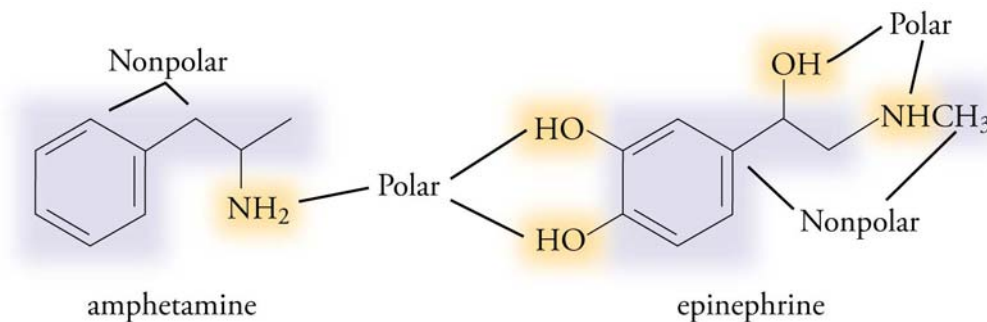


Chapter 13

Solution Dynamics



◆ Review Skills

13.1 Why Solutions Form

- The Natural Tendency to Spread Out
 - Why Do Solutions Form?
- Internet: Ethanol and Water Mixing*
- Predicting Solubility
 - Hydrophobic and Hydrophilic Substances

13.2 Fats, Oils, Soaps, and Detergents

13.3 Saturated Solutions and Dynamic Equilibrium

- Two Opposing Rates of Change
- Net Rate of Solution
- Saturated Solutions

Internet: Supersaturated Solutions

13.4 Solutions of Gases in Liquids

- Gas Solubility
- Partial Pressure and Gas Solubility
- Gas Solubility and Breathing

Special Topic 13.1: Gas Solubility, Scuba Diving, and Soft Drinks

Internet: Temperature and Solubility

Special Topic 13.2: Global Warming, the Oceans, and CO₂ Torpedoes

◆ Chapter Glossary

Internet: Glossary Quiz

◆ Chapter Objectives

Review Questions

Key Ideas

Chapter Problems

Section Goals and Introductions

Section 13.1 Why Solutions Form

Goals

- *To explain why changes that lead to greater dispersal of matter are likely to take place.*
- *To explain why liquids tend to mix and form solutions.*
- *To show how you can predict whether substances are soluble in water.*
- *To show how you can predict whether substances are soluble in hexane.*
- *To show how you can predict which of two substances would be more soluble in water.*
- *To show how you can predict which of two substances would be more soluble in hexane.*

This section introduces some key ideas that relate to how scientists explain why changes take place. This understanding is extremely important, so plan to spend some extra time on it, if necessary.

This section explains why some substances mix to form solutions and why others do not. This leads us to some guidelines that allow us to predict the relative solubilities of substances in water and hexane.

See the related section on our Web site:

Internet: Ethanol and Water Mixing

Section 13.2 Fats, Oils, Soaps, and Detergents

Goals

- *To describe fats, oils, soaps, and detergents.*
- *To explain how soap is made.*
- *To explain why soaps and detergents aid the cleaning process.*

This section uses what was described in Section 13.1 to explain why soaps and detergents aid the cleaning process. You will also learn about the structure of fats and oils, how soap is made, and the similarities and differences between soap and detergent.

Section 13.3 Saturated Solutions and Dynamic Equilibrium

Goals

- *To describe the factors that affect the rate at which substances dissolve and to explain why these factors have the effect they do.*
- *To describe the factors that affect the rate at which substances return from solution to the undissolved form.*
- *To describe saturated and unsaturated solutions.*
- *To explain how saturated solutions form.*

This section strengthens your ability to visualize the particle-nature of matter by describing the changes that take place on the submicroscopic level when substances dissolve and when they return to the undissolved state. This mental image will help you understand why certain factors affect the rate at which substances dissolve and also help you understand why some substances have a solubility limit. See the related section on our Web site:

