste beaker. Use a minimum amount of rinse water while doing this. We want to minimize the amount of waste generated.**
 - d. Repeat steps (1a) through (1c) using the remaining nitrate salts in the left hand column.
- 2. Set 2: Complete Table 2 in the Data and Results section by doing the following:**
- a. Place **four drops** of the magnesium nitrate solution, $\text{Mg}(\text{NO}_3)_2$, into one well on your spot plate, **four drops** of the cobalt (II) nitrate solution, $\text{Co}(\text{NO}_3)_2$, in a second well, **four drops** of the barium nitrate solution, $\text{Ba}(\text{NO}_3)_2$, in a third well and **four drops** of the sodium nitrate, NaNO_3 , solution in a fourth well. Into each of these four wells place **two to three drops** of the 1 M NH_3 solution, stir with a clean toothpick and observe. Record in Table 2 any changes that indicate if a reaction has taken place. **Be as specific as possible in your written observations!** If no reaction occurs indicate this in the table by writing NR.
 - b. **Rinse the spot plate using a wash bottle into a waste beaker. Use a minimum amount of rinse water while doing this. We want to minimize the amount of waste generated.**
- 3. Set 3: Complete Tables 3a and 3b in the Data and Results section by doing the following:**
- a. Place **four drops** of the sodium carbonate solution, Na_2CO_3 , into one well on your spot plate, **four drops** of the sodium hydrogen carbonate solution, NaHCO_3 , into a second well, **four drops** of the sodium nitrate solution, NaNO_3 , into a third well, **four drops** of the silver nitrate solution, AgNO_3 , into a fourth well and **four drops** of the sodium sulfate solution, Na_2SO_4 , into a fifth well. Into each of these five wells place **two to three drops** of the 6 M HCl solution, stir with a clean toothpick and observe. Record in Table 3a any changes that indicate if a reaction has taken place. **Be as specific as possible in your written observations!** If no reaction occurs indicate this in the table by writing NR.
 - b. Now place a **very small** amount of solid calcium carbonate into a sixth well, a small piece of solid zinc (Zn) into a seventh well and a **very small** amount (about the size of this dot •) of solid magnesium hydroxide, $\text{Mg}(\text{OH})_2$, into an eighth well. Into each of the wells containing the solid samples place about **six drops** of deionized water, stir each with a clean toothpick and record your observations in Table 3b, noting if the substance is soluble in the water or if a reaction occurs. Next place **five to six drops** of the 6 M HCl solution into these three wells, stir again and observe. Record in Table 3b any changes that indicate if a reaction has taken place upon addition of the HCl(aq). **Be as specific as possible in your written observations!** If no reaction occurs indicate this in the table by writing NR.
 - c. **Rinse the spot plate using a wash bottle into a waste beaker. Use a minimum amount of rinse water while doing this. We want to minimize the amount of waste generated.**
- 4. Throw the used toothpicks into the trash. DO NOT leave them scattered about on the lab benches. Dispose of the mixture in your waste beaker in the container labeled Reaction Types Experiment Waste.**

Data and Results:

Data Table 1: Results for Reagent Set 1

Solution Used (4 drops)	Solution Used (2 to 3 drops)				
	Na ₂ CO ₃	Na ₂ SO ₄	1 M NaOH	NaCl	NaC ₂ H ₃ O ₂
Ba(NO ₃) ₂					
Ca(NO ₃) ₂					
Mg(NO ₃) ₂					
AgNO ₃					
Co(NO ₃) ₂					
Cu(NO ₃) ₂					
Al(NO ₃) ₃					
NH ₄ NO ₃					

For any reactions observed, give the net ionic equation, including phase labels, and the reaction type (precipitation, acid-base, acid-base with gas formation, or redox) in the space below.

Net Ionic equation

Type of Reaction

Data Table 2: Results for Reagent Set 2

Solution Used (2 to 3 drops)	Solution Used (4 drops)			
	Mg(NO ₃) ₂	Co(NO ₃) ₂	Ba(NO ₃) ₂	NaNO ₃
NH ₃				

For any reactions observed, give the net ionic equation, including phase labels, and the reaction type (precipitation, acid-base, acid-base with gas formation, or redox) in the space below. A hint to help you write these equations is to remember that ammonia is a weak base that reacts with water producing hydroxide ions (Refer to the Nomenclature Exercise and to section 4.3 of the textbook).

Net Ionic equation

Type of Reaction

Data Table 3a: Results for Reagent Set 3 Solutions

Solution Used (2 to 3 drops)	Solution Used (4 drops)				
	Na ₂ CO ₃	NaHCO ₃	NaNO ₃	AgNO ₃	Na ₂ SO ₄
6 M HCl					

For any reactions observed, give the net ionic equation, including phase labels, and the reaction type (precipitation, acid-base, acid-base with gas formation, or redox) in the space below.

Net Ionic equation

Type of Reaction

Data Table 3b: Results for Reagent Set 3 Solids

Add	Solid Used- very small amount (about the size of this dot •)		
	CaCO ₃	Zn	Mg(OH) ₂
Deionized Water (6 drops)			
6 M HCl (5 to 6 drops)			

For any reactions observed, give the net ionic equation, including phase labels, and the reaction type (precipitation, acid-base, acid-base with gas formation, or redox) in the space below.

