4.5 Stoichiometry

Essential knowledge statements from the AP Chemistry CED:

- Because atoms must be conserved during a chemical process, it is possible to calculate product amounts by using known reactant amounts, or to calculate reactant amounts given known product amounts.
- Coefficients of balanced chemical equations contain information regarding the proportionality of the amounts of substances involved in the reaction. These values can be used in chemical calculations involving the mole concept.
- Stoichiometric calculations can be combined with the ideal gas law and calculations involving molarity to quantitatively study gases and solutions.

$$4\ NH_3 \quad + \quad 5\ O_2 \quad \rightarrow \quad 4\ NO \quad + \quad 6\ H_2O$$

1. Ammonia, NH_3, reacts with oxygen gas, O_2, to produce nitrogen monoxide and water vapor, according to the chemical equation shown above.

   (a) Calculate the number of moles of O_2 that is required to react completely with 28.3 moles of NH_3 in this chemical reaction.

   (b) Calculate the mass, in grams, of NH_3 that is required to react completely with 175 grams of O_2.

The **limiting reactant** in a chemical reaction is the reactant that

- is completely consumed when the chemical reaction is completed
- determines the maximum amount of product that can be produced, which is known as the **theoretical yield**

$$2\ CH_3OH(g) \quad + \quad 3\ O_2(g) \quad \rightarrow \quad 2\ CO_2(g) \quad + \quad 4\ H_2O(g)$$

2. Equimolar amounts of $CH_3OH(g)$ and $O_2(g)$ are introduced into a rigid, previously evacuated reaction vessel. The mixture is sparked and a chemical reaction occurs according to the equation shown above until one of the reactants is completely consumed. Which substance, $CH_3OH(g)$ or $O_2(g)$, is used up completely in this experiment? Justify your answer.

There are two strategies summarized below to determine the identity of the limiting reactant.

Compare How Much Reactant is Needed with How Much Reactant is Available
Use stoichiometry calculations to convert the available amount of each reactant into the amount of the other reactant that is needed to react completely with it. • If the amount of a reactant that is needed is greater than the amount that is available, then that reactant is the limiting reactant. • If the amount of a reactant that is needed is less than the amount that is available, then that reactant is the excess reactant.

Calculate the Theoretical Yield of Product, Starting from Each Reactant
Use stoichiometry calculations to convert the available amount of each reactant into the amount of the product that could be produced from it. • The reactant that leads to the smaller amount of product is the limiting reactant. • The reactant that leads to the larger amount of product is the excess reactant.

$$2\ H_2(g) \quad + \quad O_2(g) \quad \rightarrow \quad 2\ H_2O(g)$$

3. Hydrogen gas reacts with oxygen gas to form water vapor according to the equation above. For each of the following experiments, identify the limiting reactant and calculate the theoretical yield of H_2O that would be produced, in units of moles or grams as shown in the table. Use the space below the table for scratch work and calculations.

Experiment	Amount of H_2 Available	Amount of O_2 Available	Identity of the Limiting Reactant	Theoretical Yield of H_2O
1	5.4 mol	2.5 mol		mol H_2O
2	13.2 mol	6.8 mol		mol H_2O
3	24.5 g	201 g		g H_2O
4	31.8 g	237 g		g H_2O

$$2\,K(s) \quad + \quad Cl_2(g) \quad \rightarrow \quad 2\,KCl(s)$$

4. The elements potassium and chlorine react to form potassium chloride according to the equation shown above. In a certain experiment, a reaction occurred between 100.0 g of $K(s)$ and 100.0 g of $Cl_2(g)$ until one of the reactants was completely consumed.

   (a) Identify the limiting reactant in this experiment. Justify your choice with both an explanation in words and supporting calculations.

   (b) Determine the theoretical yield, in grams, of $KCl(s)$ in this experiment.

   (c) Determine the mass, in grams, of the reactant that is leftover (unreacted) at the end of this experiment.