Internet: Supersaturated Solutions

Section 13.4 Solutions of Gases in Liquids

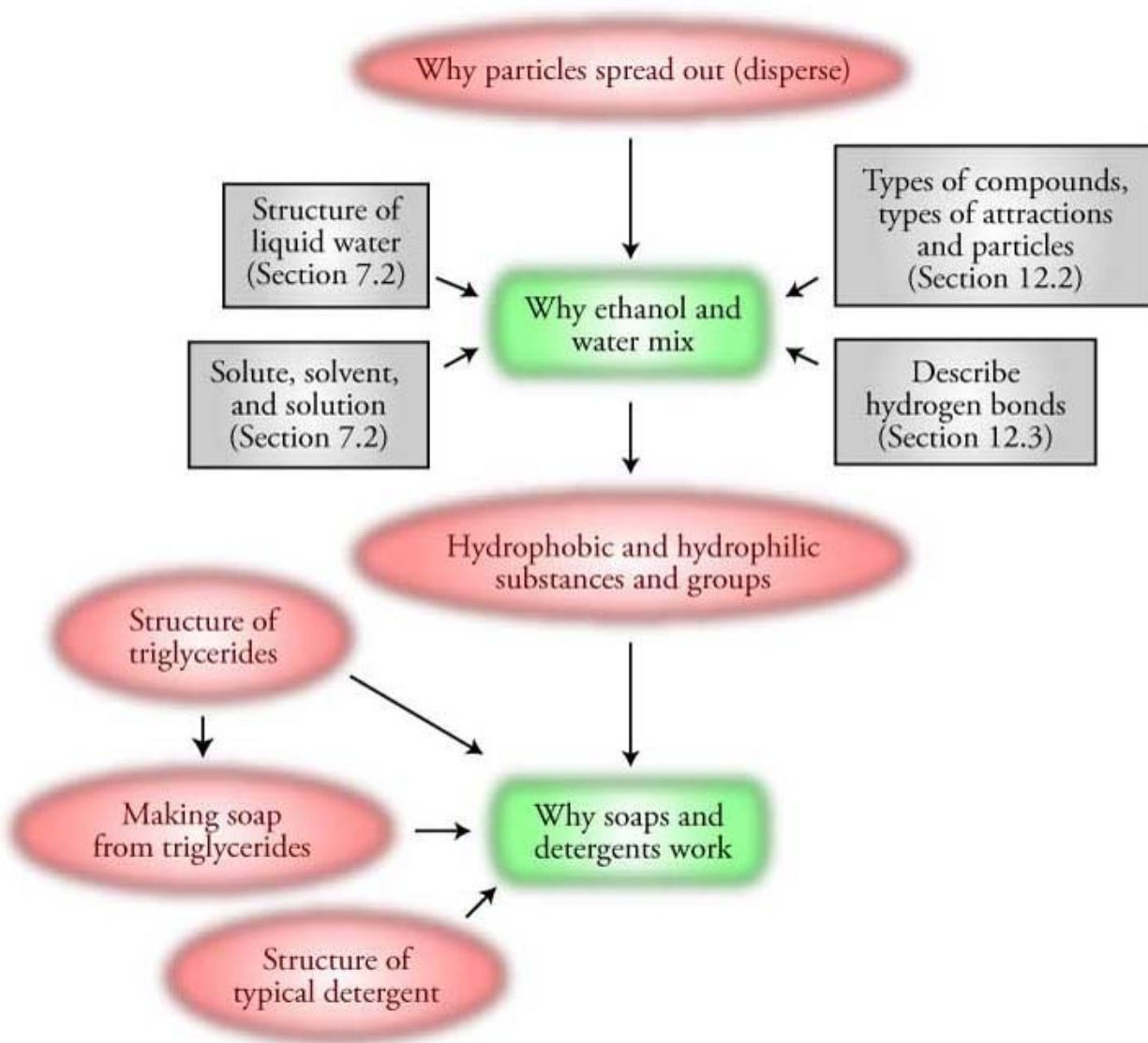
Goals

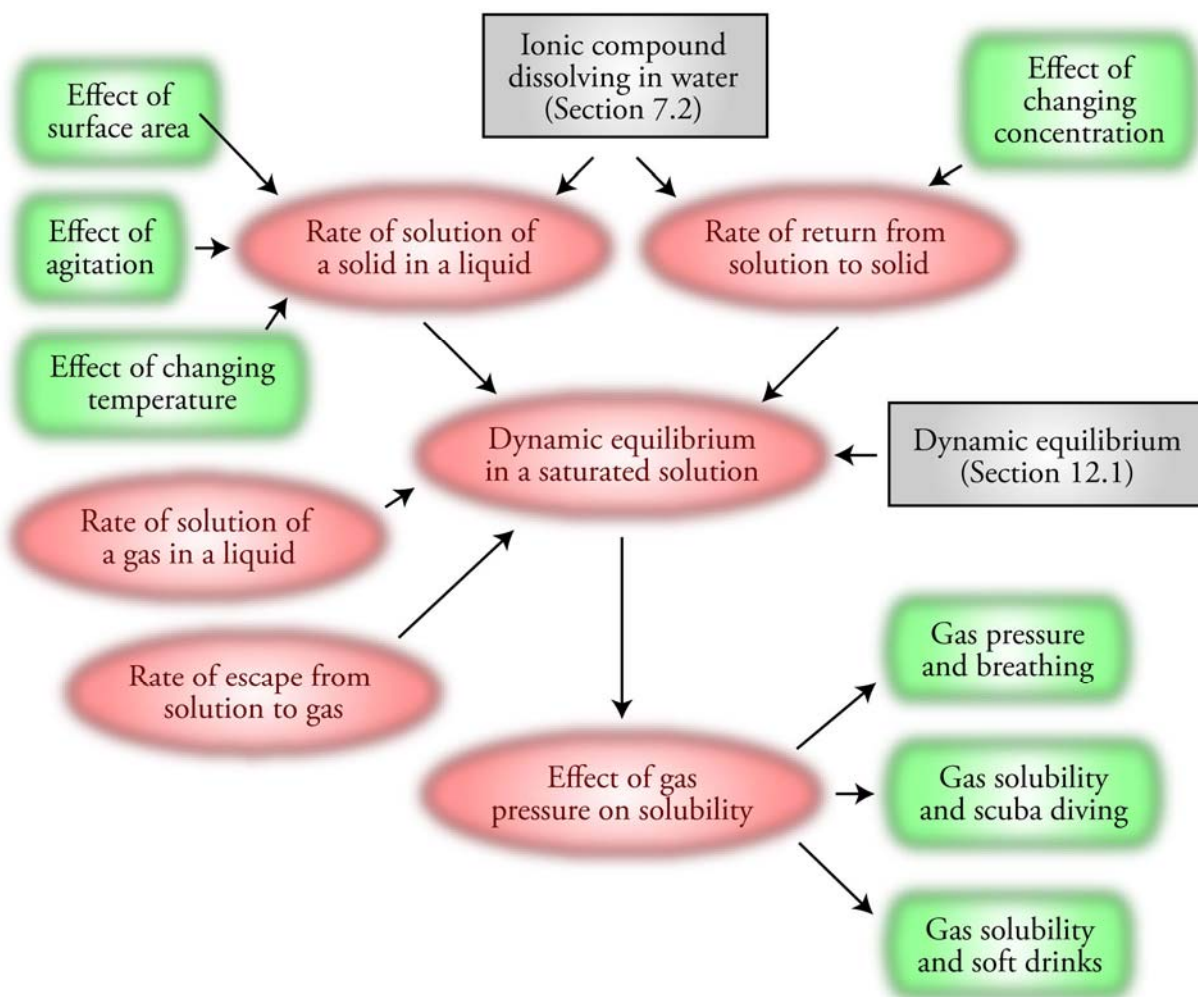
- To describe the process by which gases dissolve in liquids.
- To explain why gases have a solubility limit in liquids.
- To explain why increased partial pressure of a gas over a liquid will lead to an increase in the solubility of that gas.

