6

BIG IDEA 2: SOLUTIONS

Big Idea 2

Chemical and physical properties of materials can be explained by the structure and the arrangement of atoms, ions, or molecules and the forces between them.

In this section, the properties of liquid solutions will be reviewed. Solution composition and factors affecting solubility will be covered.

You should be able to

- Perform calculations with different solution concentrations such as molarity and dilution (note that these are described in more detail in Big Idea 3).
- Explain how the attractions between ions and solvents affect factors determining the solubility of ionic solids and molecules in water and other solvents.
- Draw pictures of or explain representations of solutions that illustrate the interactions between solute and solvent.
- Design or explain the results of separation experiments (chromatography, filtration, distillation) based on the relative strengths of interactions among and between the components. Draw pictures of or explain representations of solutions that illustrate the interactions.

AP Tip

Questions from this section may appear on both the free-response and multiple-choice sections of the AP Exàm. Questions on the solubility or miscibility of substances may appear in the essay section.

SOLUTIONS AND THEIR COMPOSITIONS

(*Chemistry* 8th ed. pages 498–500/9th ed. pages 511–513)

TYPES OF SOLUTIONS

(*Chemistry* 8th ed. page 498/9th ed. page 511)

A solution is a homogeneous mixture. The table below summarizes the different types of solutions that can exist. In this chapter, the focus will be on liquid solutions.

Various Types of Solutions

Example	State of Solution	State of Solute	State of Solvent
Air, natural gas	Gas	Gas	Gas
Alcohol in water, antifreeze	Liquid	Liquid	Liquid
Brass (copper and zinc)	Solid	Solid	Solid
Carbonated water (soda)	Liquid	Gas	Liquid
Seawater, sugar solution	Liquid	Solid	Liquid
Hydrogen in platinum	Solid	Gas	Solid

The substance being dissolved is the *solute*. When referring to a liquid-liquid or gas-gas solution, the *solvent* is the substance present in the largest amount.

COMPOSITION

(*Chemistry* 8th ed. pages 498–500/9th ed. pages 511–513)

MOLARITY The molarity, M, of a solution (its concentration) is the number of moles of solute per liter of solution.

EXAMPLE: A solution is prepared by mixing 30.0 mL of butane (C_4H_{10}, d = 0.600 g/mL) with 65.0 mL of octane (C_8H_{18}, d = 0.700 g/mL). Assuming that the volumes add in mixing, calculate concentration of butane in the solution.

SOLUTION:

Butane is the solute because less of it is used. First find the moles of butane.

$$30.0 \text{ mL} \times \frac{0.600 \text{ g}}{1 \text{ mL}} \times \frac{1 \text{ mol}}{58.1 \text{ g}} = 0.310 \text{ mol } C_4H_{10}$$

The new solution volume is 95.0 mL, or 0.0950 L. Use this to find the molarity.

$$\frac{0.310 \text{ mol } C_4H_{10}}{0.0950 \text{ L}} = 3.26 \, M$$

FACTORS AFFECTING SOLUBILITY

(*Chemistry* 8th ed. pages 504–507/9th ed. pages 517–520)

The formation of a liquid solution begins by separating the solute into its individual components. Next, the solvent's intermolecular forces must be overcome to make room for the solute. The solute and solvent then interact to form the solution.

STRUCTURAL EFFECTS

Solubility is favored if the solute and solvent have similar intermolecular forces, as determined by their structure. The table below summarizes the solubility of different types of solutes in different types of solvents.

Type of Solute	Type of Solvent	Solubility	Example
Ionic	Polar	Usually soluble	LiCl in H_2O
Polar	Polar	Soluble (miscible)	CH_3OH in H_2O
Nonpolar	Polar	Insoluble (immiscible)	C_6H_{14} in H_2O
Nonpolar	Nonpolar	Soluble (miscible)	C_6H_{14} in CCl_4

EXAMPLE: Discuss the solubility of each of the following solutes in carbon tetrachloride (CCl_4): ammonium nitrate (NH_4NO_3), 1-pentanol ($CH_3CH_2CH_2CH_2CH_2OH$), and pentane ($CH_3CH_2CH_2CH_2CH_3$). Explain why each solute will or will not dissolve.