Net Ionic equation

Type of Reaction

Follow-Up Questions:

Be complete in your answers.

1. **Using data table 1**, fill in the following solubility chart. Place an *S* (soluble) in the grid for combinations of ions that do not precipitate, and an *I* (insoluble) for those that do. One row, is filled in for you.

Cations	Anions				
	CO_3^{2-}	SO_4^{2-}	OH^-	Cl^-	$\text{C}_2\text{H}_3\text{O}_2^-$
Group 1A	S	S	S	S	S
Ba^{2+}					
Ca^{2+}					
Mg^{2+}					
Ag^+					
Co^{2+}					
Cu^{2+}					
Al^{3+}					
NH_4^+					

2. **Referring to the chart you have completed**, answer the following questions: **(Use the information in your chart only, do not use any other source, including your textbook!)**
 - a. Are ionic compounds containing the ammonium ion generally soluble or insoluble? Are there any exceptions?

 - b. Are ionic compounds containing the carbonate ion generally soluble or insoluble? Are there any exceptions?

- c. Are ionic compounds containing the sulfate ion generally soluble or insoluble? Are there any exceptions?

- d. Are ionic compounds containing the hydroxide ion generally soluble or insoluble? Are there any exceptions?

- e. Are ionic compounds containing the chloride ion generally soluble or insoluble? Are there any exceptions?

- f. Are ionic compounds containing the acetate ion generally soluble or insoluble? Are there any exceptions?

3. Do your results agree with the solubility guidelines given on page 121 of the textbook? If not, where do they differ?

4. Looking at Data Table 2, does a precipitate form when aqueous ammonia is added to
 - a. an aqueous solution of NaNO_3 ?

 - b. an aqueous solution of $\text{Mg}(\text{NO}_3)_2$?

 - c. Why do solutions of these two compounds, NaNO_3 and $\text{Mg}(\text{NO}_3)_2$, behave differently when aqueous ammonia is added?

5. Referring to Data Table 3a, do nitrates and sulfates react with acids in a gas forming reaction similar to the way carbonates and hydrogen carbonates react? **What observations form the basis for your answer to this question?**
6. A compound is known to be Na_2CO_3 , Na_2SO_4 , NaOH , NaCl , $\text{NaC}_2\text{H}_3\text{O}_2$ or NaNO_3 . When a barium nitrate solution is added to a solution containing the unknown a white precipitate forms. No precipitate is observed when a magnesium nitrate solution is added to a solution containing the unknown. What is the identity of the unknown compound? **Clearly and completely explain your reasoning.**
7. Write the net-ionic equation for the following reactions: **Include phase labels for both reactants and products. Also classify each reaction, giving its type.**
- a. $\text{HNO}_3(\text{aq}) + \text{KOH}(\text{aq}) \rightarrow \text{KNO}_3 + \text{H}_2\text{O}$
Net Ionic Equation: _____ **Reaction Type:** _____
- b. $2\text{Na}(\text{s}) + 2\text{H}_2\text{O}(\text{l}) \rightarrow 2\text{NaOH} + \text{H}_2$
Net Ionic Equation: _____ **Reaction Type:** _____
- c. $2\text{HC}_2\text{H}_3\text{O}_2(\text{aq}) + \text{Ba}(\text{OH})_2(\text{aq}) \rightarrow \text{Ba}(\text{C}_2\text{H}_3\text{O}_2)_2 + 2\text{H}_2\text{O}$
Net Ionic Equation: _____ **Reaction Type:** _____
- d. $2\text{Li}(\text{s}) + \text{Cu}(\text{NO}_3)_2(\text{aq}) \rightarrow 2\text{LiNO}_3 + \text{Cu}$
Net Ionic Equation: _____ **Reaction Type:** _____
- e. $3\text{Na}_2\text{CO}_3(\text{aq}) + 2\text{Fe}(\text{NO}_3)_3(\text{aq}) \rightarrow \text{Fe}_2(\text{CO}_3)_3 + 6\text{NaNO}_3$
Net Ionic Equation: _____ **Reaction Type:** _____

Pre-laboratory Exercise:

Complete the following and turn it in at the start of lab lecture. Be complete in your answers.

1. Indicate whether the following compounds are strong electrolytes (SE), weak electrolytes (WE) or non-electrolytes (NE).

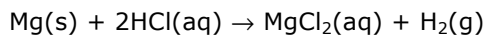
NaNO₃_____ HCl_____ HC₂H₃O₂_____ NH₃_____ sucrose(C₁₂H₂₂O₁₁)_____

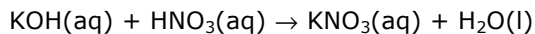
2. Classify each of the reactions given below as one of the following:

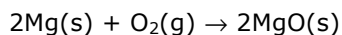
- Precipitation.
- acid-base.
- acid-base with the formation of a gas.
- oxidation-reduction (redox).

Reaction

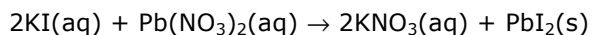
Classification











3. Describe how you will properly dispose of the waste in this experiment.