The ability to visualize the changes described in this section that take place when gases dissolve in liquids will help you understand how carbonated beverages get their bubbles and also help you understand some of the issues that concern scuba divers and athletes. See the related section on our Web site:

Internet: Temperature and Solubility

Chapter 13 Maps





Chapter Checklist

- Read the Review Skills section. If there is any skill mentioned that you have not yet mastered, review the material on that topic before reading this chapter.
- Read the chapter quickly before the lecture that describes it.
- Attend class meetings, take notes, and participate in class discussions.
- Work the Chapter Exercises, perhaps using the Chapter Examples as guides.
- Study the Chapter Glossary and test yourself on our Web site:
Internet: Glossary Quiz
- Study all of the Chapter Objectives. You might want to write a description of how you will meet each objective.
- This chapter has logic sequences in Figures 13.14, 13.17, 13.19, 13.20, 13.23, and 13.24. Convince yourself that each of the statements in these sequences logically leads to the next statement.
- To get a review of the most important topics in the chapter, fill in the blanks in the Key Ideas section.

- Work all of the selected problems at the end of the chapter, and check your answers with the solutions provided in this chapter of the study guide.
- Ask for help if you need it.

Web Resources

Internet: Ethanol and Water Mixing

Internet: Saturated Solutions

Internet: Temperature and Solubility

Internet: Glossary Quiz

Exercises Key

Exercise 13.1 – Predicting Water Solubility: Predict whether each of the following compounds is soluble in water. (See Section 12.3 if you need to review the list of compounds that you are expected to recognize as composed of either polar or nonpolar molecules.) (*Obj 6*)

- a. sodium fluoride, NaF (used to fluoridate water) **soluble**
- b. acetic acid, CH₃CO₂H (added to foods for tartness) **soluble**
- c. acetylene, C₂H₂ (used in torches designed for welding and cutting) **insoluble**
- d. methanol, CH₃OH (a common solvent) **soluble**

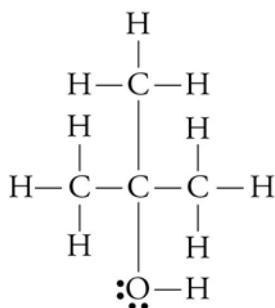
Exercise 13.2 – Predicting Solubility in Hexane: Predict whether each of the following compounds is soluble in hexane, C₆H₁₄. (*Obj 7*)

- a. sodium perchlorate, NaClO₄ (used to make explosives) *ionic compound, so insoluble*
- b. propylene, CH₃CHCH₂ (used to make polypropylene plastic for children's toys) *nonpolar molecular compound, so soluble*

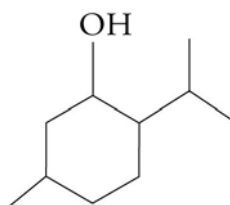
Exercise 13.3 – Predicting Relative Solubility in Water and Hexane: Predict whether each of the following compounds is more soluble in water or in hexane. (*Obj 8*)

- a. sodium iodate, NaIO₃ (used as a disinfectant) *ionic compound, so more soluble in water*
- b. 2,2,4-trimethylpentane (sometimes called isooctane), (CH₃)₃CCH₂CH(CH₃)₂ (used as a standard in the octane rating of gasoline) *nonpolar molecular compound, so more soluble in hexane*

Exercise 13.4 – Predicting Relative Solubility in Water: The compound to the left below, 2-methyl-2-propanol, which is often called t-butyl alcohol, is an octane booster for unleaded gasoline. The other compound, menthol, when added to foods and medicines affects the cold receptors on the tongue in such a way as to produce a “cool” taste. Which of these two compounds would you expect to be more soluble in water? (*Obj 9*)



2-methyl-2-propanol



menthol

The **2-methyl-2-propanol** has a greater percentage of its structure that is polar, so we expect it to be **more soluble** in water.

