

UNIT (5) SOLUTIONS

A *solution* is a homogeneous mixture of two or more substances.

5.1 | Solution Terminology

Solute and Solvent A simple solution has two components, a solute, and a solvent. The substance in smaller amount is called the **solute**; the substance in larger amount is called the **solvent**. When sugar is dissolved in water to form a solution, sugar is a solute and water is a solvent.

Aqueous Solutions The most common solutions are those containing water as the solvent. These solutions are called **aqueous solutions**.

Concentrated and Dilute A **concentrated** solution has a relatively large amount of a solute per unit of solution, and a **dilute** solution has a relatively small amount of the same solute per unit of solution.

Miscible and Immiscible are terms limited to solutions of liquids in liquids. If two liquids dissolve in each other they form a single continuous layer (like water and alcohol) and are **miscible**. Liquids that are not soluble in each other form two distinct layers (like water and oil) and are **immiscible**.

Saturated and Unsaturated A solution whose concentration is at the solubility limit at a given temperature is a **saturated** solution. If the concentration of a solute is less than the solubility limit the solution is **unsaturated**.

Common Aqueous Solutions

Solute	Solvent	Example
gas	in water	carbonated water (CO ₂ in water)
liquid	in water	beer (ethanol in water)
ionic solid	in water	saline solution (NaCl in water)
molecular solid	in water	sugar solution (C ₁₂ H ₂₂ O ₁₁ in water)

5.2 | Water as a Solvent

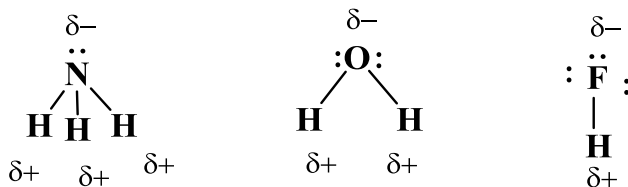
Water is called the *universal solvent* because of its ability to dissolve or dissociate many compounds. The properties that make water such a good solvent are its **polarity** (see *unit 3*) and its **hydrogen bonding** capability.

A) Hydrogen Bonding

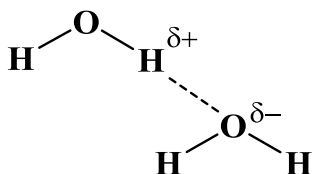
Recall that the O-H bonds in water are highly polar. This is due to the large electronegativity difference between oxygen and hydrogen. The oxygen atom has a partial negative charge (δ^-) and each hydrogen atom has a partial positive charge (δ^+). As a result, a partially positive H atom in one molecule can be attracted to a partially negative oxygen atom in another molecule of water (opposites attract). This interaction between H and O in different molecules (intermolecular) is called a **hydrogen bond** due to the involvement of hydrogen.

Hydrogen bond formation is possible whenever two molecules are the same (water-water) or different (water-alcohol).

Hydrogen bonding is possible between two molecules if one of them contains O, F, or N atom and the other contains O-H, O-F, or N-H bond.



The hydrogen bond between molecules appears as dashed lines to differentiate it from the covalent bonds within the water molecule.



B) How Water Dissolves Ionic Compounds

We learned in Unit (3) that ionic compounds are composed of ions and are held together by ionic bonds. For NaCl, attractions occur between the cations (Na^+) and the anions (Cl^-). Water, a polar molecule, is a good solvent for many ionic compounds. When NaCl crystals are added to water, the ions at the surface of the crystal become surrounded by water molecules. The cations (Na^+) attract the negative ends of water molecules, and the

anions (Cl^-) attract the positive ends of water molecules. These attractive forces between the adjacent water molecules and the ions in NaCl are sufficient to overcome the attractions that exist between ions in the solid sodium chloride. The ions then leave the sodium chloride crystals and enter the solution. Once in solution, Na^+ and Cl^- ions are completely surrounded by water molecules, a phenomenon called **hydration**. The process of dissolving NaCl in water can be shown as:

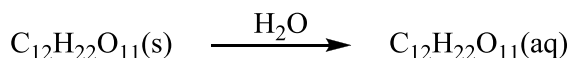


The “ H_2O ” above the arrow represents a large number of water molecules required to break up the crystal and hydrate the ions but it is not a reactant in the usual sense. The (aq) indicates that the ions are surrounded by water molecules. Recall (aq) is the symbol for “in water.”