   (d) When this experiment was performed in the laboratory, the actual yield of $KCl(s)$ recovered was equal to 162.1 g. Calculate the percent yield of $KCl(s)$.

$$\text{percent yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100\%$$

In Topic 3.7 (Solutions and Mixtures) from the AP Chemistry Course and Exam Description (CED), the following information is given.

- Solution composition can be expressed in a variety of ways; molarity is the most common method used in the laboratory.

$$\text{molarity } (M) = \frac{\text{moles of solute}}{\text{liters of solution}}$$

$$3\ Cu(NO_3)_2(aq) \quad + \quad 2\ Na_3PO_4(aq) \quad \rightarrow \quad 6\ NaNO_3(aq) \quad + \quad Cu_3(PO_4)_2(s)$$

5. A student took a 25.0 mL sample of a $Cu(NO_3)_2(aq)$ solution of unknown concentration and added an excess amount of 1.0 M $Na_3PO_4(aq)$, causing a precipitate of $Cu_3(PO_4)_2(s)$ to form according to the chemical equation shown above. The solid precipitate was filtered from the solution, dried, and weighed.

   (a) The mass of $Cu_3(PO_4)_2(s)$ was recorded as 7.19 g. Calculate the number of moles of $Cu_3(PO_4)_2(s)$ recovered in this experiment.

   (b) Calculate the concentration, in mol/L, of the $Cu(NO_3)_2(aq)$ solution used in this experiment.

6. Magnesium metal, $Mg(s)$, reacts with a solution of nitric acid, $HNO_3(aq)$, to produce aqueous magnesium nitrate and hydrogen gas.

   (a) Write the balanced molecular equation for the reaction that occurs between magnesium and nitric acid. Include the phases of matter symbols (s), (aq) or (g) for each reactant and product.

   Nitric acid, HNO_3, is classified as a strong acid, which means that in an aqueous solution of $HNO_3(aq)$, the acid is completely ionized to produce the ions H^+ and NO_3^-, as shown in the following equation.

$$HNO_3(aq) \quad \rightarrow \quad H^+(aq) \quad + \quad NO_3^-(aq)$$

   (b) Write the balanced complete ionic equation for the reaction that occurs between magnesium and nitric acid. Include the phases of matter symbols (s), (aq) or (g) for each reactant and product.

6. (continued)

(c) Write the balanced net ionic equation for the reaction that occurs between magnesium and nitric acid. Include the phases of matter symbols (*s*), (*aq*) or (*g*) for each reactant and product.

(d) Calculate the mass of magnesium metal that is required to react completely with 50.0 mL of 0.625 M $HNO_3(aq)$.

7. Aluminum metal, Al(*s*) reacts with a solution of sulfuric acid, $H_2SO_4(aq)$, to produce aqueous aluminum sulfate and hydrogen gas.

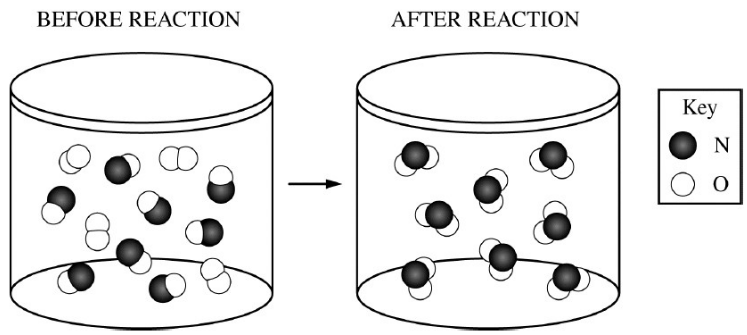
(a) Write the balanced molecular equation for the reaction that occurs between aluminum and sulfuric acid. Include the phases of matter symbols (*s*), (*aq*) or (*g*) for each reactant and product.

(b) In a certain experiment, 15.3 g Al(*s*) is reacted with a solution of 6.00 M $H_2SO_4(aq)$.

(i) Calculate the minimum volume, in mL, of 6.00 M $H_2SO_4(aq)$ that is required to react completely with 15.3 g Al(*s*) in this experiment.