SOLUTION: First decide which substances are polar. CCl_4 has a central C covalently bonded to identical Cl atoms, so it is nonpolar and nonpolar solutes will dissolve in it. Ammonium nitrate is an ionic compound so it will dissolve in a polar solvent like water; it will not dissolve in a nonpolar solvent. 1-Propanol contains a polar hydroxyl group and will not be soluble in CCl_4. Pentane is a chain of carbons covalently bonded to each other and to hydrogen atoms, so it is nonpolar. It will be miscible (will form a homogeneous mixture) with CCl_4.

MULTIPLE-CHOICE QUESTIONS

No calculators may be used on this part of the exam.

1. The number of moles of $Al(NO_3)_3$ which must be added to water to form 2.00 L of 0.30 *M* NO_3^- ions is
   (A) 0.60 mol
   (B) 0.20 mol
   (C) 2.4 mol
   (D) 8.0 mol

2. When an ionic salt dissolves in water, the solute–solvent interaction is
   (A) hydrogen bonding
   (B) London forces
   (C) ion–ion forces
   (D) ion–dipole forces

3. When a polar molecule dissolves in water, the solute–solvent interaction is
   (A) hydrogen bonding
   (B) London forces
   (C) dipole–dipole forces
   (D) either (A) or (C)

4. Distillation separates molecules based on differences in
   (A) solubility
   (B) boiling points
   (C) freezing points
   (D) conductivity

5. Why do mineral deposits accumulate on the heating coil of a water distiller?
   (A) The minerals are attracted to the metal surface.
   (B) The water contains solids that are not visible.
   (C) Heating water reduces salt solubility.
   (D) When the water vaporizes, soluble salts precipitate out.

6. How much 12.0 *M* hydrochloric acid must be used to prepare 2.00 L of a 3.00 *M* hydrochloric acid solution?
   (A) 250.0 mL
   (B) 50.0 mL
   (C) 500.0 mL
   (D) 100.0 mL

7. In column chromatography, the first substance eluted
   (A) has a high affinity for the mobile phase
   (B) is insoluble in the mobile phase
   (C) precipitates out of the mobile phase
   (D) moves more slowly through the stationary phase than other substances in solution

8. Which of the following pairs of compounds will not form a homogeneous solution?
   (A) sodium chloride and water
   (B) sodium chloride and mineral oil
   (C) water and ethanol
   (D) water and sucrose

9. Over time, a solution of ethanol in water left open to the atmosphere
   (A) does not change concentration because the hydrogen bonds between OH groups of ethanol and OH groups of water are strong
   (B) becomes more concentrated because water is more volatile than ethanol
   (C) becomes less concentrated because ethanol is more volatile than water
   (D) changes in volume, but not concentration, because the hydrogen bonds between OH groups of ethanol and OH groups of water are strong

10. A small amount of copper is added to silver to form sterling silver. This is
    (A) a chemical reaction because the metal atoms bond with each other
    (B) a solution formation, with copper as the solvent and silver as the solute
    (C) a solution formation, with silver as the solvent and copper as the solute
    (D) a chemical reaction because the metals will exchange electrons

11. When a mixture of oil and water sits undisturbed, two distinct layers will form. This is because
    (A) oil molecules are attracted to each other by London dispersion forces and water molecules are attracted to each other by hydrogen bonding, so the two substances separate
    (B) oil and water react to form a new substance that rises to the top
    (C) the less dense substance will rise to the top
    (D) (A) and (C) are true