C) How Water Dissolves Molecular Compounds

Sugar, $\text{C}_{12}\text{H}_{22}\text{O}_{11}$, is one example of molecular compound that is very soluble in water. The reason that sugar is so soluble in water lies in the structure of sugar. A sugar molecule contains a large number of polar O-H bonds, each of which is capable of forming a hydrogen bond to any adjacent water molecule. Water molecules are attracted to the polar sugar molecules and pull the molecules of sugar into the solution. Several water molecules surround each sugar molecule in the solution.

The process of dissolving sugar in water can be shown as:



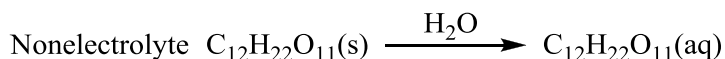
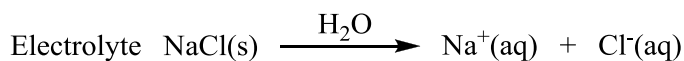
Notice that in aqueous solutions of molecular compounds no ions are present.

5.3 | Electrolytes and Nonelectrolytes

Substances whose aqueous solutions are conductors of electricity are called **electrolytes**. Substances whose aqueous solutions are not conductors of electricity are called **nonelectrolytes**.

In order for a solution to conduct an electric current, ions must be present.

Electrolytes produce ions in aqueous solutions. Nonelectrolytes do not produce ions.



5.4 | Solubility

A good rule of thumb for determining the solubility is “like dissolves like”.

Polar solvents dissolve polar substances, nonpolar solvents dissolve nonpolar substances. Solubility is the maximum amount of solute that can dissolve in a given amount of solvent.

For most solids the solubility increases with increasing temperature. In contrast, gases are less soluble in water at higher temperature.

5.5 | Solution Concentration

When dealing with solutions, it is important to know how much solute is present per given amount of solution. As a “*per*” expression, the concentration has the form of a fraction.

$$\text{Concentration} = \frac{\text{amount of solute}}{\text{amount of solution}}$$

(Amount of solution = amount of solute + amount of solvent)

There are several ways to express concentration; we will consider mass percent (%**m/v**), parts per thousand (**ppt**), parts per million (**ppm**), parts per billion (**ppb**), and **molarity**.

A) Concentration Based on Mass “parts per”

$$\text{Parts per hundred (\% m/v)} = \frac{\text{g of solute}}{\text{mL of solution}} \times 100$$

$$\text{Parts per thousand (ppt)} = \frac{\text{g of solute}}{\text{mL of solution}} \times 1000$$

$$\text{Parts per million (ppm)} = \frac{\text{g of solute}}{\text{mL of solution}} \times 1,000,000$$

$$\text{Parts per billion (ppb)} = \frac{\text{g of solute}}{\text{mL of solution}} \times (1 \times 10^9)$$

Worked Example 5-1

Calculate the % (m/v) of a solution containing 8.92 g of KCl in 455 mL of solution.

Solution

$$\text{Parts per hundred (\% m/v)} = \frac{8.92 \text{ g}}{455 \text{ mL}} \times 100 = 1.96\% \text{ (m/v)}$$

Practice 5-1

A 5.00 mL sample of solution has 3.8×10^{-5} g of calcium ion. Calculate the concentration in each of the following units: a) % (m/v) b) ppt c) ppm.

Answer

Percent Concentrations as Conversion Factors

Worked Example 5-2

Calculate the grams of NaCl in 85 mL of a 4.0% (m/v) NaCl solution.

Solution

The percent (m/v) indicates the mass of solute in 100 mL of a solution. Since the solution concentration is 4.0%, we can write two conversion factors:

$$\frac{4.0 \text{ g NaCl}}{100 \text{ mL solution}} \quad \text{and} \quad \frac{100 \text{ mL solution}}{4.0 \text{ g NaCl}}$$

The volume of the solution is converted to mass of solute by selecting the first conversion factor.

$$85 \text{ mL solution} \times \frac{4.0 \text{ g NaCl}}{100 \text{ mL solution}} = 3.4 \text{ g NaCl}$$

Practice 5-2

Calculate the number of grams of KCl in 150.0 mL of a 6.80% (m/v).

Answer

Worked Example 5-3

How many mL of 12.0% (m/v) sucrose solution would contain 3.47 g of sucrose?

Solution

Conversion Factors:

$$\frac{12.0 \text{ g sucrose}}{100 \text{ mL solution}} \quad \text{and} \quad \frac{100 \text{ mL solution}}{12.0 \text{ g sucrose}}$$

$$3.47 \text{ g sucrose} \times \frac{100 \text{ mL solution}}{12.0 \text{ g sucrose}} = 28.9 \text{ mL solution}$$

Practice 5-3

How many mL of a 3.0% (m/v) H₂O₂ solution would contain 7.8 g of H₂O₂?