(ii) Assuming that 15.3 g Al(*s*) reacts completely with an excess amount of $H_2SO_4(aq)$, calculate the theoretical yield of $H_2(g)$ produced in this experiment.

(iii) When this experiment was performed in the laboratory, the actual yield of $H_2(g)$ was recorded as 1.35 g. Calculate the percent yield of $H_2(g)$.



8. The reaction between $NO(g)$ and $O_2(g)$ to produce $NO_2(g)$ in a rigid reaction vessel is represented in the diagram above. The pressure inside the container is recorded using a pressure gauge.

(a) Write the balanced molecular equation for the reaction that occurs between $NO(g)$ and $O_2(g)$ to produce $NO_2(g)$.

(b) Which of the following statements correctly predicts the change in pressure as this reaction goes to completion at constant temperature, and provides the correct explanation?

_________ The pressure will increase because the product molecules have a greater mass than either of the reactant molecules.

_________ The pressure will decrease because there are fewer molecules of product than reactants.

_________ The pressure will decrease because the product molecules have a lower average speed than the reactant molecules.

_________ The pressure will not change because the total mass of the product molecules is the same as the total mass of the reactant molecules.

$$CH_3OH(g) \rightarrow CO(g) + 2\ H_2(g)$$

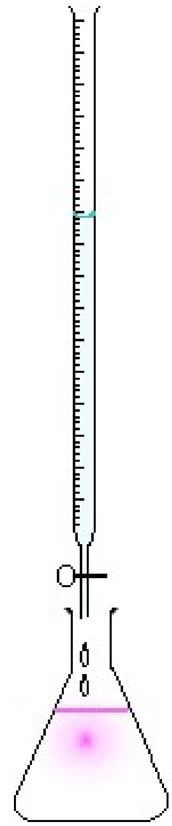
9. The reaction represented above goes essentially to completion. The reaction takes place in a rigid reaction vessel that is initially at 600 K. A sample of $CH_3OH(g)$ is placed in the previously evacuated reaction vessel with an initial pressure of 1.74 atm at 600 K. Calculate the final pressure in the reaction vessel after the reaction is complete and the contents of the vessel are returned to a temperature of 600 K.

4.6 Introduction to Titration

Essential knowledge statement from the AP Chemistry CED:

- Titrations may be used to determine the concentration of an analyte in solution. The titrant has a known concentration of a species that reacts specifically and quantitatively with the analyte. The equivalence point of the titration occurs when the analyte is totally consumed by the reacting species in the titrant. The equivalence point is often indicated by a change in a property (such as color) that occurs when the equivalence point is reached. This observable event is called the endpoint of the titration.

The following is a list of details related to a titration experiment.