12. Which equation for dissolving a salt in water is written correctly?
    (A) $Na_2SO_4 \rightarrow Na_2^{2+} + SO_4^{2-}$
    (B) $Na_2SO_4 \rightarrow 2\ Na^+ + SO_4^{2-}$
    (C) $Na_2SO_4 \rightarrow 2\ Na^+ + S^{2-} + 4\ O^{2-}$
    (D) $Na_2SO_4 \rightarrow\ Na_2^{2+} + S^{2-} + 4\ O^{2-}$

13. Which solute would dissolve in carbon tetrachloride, CCl_4?
    (A) SrF_2
    (B) CH_3OH
    (C) CH_2O
    (D) NaCl

14. Order the following solvents from least polar to most polar:

C_6H_{14} H_2O CH_3OH $CHCl_3$

(A) $H_2O < CH_3OH < CHCl_3 < C_6H_{14}$
(B) $C_6H_{14} < CH_3OH < CHCl_3 < H_2O$
(C) $CHCl_3 < C_6H_{14} < CH_3OH < H_2O$
(D) $C_6H_{14} < CHCl_3 < CH_3OH < H_2O$

15. What is the sodium ion concentration when 70.0 mL of 3.0 *M* Na_2CO_3 is added to 30.0 mL of 1.0 *M* $NaHCO_3$?
(A) 0.45 *M*
(B) 4.5 *M*
(C) 2.4 *M*
(D) 5.1 *M*

FREE-RESPONSE QUESTIONS

1. You are given a sample of seawater contaminated by an oil spill. Describe how you would separate the various components of this mixture to determine the mass of each present (dissolved solids, water, oil). Indicate which mass measurement will be least accurate. The oil may contain some volatile nonpolar substances that are slightly soluble in water. The following equipment is available for you to use:

Safety goggles	Hot plate	
Wash bottle of distilled water	Ring stand	
Beakers of various sizes	Watch glass	
Filter paper and funnel	Evaporating dish	Desiccator
Distillation apparatus	Wash bottle of acetone	

Electronic balance with accuracy of ± 0.001 g

2. Sodium chloride is soluble in water but only slightly soluble in ethanol. Use illustrations labeled with the relevant intermolecular forces to explain these observations.

Answers

MULTIPLE-CHOICE QUESTIONS

1. **B** Since every $Al(NO_3)_3$ unit contains 3 units of NO_3^- ions, you need 1/3 as many $Al(NO_3)_3$ units as NO_3^- units. Needed are 0.30 mol/L of $NO_3^- \times 2.00$ L = 0.60 mol NO_3^-. Hence $1/3 \times 0.60$ mol = 0.20 mol $Al(NO_3)_3$ required (*Chemistry* 8th ed. page 499/9th ed. page 512). LO 2.9

2. **D** Water has a dipole which can either be attracted to the negative anion within the crystal lattice or the positive cation (*Chemistry* 8th ed. pages 130–132, 501–505/9th ed. pages 139–141, 514–518). LO 2.15

3. **D** Water has a dipole which can either be attracted to the positive or negative end of a polar molecule. Water can also form hydrogen bonds with molecules that can also form hydrogen bonds

(*Chemistry* 8th ed. pages 130–132, 501–505/9th ed. pages 139–141, 514–518). LO 2.13

4. **B** In distillation, solutions are heated so that components are separated based on their boiling temperatures, with the most volatile substances evaporating first (*Chemistry* 8th ed. page 27/9th ed. page 29). LO 2.10

5. **D** When the water vaporizes, dissolved salts do not. The concentration of ions increases until precipitation occurs (*Chemistry* 8th ed. page 508/9th ed. page 520). LO 2.10

6. **C** Use the expression $M_1V_1 = M_2V_2$. Remember that the volume unit you are solving for will be the same as the volume unit you know, in this case liters, so you will have to convert from L to mL.

$$2.00\ \text{L} \times \frac{3.00\ M}{12.0\ M} = 0.500\ \text{L}$$

(*Chemistry* 8th ed. pages 141–144/9th ed. pages 150–153). LO 2.9

7. **A** The component with the highest affinity for the mobile phase will elute first (*Chemistry* 8th ed. pages 28, 440–443/9th ed. pages 30, 455–458). LO 2.7