Answer**B) Molarity (Concentration Based on Moles)**

The most common way of expressing concentration in chemistry is called molarity.

Molarity (M) is the moles of solute per liter of solution.

$$\text{Molarity (M)} = \frac{\text{moles of solute}}{\text{liters of solution}} = \frac{\text{mol}}{\text{L}}$$

For example if a solution contains 1.20 mol of sodium hydroxide per liter, its molar concentration is 1.20 M NaOH.

Worked Example 5-4

What is the molarity of 5.88 g of CaCl_2 in 0.265 L of solution?

Solution

$$5.88 \text{ g CaCl}_2 \times \frac{1 \text{ mol CaCl}_2}{110.98 \text{ g CaCl}_2} = 0.0530 \text{ mol CaCl}_2$$

$$M = \frac{0.0530 \text{ mol CaCl}_2}{0.265 \text{ L}} = 0.200 \text{ M}$$

Practice 5-4

What is the molarity of a solution made by dissolving 22.50 g of $\text{Mg}(\text{NO}_3)_2$ in enough water to make 450.0 mL of solution?

Answer

Molarity as a Conversion Factor

Worked Example 5-5

Calculate the mass of NaCl required to prepare 1.50 L of 0.250 M NaCl.

Solution

Like percent concentrations, we can write two conversion factors for molarity:

$$\frac{0.250 \text{ mol NaCl}}{1 \text{ L solution}} \quad \text{and} \quad \frac{1 \text{ L solution}}{0.250 \text{ mol NaCl}}$$

$$1.50 \text{ L solution} \times \frac{0.250 \text{ mol NaCl}}{1 \text{ L solution}} = 0.375 \text{ mol NaCl}$$

We use the molar mass of NaCl from the periodic table to calculate the mass of NaCl (1 mol NaCl = 58.44 g NaCl).

$$0.375 \text{ mol NaCl} \times \frac{58.44 \text{ g NaCl}}{1 \text{ mol NaCl}} = 21.9 \text{ g NaCl}$$

Practice 5-5

Calculate the volume, in liters, of 3.00 M NaOH containing 0.456 mol of NaOH.

Answer

5.6 | Dilution Calculations

Dilution is the process of adding more solvent to a solution in order to lower its concentration.

A simple relationship exists between the concentration and volume of the concentrated and diluted solutions.

$$C_1 \times V_1 = C_2 \times V_2$$

C_1 = concentration *before* dilution

V_1 = volume *before* dilution

C_2 = concentration *after* dilution

V_2 = volume *after* dilution

Worked Example 5-6

You begin with 45.0 mL of 16% (m/v) of sugar solution and add enough water to give a final volume of 55.0 mL. What is the new concentration?

Solution

$$C_1 \times V_1 = C_2 \times V_2$$

$$C_2 = \frac{C_1 \times V_1}{V_2} \quad C_2 = \frac{16\% \times 45.0 \text{ mL}}{55.0 \text{ mL}} = 13\%$$

Practice 5-6

An aqueous solution contains 75 ppm Cu^{2+} . What volume of this solution is needed to prepare 350.0 mL of a solution that is 18 ppm Cu^{2+} ?

Answer

Worked Example 5-7

A 25.0-mL sample of KNO_3 solution is diluted to a volume of 75.0 mL. If the concentration of the diluted solution is found to be 0.840 M, calculate the concentration of KNO_3 in the original solution?

Solution

$$C_1 \times V_1 = C_2 \times V_2$$

$$C_1 = \frac{C_2 \times V_2}{V_1} \quad C_1 = \frac{0.840 \text{ M} \times 75.0 \text{ mL}}{25.0 \text{ mL}} = 2.52 \text{ M}$$

Practice 5-7

To what volume should you dilute 75.0 mL of a 10.0 M HCl solution to obtain a 1.20 M HCl solution?

Answer

5.7 | Osmosis and Osmotic Pressure

Osmosis

Water movement across cell membranes is an important biological process.

Osmosis is the passage of water through a semi-permeable membrane from a region of high water concentration to a region of low water concentration.

A *Semipermeable membrane* is a thin layer of material that allows small molecules such as water to pass freely through the membrane but prevents larger molecules or ions from passing through.

Osmotic Pressure

The amount of pressure that is required to prevent the net flow of solvent (water) across the membrane and into the more concentrated solution is called osmotic pressure.

The greater the concentration differences between the separated solutions, the greater the magnitude of the osmotic pressure.