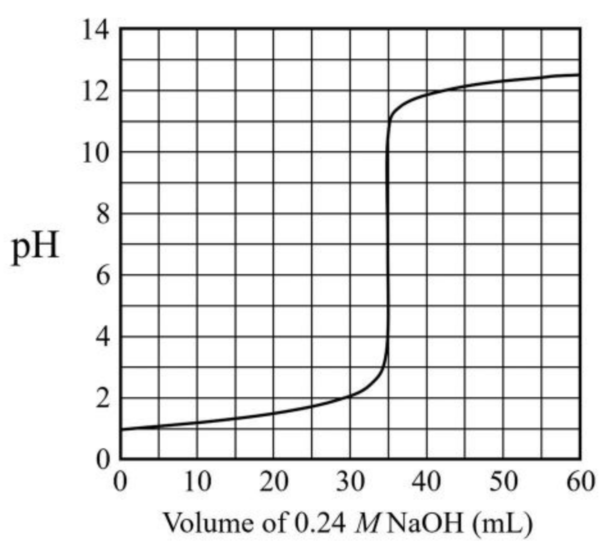


- A **standard solution** is used, containing a known amount of a certain reactant.
- An **analyte solution** is used, containing an unknown amount of another reactant.
- A balanced chemical equation is needed to describe the reaction that occurs when the two solutions are combined. An acid-base reaction is a common scenario for a titration experiment. However, a titration can also be performed with a precipitation reaction or an oxidation-reduction reaction.
- A **buret** is filled with a solution containing one of the reactants. The buret normally has graduation marks that are in 0.1 mL increments. The volume measurement is normally estimated to the nearest 0.01 mL.
- The solution in the buret is called the **titrant**, and it is added in small amounts to the other solution, which is usually in an Erlenmeyer flask. The flask is swirled frequently to mix the contents during the titration.
- The **equivalence point** is reached when one reactant has reacted completely with the other reactant, according to the stoichiometry of the chemical equation.
- An **indicator** can be used that will change color to give a signal when the equivalence point is reached.
- The **end point** is an observation that indicates when to stop adding the titrant. Then the final volume on the buret should be recorded.
- In an acid-base titration, the pH of the solution in the flask can be monitored during the experiment. The pH data can be used to create a titration curve. The pH is usually plotted on the y-axis, and the volume of the titrant added is plotted on the x-axis. The equivalence point of the acid-base titration occurs when there is a rapid change in pH.

10. The pH curve from a titration experiment is shown at right.

    (a) Determine the volume of 0.24 *M* NaOH(*aq*) that is required to reach the equivalence point in this titration.

    (b) Calculate the number of moles of NaOH that is required to reach the equivalence point in this titration.

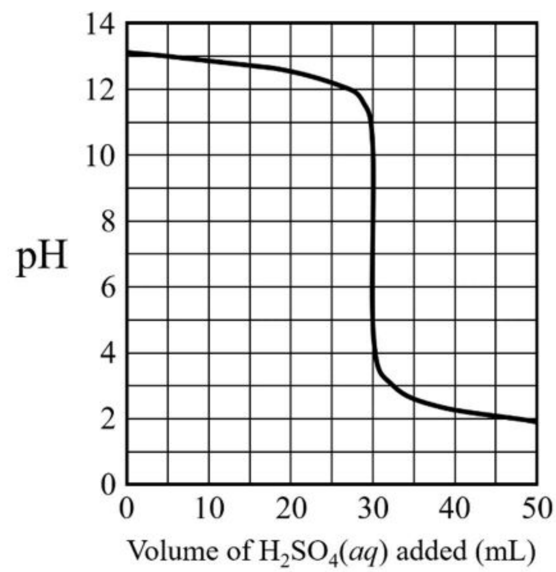


11. A student performs an experiment in which a solution of potassium hydroxide, KOH(*aq*), is titrated with a solution of sulfuric acid, H_2SO_4(*aq*). The purpose of the experiment is to determine the concentration of KOH in the KOH(*aq*) solution.

(a) Write the balanced molecular equation for the reaction that occurs between solutions of sulfuric acid and potassium hydroxide. The products of the reaction are water and aqueous potassium sulfate. Include the phases of matter symbols (*aq*) or (*l*) for each reactant and product.

(b) A student prepares a solution of H_2SO_4(*aq*) by adding 25.0 mL of 3.50 *M* H_2SO_4(*aq*) to a volumetric flask and diluting the solution to a final volume of 500.0 mL. Calculate the concentration, in mol/L, of H_2SO_4 in the diluted solution in the volumetric flask.

In order to determine the concentration of a KOH(*aq*) solution, a titration experiment is performed. A clean buret is filled with the H_2SO_4(*aq*) solution that was prepared in the procedure described in part (b). A 50.0 mL sample of KOH(*aq*) is added to a clean Erlenmeyer flask. The pH is monitored during the titration experiment, and the experimental results are plotted in the graph shown at right.



(c) Determine the volume of H_2SO_4(*aq*) that is required to reach the equivalence point in this titration.

(d) Calculate the concentration, in mol/L, of the KOH(*aq*) solution used in this experiment.

The following is a common procedure used to prepare a buret.