8. **B** Mineral oil only has London dispersion forces and cannot dissolve charged substances to any great extent. Water has dipole–dipole forces which strongly attract ions (*Chemistry* 8th ed. pages 440–443/9th ed. pages 455–458). LO 2.13

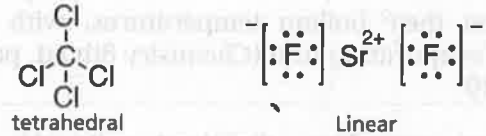
9. **C** Both liquids will evaporate, but ethanol will evaporate more. Water can make two hydrogen bonds per molecule, but ethanol can only make one. Because ethanol has fewer intermolecular forces of attraction, it will evaporate more quickly than water, lowering the solution concentration (*Chemistry* 8th ed. pages 471–474/9th ed. pages 483–486). LO 2.16

10. **C** The two metals combine to form an alloy. Copper is present in the smallest amount, so it is the solute, and silver is the solvent (*Chemistry* 8th ed. pages 455–457/9th ed. pages 469–471). LO 2.25

11. **D** Polar and nonpolar liquids will separate from each other. Oil is less dense than water, so it will form the top layer (*Chemistry* 8th ed. pages 440–443/9th ed. pages 455–458). LO 2.13

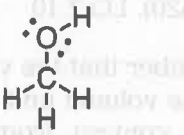
12. **B** The cation is Na^+, and the anion is the polyatomic sulfate, SO_4^{2-} (*Chemistry* 8th ed. page 28/9th ed. page 30). LO 2.23

13. C Draw Lewis structures to determine the polarity of the various substances. CH_2O is only slightly polar, so it will dissolve in CCl_4, which is nonpolar



tetrahedral
nonpolar
dipoles cancel

Linear
ionic, polar

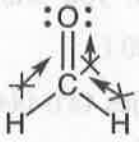


tetrahedral
polar
lone pairs on oxygen

Linear
ionic, polar

EN difference C–O > C–H

EN difference C–H > C–O

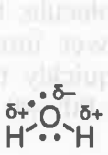


Trigonal planar
slightly polar
dipoles don't cancel each other out

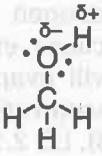
EN difference C–O > C–H

(*Chemistry* 8th ed. pages 346–349, 365–371, 440–443/9th ed. pages 358–361, 376–382, 455–458). LO 2.21

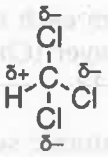
14. D



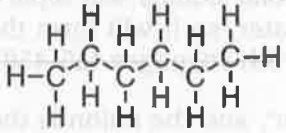
permanent dipole
forms 2 H-bonds
per molecule



permanent dipole
forms 1 H-bond
per molecule



small permanent dipole
larger EN difference between
C–Cl than C–H



induced dipole
(London dispersion)
only nonpolar

(*Chemistry* 8th ed. pages 346–349, 365–371, 440–443/9th ed. pages 358–361, 376–382, 455–458). LO 2.21

15. B First, find the moles of Na^+ each solution contributes.

Note that there are 2 moles of Na^+ per mole of Na_2CO_3, so the effective $[Na^+]$ is 6.0 *M* in Na_2CO_3:

$$70.0 \text{ mL} \times \frac{6.0 \text{ mol}}{1000 \text{ mL}} = 0.420 \text{ mol } Na^+$$

The moles of Na^+ from $NaHCO_3$ are:

$$30.0 \text{ mL} \times \frac{1.0 \text{ mol}}{1000 \text{ mL}} = 0.030 \text{ mol } Na^+$$