Review Questions Key

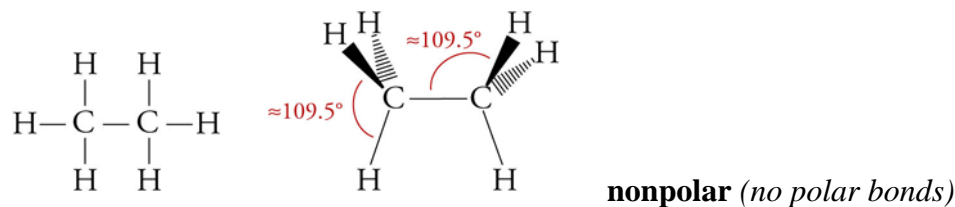
1. In the past, sodium bromide was used medically as a sedative. Describe the process by which this ionic compound dissolves in water, including the nature of the particles in solution and the attractions between the particles in the solution. Identify the solute and the solvent in this solution.

When solid sodium bromide is added to water, all of the ions at the surface of the solid can be viewed as shifting back and forth between moving out into the water and returning to the solid surface. Sometimes when an ion moves out into the water, a water molecule collides with it, helping to break the ionic bond, and pushing it out into the solution. Water molecules move into the gap between the ion in solution and the solid and shield the ion from the attraction to the solid.

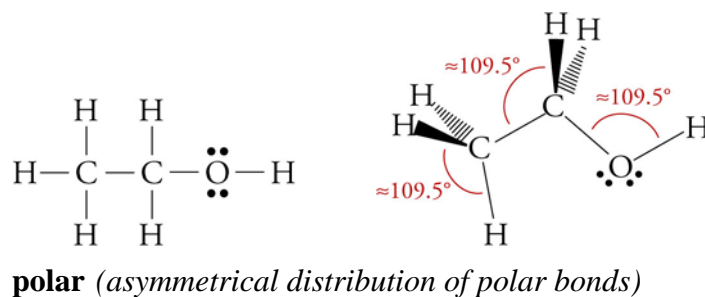
The ions are kept stable and held in solution by attractions between them and the polar water molecules. The negatively charged oxygen ends of water molecules surround the sodium ions, and the positively charged hydrogen ends of water molecules surround the bromide ions. (See Figures 7.7 and Figure 7.8 in the text with Br^- in the place of Cl^- .) The sodium bromide is the solute, and the water is the solvent.

2. Draw a reasonable Lewis structure and a geometric sketch for each of the following molecules. Identify each compound as polar or nonpolar.

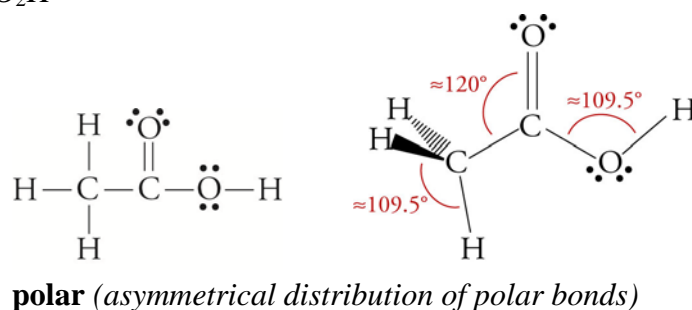
a. C_2H_6



b. CH_3CH_2OH



c. CH_3CO_2H



3. For each of the following substances, write the name for the type of particle viewed as forming the structure of its solid, liquid, or gas, and write the name of the type of attraction that holds these particles in the solid or liquid form.

- | | |
|---------------------------------|---|
| a. heptane, C_7H_{16} | nonpolar molecules / London forces |
| b. formic acid, HCO_2H | polar molecules / hydrogen bonds |
| c. copper(II) sulfate, $CuSO_4$ | cations and anions / ionic bonds |
| d. methanol, CH_3OH | polar molecules / hydrogen bonds |
| e. iodine, I_2 | nonpolar molecules / London forces |
| f. carbon dioxide, CO_2 | nonpolar molecules / London forces |

4. When liquid propane is pumped into an empty tank, some of the liquid evaporates, and after that, both liquid and gaseous propane are present in the tank. Explain why the system adjusts so that there is a constant amount of liquid and gas in the container. With reference to the constant changes that take place inside the container, explain why this system can be described as a dynamic equilibrium.

As soon as the liquid propane is added to the tank, the liquid begins to evaporate. In the closed container, the vapor particles that have escaped from the liquid are trapped. The concentration of propane vapor rises quickly to the concentration that makes the rate of condensation equal to the rate of evaporation, so there is no net change in the amount of

liquid or vapor in the tank. There are constant changes (from liquid to vapor and vapor to liquid), but because the rates of these two changes are equal (the rate of evaporation equals the rate of condensation), there is no net change in the system (the amount of liquid and vapor remains constant). Thus the system is a dynamic equilibrium.