Step	Purpose	Procedure
1	Rinse Buret with Water	Add a small amount of distilled water to the buret. Hold the buret horizontally and rotate it so that the interior surfaces are rinsed with water. Drain the buret. Repeat this step three times.
2	Rinse Buret with Standard Solution	Add a small amount of standard solution to the buret. Hold the buret horizontally and rotate it so that the interior surfaces are rinsed with the standard solution. Drain the buret. Repeat this step three times.
3	Load Buret with Standard Solution	Fill the buret with the standard solution. Allow some of the standard solution to drain out of the bottom of the buret. The buret tip should be filled with liquid, and no air bubbles should be visible in the buret tip.

You can watch a video that shows how to prepare a buret by scanning the QR code shown at right.

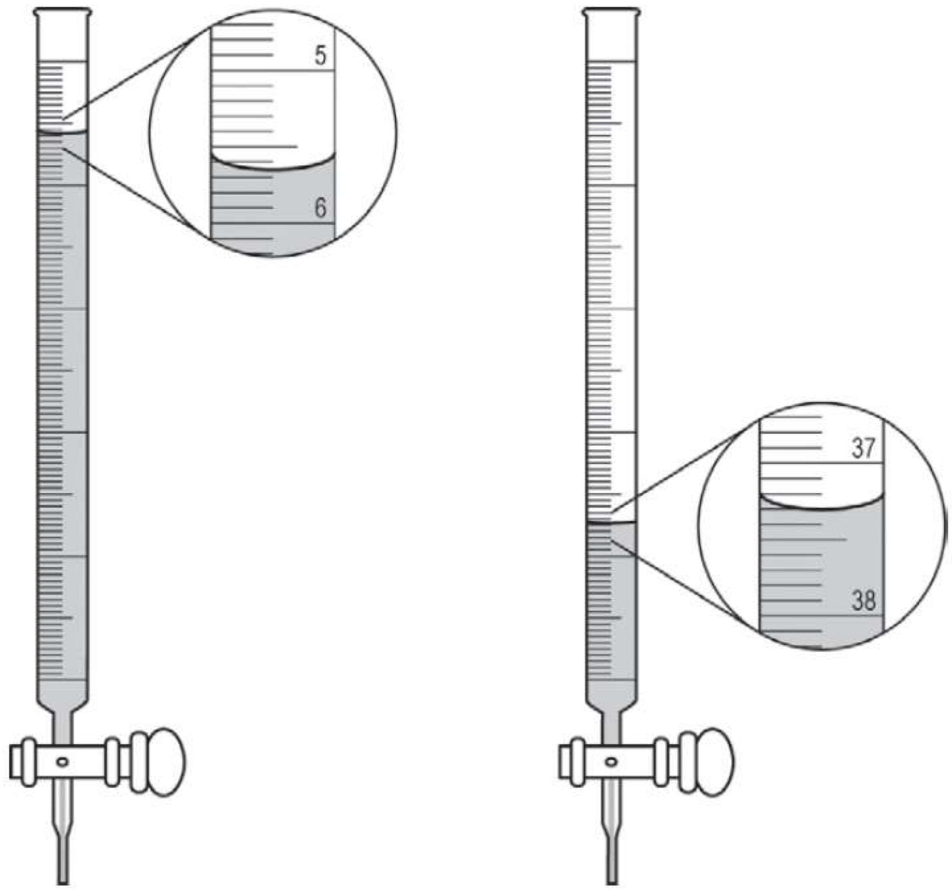
$$HC_2H_3O_2(aq) \quad + \quad NaOH(aq) \quad \rightarrow \quad H_2O(l) \quad + \quad NaC_2H_3O_2(aq)$$

12. Vinegar is a solution that contains acetic acid, $HC_2H_3O_2$. Acetic acid reacts with sodium hydroxide according to the equation above.

    A student is given a sample of vinegar and asked to do a titration experiment in order to determine the concentration of acetic acid in the vinegar solution. The student uses a standard solution of NaOH(*aq*), a buret, an Erlenmeyer flask, an appropriate acid-base indicator to signal the end point, and other laboratory equipment necessary for the titration.

    You can watch a video about the titration of vinegar by scanning the QR code shown at right.

A sample of 25.0 mL of vinegar is added to the flask in the titration experiment. The images below show the buret before the titration begins (left) and at the end point (right).