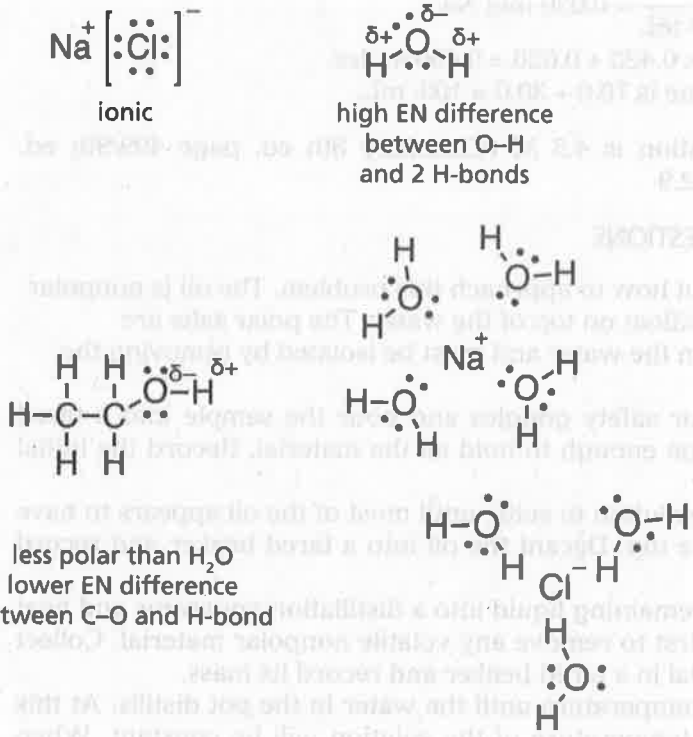
The total Na^+ is 0.420 + 0.030 = 0.450 moles.
The total volume is 70.0 + 30.0 = 100. mL.

The concentration is 4.5 *M* (*Chemistry* 8th ed. page 499/9th ed. page 512). LO 2.9

FREE-RESPONSE QUESTIONS

1. (a) Think about how to approach this problem. The oil is nonpolar and should float on top of the water. The polar salts are dissolved in the water and must be isolated by removing the water.
   (b) Put on your safety goggles and pour the sample into a tared beaker large enough to hold all the material. Record the initial mass.
   (c) Allow the solution to settle until most of the oil appears to have risen to the top. Decant the oil into a tared beaker and record its mass.
   (d) Place the remaining liquid into a distillation apparatus and heat gently at first to remove any volatile nonpolar material. Collect this material in a tared beaker and record its mass.
   (e) Raise the temperature until the water in the pot distills. At this point, the temperature of the solution will be constant. When the temperature begins going up again, indicating that most of the water has been removed, stop distillation. The material remaining in the pot will probably not be completely dry. Use a wash bottle of distilled water to transfer the mass to a tared evaporating dish.
   (f) Heat the remainder gently on a hot plate under the hood to remove any remaining water. If the solids appear gummy, indicating the presence of oil residue, wash with acetone, decanting the wash solution to an appropriate waste container, and continue heating until the solids are dry. Let cool in a desiccator to room temperature and find the mass.
   (g) The masses of oil, of volatile nonpolar material, and of dissolved solids can be found directly. The mass of water should be determined by subtraction from the original mass, since some water remained in the solids at the end of distillation. The amount of oil will be underestimated because it is difficult to remove all the oil by decanting, and whatever was not decanted remained on the salts and was washed off in step f (*Chemistry* 8th ed. pages 26–29/9th ed. pages 27–31). LO 2.10

2. Ionic substances dissolve if the forces of attraction between the cations and anions are less than the forces of attraction between the ions and the solvent. Water is very polar so the attraction between its negative oxygen and Na^+, and between its positive hydrogens and Cl^-, is greater than the attraction between Na^+ and Cl^-. Ethanol has a nonpolar end and a polar end, and is overall less polar than water. Therefore, it is not able to separate as many NaCl molecules as water can, and NaCl is less soluble in ethanol.



(*Chemistry* 8th ed. pages 440–443/9th ed. pages 455–458). LO 2.8