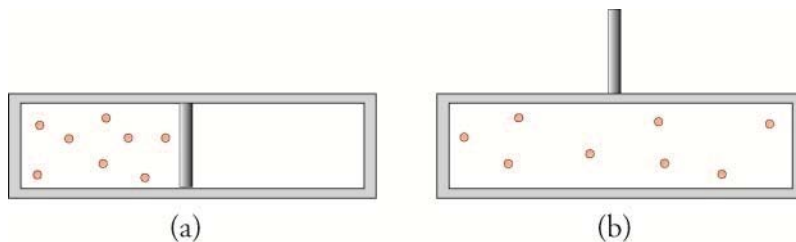
Key Ideas Answers

5. It is common for scientists to develop and explain their ideas by considering **simplified** systems first.
7. We can apply the conclusions derived from the consideration of simplified systems to **more complex** systems.
9. Because there are more possible arrangements for gas particles when they are dispersed throughout a container than when they are concentrated in one corner of it, **probability** suggests that they will spread out to fill the total volume available to them.
11. If less than 1 gram of the substance will dissolve in 100 milliliters (or 100 g) of solvent, the substance is considered **insoluble**.
13. If between 1 and 10 grams of a substance will dissolve in 100 milliliters (or 100 g) of solvent, the substance is considered **moderately** soluble.
15. Nonpolar substances are likely to dissolve in **nonpolar solvents**.
17. **Polar substances** are not likely to dissolve to a significant degree in nonpolar solvents.
19. A polar section of a molecule, which is **attracted** to water, is called hydrophilic (literally, “water loving”), and a(n) **nonpolar** part of the molecule, which is not expected to be attracted to water, is called hydrophobic (“water fearing”).
21. Soap can be made from animal **fats** and vegetable **oils**, which in turn are composed of triglycerides.
23. A soap is an ionic compound composed of a(n) **cation** (usually sodium or potassium) and an anion with the general form RCO_2^- , in which R represents a(n) **long-chain** hydrocarbon group.
25. **Hard** water is water that contains dissolved calcium ions, Ca^{2+} , magnesium ions, Mg^{2+} , and often iron ions, Fe^{2+} or Fe^{3+} . These ions bind strongly to soap anions, causing the soap to **precipitate** from hard-water solutions.
27. The net rate of solution depends on three factors: **surface area of the solute, degree of agitation or stirring, and temperature**.
29. If the partial pressure of a gas over a liquid is increased, the **solubility** of that gas is increased.

Problems Key

Section 13.1 Why Solutions Form

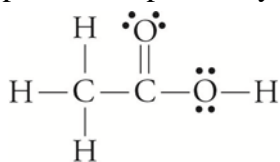
31. The container shown in (a) below consists of two chambers separated by a partition. One side contains a gas, and the other side is empty. When the partition between the two chambers is removed, the gas moves between the chambers until it is evenly distributed. Explain why this happens. Your explanation should compare the relative degree of dispersal of the particles and the number of ways to arrange the particles in the systems. (Obj 3)



Changes tend to take place when they lead to an increase in the degree of dispersal of the system. Therefore, we expect that the system will shift from the less dispersed state to the more dispersed state where they fill the whole container. The reason for this shift is that there are more ways to arrange our system in the more dispersed form than in the more concentrated form. Because the particles can move freely in the container, they will shift to the more probable and more dispersed form. See Figure 13.2 of the text.

Gas in one chamber	→	Gas in both chambers
Fewer ways to arrange particles		More ways to arrange particles
Less probable		More probable
Particles closer together		Particles more dispersed

33. The primary components of vinegar are acetic acid and water, both of which are composed of polar molecules with hydrogen bonds that link them. These two liquids will mix in any proportion. Explain why acetic acid and water are miscible. (Obj 4)



Acetic acid

Picture a layer of acetic acid that is carefully added to water (See Figure 13.3 of the text. Picture acetic acid molecules in the place of the ethanol molecules.) Because the particles of a liquid are moving constantly, some of the acetic acid particles at the boundary between the two liquids will immediately move into the water, and some of the water molecules will move into the acetic acid. In this process, water-water and acetic acid-acetic acid attractions are broken and acetic acid-water attractions are formed. Both acetic acid and water are molecular substances with O–H bonds, so the attractions broken between water molecules and the attractions broken between acetic acid molecules are hydrogen bonds. The attractions that form between the acetic acid and water molecules are also hydrogen bonds. We expect the hydrogen bonds that form between water molecules and acetic acid molecules to be similar in strength to the hydrogen bonds that are broken. Because the attractions between the particles are so

similar, the freedom of movement of the acetic acid molecules in the water solution is about the same as their freedom of movement in the pure acetic acid. The same can be said for the water. Because of this freedom of movement, both liquids will spread out to fill the total volume of the combined liquids. In this way, they will shift to the most probable, most dispersed state available, the state of being completely mixed. There are many more possible arrangements for this system when the acetic acid and water molecules are dispersed throughout a solution than when they are restricted to separate layers.