(a) In the table below. record the initial and final buret readings and the calculated value for the volume of 0.665 *M* NaOH(*aq*) required to reach the end point.

Initial buret reading	
Final buret reading at the end point	
Volume of 0.665 *M* NaOH(*aq*) required to reach the end point	

(b) Based on the given information and your answer to part (a), calculate the concentration, in mol/L, of $HC_2H_3O_2$ in the 25.0 mL sample of vinegar.

12. (c) The student performed a second trial of the titration using a 25.0 mL sample of vinegar and a standard solution of 0.665 M NaOH(aq). The student made the following mistake when they prepared the buret. After rinsing the buret with distilled water, the student did not rinse the buret with the standard NaOH(aq) solution before filling the buret with 0.665 M NaOH(aq). Based on this mistake, do you predict that the calculated value for the concentration of $HC_2H_3O_2$ in Trial 2 should be less than, greater than, or the same as the value obtained in Trial 1? Justify your answer.

$$MnO_4^-(aq) + 5\,Fe^{2+}(aq) + 8\,H^+(aq) \rightarrow Mn^{2+}(aq) + 5\,Fe^{3+}(aq) + 4\,H_2O(l)$$

13. A student obtains a solution that contains an unknown concentration of $Fe^{2+}(aq)$. The student performs a titration experiment in order to determine the concentration of $Fe^{2+}(aq)$ in the solution. The titration involves a chemical reaction between $MnO_4^-(aq)$ and $Fe^{2+}(aq)$ according to the equation above. The buret is filled with a standard solution of 0.0425 M $KMnO_4(aq)$. A sample of the $Fe^{2+}(aq)$ solution is added to an Erlenmeyer flask. Observations from the experiment are recorded in the data table below.

	Trial 1	Trial 2
Volume of solution containing $Fe^{2+}(aq)$	10.0 mL	15.0 mL
Initial buret reading	2.45 mL	19.87 mL
Final buret reading at the end point	19.87 mL	46.34 mL
Volume of 0.0425 M $KMnO_4(aq)$ required to reach the end point		

(a) Use the information in the data table to calculate the missing information in the last row.

(b) Use the information in the data table and the balanced chemical equation to calculate the concentration of $Fe^{2+}(aq)$ for both Trial 1 and Trial 2.

	Trial 1	Trial 2
Concentration of $Fe^{2+}(aq)$		

13. (c) During the second trial, the student accidentally added extra titrant past the end point, so that more $KMnO_4$(*aq*) solution was added to the flask than was needed to reach the end point. Would this error explain the difference in the calculated values of concentration of Fe^{2+}(*aq*) obtained in part (b)? Justify your answer.

$$KC_8H_5O_4(aq) \ + \ KOH(aq) \ \rightarrow \ K_2C_8H_4O_4(aq) \ + \ H_2O(l)$$

14. Potassium hydrogen phthalate, $KC_8H_5O_4$, reacts with potassium hydroxide according to the equation above. A student performs a titration experiment in which a buret is filled with a solution of KOH(*aq*) of unknown concentration. A sample of 1.25 g of $KC_8H_5O_4$(*s*) is added to a clean Erlenmeyer flask and dissolved in 50.0 mL H_2O. A few drops of an acid-base indicator is added to the flask to ensure visual detection of the end point.

(a) Calculate the number of moles of $KC_8H_5O_4$ used in this titration experiment.

(b) It is determined that 18.75 mL of KOH(*aq*) is required to reach the end point. Calculate the concentration of the KOH(*aq*) solution used in this titration experiment.

(c) The student performed a second trial of the titration. A sample of 1.25 g of $KC_8H_5O_4$(*s*) is added to a clean Erlenmeyer flask and dissolved in 30.0 mL H_2O instead of 50.0 mL H_2O (as in Trial 1). A few drops of an acid-base indicator is added to the flask to ensure visual detection of the end point.

Do you predict that the calculated value for the concentration of KOH(*aq*) in Trial 2 should be less than, greater than, or the same as the value obtained in Trial 1? Justify your answer.