Osmolarity

Osmotic pressure of a solution depends on the number of solute particles present. (Recall: if the solute is ionic, it splits into ions).

Osmolarity is used to compare the osmotic pressures of different solutions.

$$\text{Osmolarity} = \text{molarity} \times i$$

i = number of particles

Worked Example 5-8

What is the osmolarity of each of the following solutions?

- a) 3 M NaCl b) 3 M sucrose (table sugar) c) 3 M in both NaCl and sucrose

Solution

- a) Osmolarity = molarity \times i

NaCl is an ionic solute, and it dissociates in solution to give two particles (Na^+ and Cl^-). The value of i is 2. ($\text{NaCl} \rightarrow \text{Na}^+ + \text{Cl}^-$)

$$\text{Osmolarity} = 3 \text{ M} \times 2 = 6 \text{ osmol}$$

- b) Sucrose is a molecular solute and therefore nondissociating. The value of i is 1.

$$\text{Osmolarity} = 3 \text{ M} \times 1 = 3 \text{ osmol}$$

- c) This is a two-solute system. The value of i is 2 for NaCl and 1 for sucrose.

$$\text{Osmolarity} = (3 \text{ M} \times 2) + (3 \text{ M} \times 1) = 9 \text{ osmol}$$

NaCl sucrose

Practice 5-8

What is the osmolarity of each of the following solutions?

a) 0.25 M NaBr b) 0.15 M Na₂SO₄ c) 0.25 M NaBr + 0.15 M Na₂SO₄

Answer

Isotonic, Hypertonic, and Hypotonic Solutions

Isotonic Solution:

A solution with an osmotic pressure that is **equal** to that within cells. Isotonic solutions do not change cell volume because water is entering and leaving the cell at the same rate. Normal saline (0.9% NaCl) is isotonic to red-blood cells.

Hypertonic Solution:

A solution with an osmotic pressure that is **higher** than that within cells. Hypertonic solutions cause cells to shrink (crenation) because there is a net movement of water out of the cell.

Hypotonic Solution:

A solution with an osmotic pressure that is **lower** than that within cells. Hypotonic solutions cause cells to burst (lysis) because there is a net movement of water into of the cell.

Homework Problems

- 5.1 Diagram a hydrogen bond between:
- two molecules of NH_3 .
 - two molecules of HF .
 - water molecule and $\text{CH}_3\text{-OH}$ molecule.
- 5.2 Write an equation for the dissociation of each of the following ionic compounds in water.
- LiOH
 - K_2CrO_4
 - CaCl_2
 - $(\text{NH}_4)_3\text{PO}_4$
 - $\text{Mg}(\text{C}_2\text{H}_3\text{O}_2)_2$
 - AlBr_3
 - Na_2HPO_4
 - $\text{Fe}(\text{NO}_3)_2$
- 5.3 Calculate the following concentrations in a given units:
- A teardrop with a volume of 0.5 mL contains 50 mg NaCl .
What is the % (m/v) concentration?
 - A 250 mL sample of orange juice contains 75 mg vitamin C.
What is the concentration in ppt?
 - An 8-Ounce (237 mL) sample of green tea contains 15 mg of caffeine.
What is the concentration in ppm?
 - The concentration of arsenic in water was found to be 0.02 mg per 100 mL.
Express the concentration in ppb.
- 5.4 Calculate the mass of solute in each of the following:
- 85.0 mL of 4.5% (m/v) sucrose solution
 - 275 mL of 10.5% (m/v) NaOH solution
 - 1.80 L of 22.0% (m/v) LiNO_3 solution.
- 5.5 Calculate the volume, in liters, of solution required to supply each of the following:
- 0.85 mol of Na_2CO_3 from a 0.74 M Na_2CO_3
 - 1.35 mol of MgCl_2 from a 0.62 M MgCl_2
 - 150.0 g of glucose ($\text{C}_6\text{H}_{12}\text{O}_6$) from a 2.75 M glucose solution.

5.6 Dilution Problems

- a. What volume of a 3.6% (m/v) NaOH solution can be prepared by diluting 15.0 mL of 8.5% (m/v) NaOH solution?
- b. What is the molarity of a solution prepared when 25.0 mL of 6.0 M HCl is diluted to a volume of 85.0 mL?
- c. How many milliliters of water should be added to 75.0 mL of 2.60 M AgNO₃ to produce a 2.15 M solution?

5.7 A solution was prepared by dissolving 4.65 g of AlCl₃ in enough water to give 250.0 mL of AlCl₃ solution:

- a. calculate the molarity of the solution.
- b. calculate the osmolarity of the solution.