36. Would the following combinations be expected to be soluble or insoluble?
- | | |
|---|----------------------|
| a. polar solute and polar solvent | soluble |
| b. nonpolar solute and polar solvent | insoluble |
| c. ionic solute and water | often soluble |
| d. molecular solute with small molecules and hexane | often soluble |
| e. hydrocarbon solute and water | insoluble |
38. Write the chemical formula for the primary solute in each of the following solutions. Explain how the solubility guideline *like dissolves like* leads to the prediction that these substances would be soluble in water.
- vinegar Acetic acid, $\text{HC}_2\text{H}_3\text{O}_2$, is like water because both are composed of small, polar molecules with hydrogen bonding between them.
 - household ammonia Ammonia, NH_3 , is like water because both are composed of small, polar molecules with hydrogen bonding between them.
40. Predict whether each of the following compounds is soluble in water. (*Obj 6*)
- the polar molecular compound 1-propanol, $\text{CH}_3\text{CH}_2\text{CH}_2\text{OH}$ (a solvent for waxes and vegetable oils)
soluble (*Small alcohols and other small polar molecular substances tend to be soluble in water.*)
 - cis-2-pentene, $\text{CH}_3\text{CHCHCH}_2\text{CH}_3$ (a polymerization inhibitor)
insoluble (*Hydrocarbon molecules and other nonpolar molecular substances are insoluble in water.*)
 - the polar molecular compound formic acid, HCO_2H (transmitted in ant bites)
soluble (*Small polar molecular substances tend to be soluble in water.*)
 - strontium chlorate, $\text{Sr}(\text{ClO}_3)_2$ (used in tracer bullets)
soluble (*Ionic compounds tend to be soluble in water.*)
42. Predict whether each of the following compounds is soluble in hexane, C_6H_{14} . (*Obj 7*)
- butane, C_4H_{10} (fuel for cigarette lighters)
soluble (*Hydrocarbon molecules and other nonpolar molecular substances tend to be soluble in hexane.*)
 - potassium hydrogen oxalate, KHC_2O_4 (used to remove stains)
insoluble (*Ionic compounds are insoluble in hexane.*)

44. Predict whether each of the following compounds would be more soluble in water or hexane. (Obj 8)

a. toluene, $C_6H_5CH_3$ (in aviation fuels)

hexane (*Hydrocarbon molecules and other nonpolar molecular substances are more soluble in hexane than in water.*)

b. lithium perchlorate, $LiClO_4$ (in solid rocket fuels)

water (*Ionic compounds are more soluble in water than in hexane.*)

47. Would you expect acetone, CH_3COCH_3 (in some nail polish removers), or 2-hexanone, $CH_3COCH_2CH_2CH_2CH_3$ (a solvent), to be more soluble in water? Why? (Obj 9)

*Acetone molecules have a higher percentage of their structure that is polar, so **acetone** is more soluble in water.*

49. Would you expect ethane, C_2H_6 (in natural gas), or strontium perchlorate, $Sr(ClO_4)_2$ (in fireworks), to be more soluble in hexane, C_6H_{14} ? Why? (Obj 9)

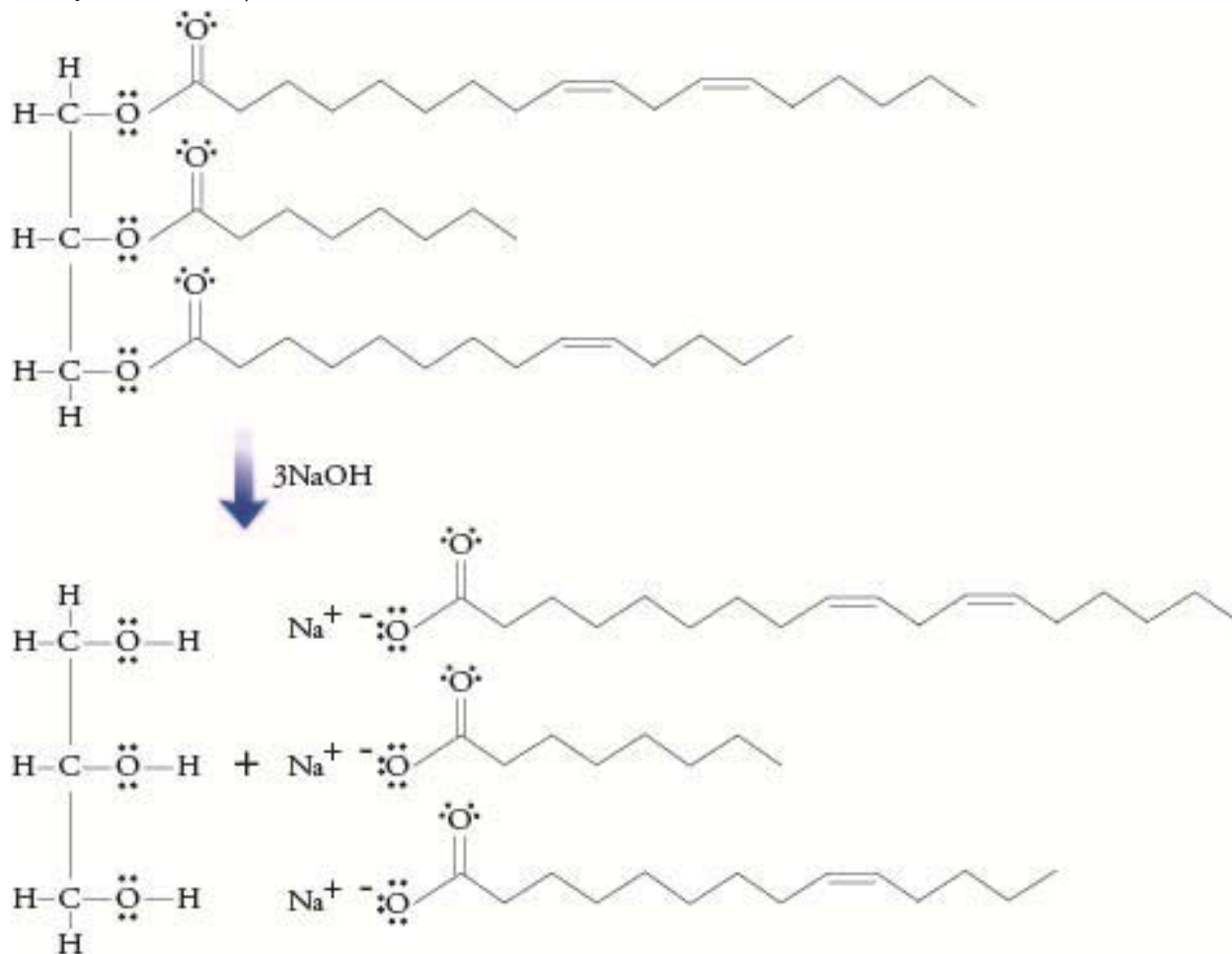
*Nonpolar substances, such as **ethane**, are **more soluble** in the nonpolar solvent hexane than highly polar ionic compounds, such as strontium perchlorate.*

51. Explain why amphetamine can pass through the blood-brain barrier more easily than epinephrine. (Obj 10)

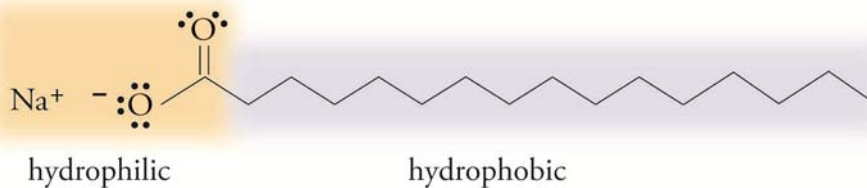
The three $-OH$ groups and the $N-H$ bond in the epinephrine structure give it a greater percentage of its structure that is polar, so we predict that epinephrine would be more attracted to polar substances than amphetamine. The cell membranes that separate the blood stream from the inside of brain cells have a nonpolar interior and a polar exterior. More polar molecules, such as epinephrine, are more attracted to the polar exterior of the cell membrane. Therefore, they are slowed more when they collide with the membrane, making it less likely that they will pass into the cell.

Section 13.2 Fats, Oils, Soaps, and Detergents

53. What are the products of the reaction between the following triglyceride and sodium hydroxide? (Obj 13)



55. What part of the following soap structure is hydrophilic and what portion is hydrophobic? (Obj 14)

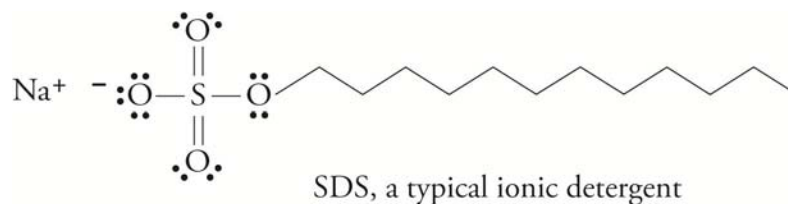


The very polar, ionic end on the left is hydrophilic (attracted to water), and the nonpolar, hydrocarbon portion of the structure is hydrophobic.

57. If you live in an area that has very hard water, detergents are a better choice for cleaning agents than soap. Describe the difference in structure between a typical anionic detergent and a typical soap. Describe what makes water hard, and explain why detergents work better in hard water than soap does. (*Obj's 16 & 17*)

For soap to work, its anions must stay in solution. Unfortunately, they tend to precipitate from solution when the water is "hard." Hard water is water that contains dissolved calcium ions, Ca^{2+} , magnesium ions, Mg^{2+} , and often iron ions, Fe^{2+} or Fe^{3+} . These ions bind strongly to soap anions, causing the soap to precipitate from hard water solutions.

Detergents have been developed to avoid this problem of soap in hard water. Their structures are similar to (although more varied than) soap but less likely to form insoluble compounds with hard water ions. Some detergents are ionic like soap, and some are molecular. For example, in sodium dodecyl sulfate (SDS), a typical ionic detergent, the $-\text{CO}_2^-$ portion of the conventional soap structure is replaced by an $-\text{OSO}_3^-$ group, which is less likely to link with hard water cations and precipitate from the solution:



Section 13.3 - Saturated Solutions and Dynamic Equilibrium

59. Epsom salts, a common name for magnesium sulfate heptahydrate, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, can be used to help reduce swelling caused by injury. For example, if you want to reduce the swelling of a sprained ankle, you can soak the ankle in a saturated solution of magnesium sulfate prepared by adding an excess of Epsom salts to water and waiting until the greatest possible amount of solid dissolves.
- Describe the reversible change that takes place as the MgSO_4 dissolves. (You do not need to mention the water of hydration that is attached to the magnesium sulfate.) (*Obj 18*)

Picture the MgSO_4 solid sitting on the bottom of the container. The magnesium and sulfate ions at the surface of the solid are constantly moving out into the water and being pulled back by the attractions to the other ions still on the surface of the solid. Sometimes when an ion moves out into the water, a water molecule collides with it and pushes it farther out into the solution. Other water molecules move into the gap between the ion in solution and the solid and shield the ion from the attraction to the solid. The ion is kept stable and held in solution by attractions between the polar water molecules and the charged ions. The negative oxygen atoms of the water molecules surround the cations, and the positive hydrogen ends of water molecules surround the anions.

Once the ions are in solution, they move throughout the solution like any particle in a liquid. Eventually they collide with the surface of the solid. When this happens, they come back under the influence of the attractions that hold the particles in the solid, and they are likely to return to the solid form.

- b. Explain why an increase in the concentration of solute particles in this solution containing undissolved solid leads to an increase in the rate of return of the solute to the solid form. (*Obj 19*)

The more particles of solute there are per liter of solution, the more collisions there will be between solute particles and the solid. More collisions lead to a greater rate of return of solute particles from the solution to the solid (See Figures 13.14 and 13.15 in the textbook.)

- c. Why does the magnesium sulfate dissolve faster if the solution is stirred? (*Obj 23*)

As particles leave the solid and go into solution, localized high concentrations of dissolved solute form around the surface of the solid. Remember that the higher concentration of solute leads to a higher rate of return to the solid form. A higher rate of return leads to a lower overall net rate of solution. If you stir or in some way agitate the solution, the solute particles near the solid will be moved more quickly away from the solid, and the localized high concentrations of solute will be avoided. This will diminish the rate of return and increase the net rate of solution. This is why stirring the mixture of water and Epsom salts dissolves the magnesium sulfate more rapidly. (See Figures 13.17 and 13.18 of the textbook.)

- d. When the maximum amount of magnesium sulfate has dissolved, does the solid stop dissolving? Explain.

The solution becomes saturated when the rate of solution and the rate of return become equal. The solid continues to dissolve, but particles return to the solid from solution at the same rate. Even though the specific particles in solution are constantly changing, there is no net change in the total amount of solid or the amount of ions in solution.

61. If you wanted to make sugar dissolve as quickly as possible, would you use

- a. room temperature water or hot water? Why?

*Higher temperature increases the rate at which particles escape from a solid, increasing the rate of solution. The higher temperature also helps the escaped particles to move away from the solid more quickly, minimizing the rate of return. Together these two factors make the net rate of solution in the **hot water** higher.*

- b. powdered sugar or granular sugar? Why?

*Only particles at the surface of the solid sugar have a possibility of escaping into the solution. The particles in the center of each sugar crystal have to wait until the particles between them and the surface dissolve to have any chance of escaping. **Powdered sugar** has much smaller crystals, so a much higher percentage of the sugar particles are at the surface. This increases the rate of solution. (See Figure 13.16 of the textbook.)*

63. What does it mean to say a solution is saturated? Describe the changes that take place at the particle level in a saturated solution of sodium chloride that contains an excess of solid NaCl. Is the NaCl still dissolving?

A saturated solution has enough solute dissolved to reach the solubility limit. In a saturated solution of NaCl, Na^+ and Cl^- ions are constantly escaping from the surface of the solid and moving into solution, but other Na^+ and Cl^- ions in solution are colliding with the solid and returning to the solid at a rate equal to the rate of solution. Because the rate of solution and the rate of return to the solid are equal, there is no net shift to more or less salt dissolved.

65. Can a solution be both concentrated (with a relatively high concentration of solute) and unsaturated? Explain your answer.

Yes, a solution can be both concentrated and unsaturated. If the solubility of a substance is high, the concentration of the solute in solution can be high even in a solution where the rate of return to the undissolved solute is still below the rate of solution.

Section 13.4 Solutions of Gases in Liquids

67. Consider a soft drink bottle with a screw cap. When the cap is removed, the excess CO_2 in the space above the soft drink escapes into the room, leaving normal air above the liquid. Explain why the soft drink will lose its carbonation more quickly if the cap is left off than if the cap is immediately put back on tightly.

At the same temperature, the rate at which carbon dioxide molecules escape from the soft drink is the same whether the container is open or closed. When a soft drink is open to the air, the carbon dioxide molecules that escape can move farther from the surface of the liquid and are therefore less likely to collide with the surface of the liquid and return to the solution. This means a lower rate of return in the drink open to the air. Therefore, the difference between the rate of escape of the CO_2 from the soft drink and the rate of return will be greater in the bottle open to the air, so there is a greater net rate of escape of the gas from the soft drink.

