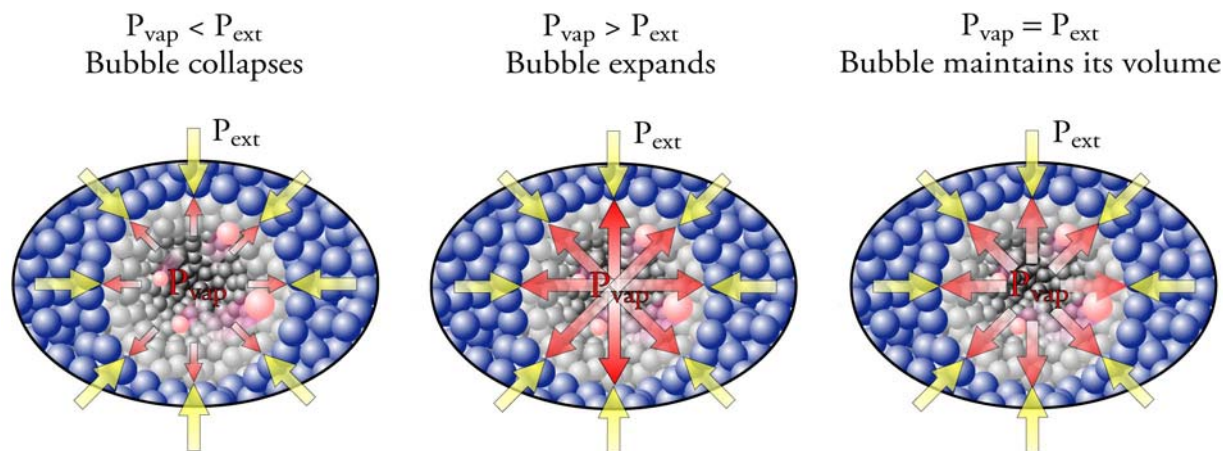


Chapter 12

Liquids: Condensation, Evaporation, and Dynamic Equilibrium



◆ Review Skills

12.1 Change from Gas to Liquid and from Liquid to Gas – An Introduction to Dynamic Equilibrium

- The Process of Condensation
- The Process of Evaporation
- How Evaporation Causes Cooling
- Rate of Evaporation
- Dynamic Equilibrium Between Liquid and Vapor
- Equilibrium Vapor Pressure

Special Topic 12.1: Chemistry Gets the Bad Guys

12.2 Boiling Liquids

- How Do Bubbles Form in Liquids?
- Response of Boiling-Point Temperature to External Pressure Changes
- Relative Boiling-Point Temperatures and Strengths of Attractions

12.3 Particle-Particle Attractions

- Dipole-Dipole Attractions
- Predicting Bond Type
- Predicting Molecular Polarity

Internet: Molecular Polarity

- Hydrogen Bonds
- London Forces

Internet: London Forces and Polar Molecules

- Particle Interaction in Pure Elements
- Summary of the Types of Particles and the Attractions Between Them

Internet: Relative Strengths of Attractions

◆ Chapter Glossary

Internet: Glossary Quiz

◆ Chapter Objectives

Review Questions

Key Ideas

Chapter Problems

Section Goals and Introductions

Section 12.1 Change from Gas to Liquid and from Liquid to Gas – An Introduction to Dynamic Equilibrium

Goals

- *To describe the process that takes place at the particle level when a gas condenses to a liquid.*
- *To describe the process that takes place at the particle level when a liquid evaporates to become a gas.*
- *To explain why liquids cool as they evaporate.*
- *To describe the factors that affect the rate at which liquids evaporate.*
- *To explain what a dynamic equilibrium is.*
- *To explain why the system in which a liquid in a closed container comes to a dynamic equilibrium between the rate of evaporation and the rate of condensation.*
- *To explain what equilibrium vapor pressure is and why it changes with changing temperature.*

This section continues the effort to help you visualize the changes that take place on the particle level for many everyday processes. The ability to picture these changes for the conversions for liquid to gas and gas to liquid will help explain why you feel cool when you step out of the shower even on a warm day; why certain substances evaporate faster than others; why the liquid in a soft drink doesn't disappear even though it is constantly evaporating into the space above the liquid; and why pressures build up in aerosol cans when they are heated. Promise yourself that you will make a special effort to “see” in your mind's eye the particle changes that accompany each of the situations described in this section.

Section 12.2 Boiling Liquids

Goals

- *To describe the changes that must take place on the particle level for a liquid to boil.*
- *To explain why a liquid must reach a certain minimum temperature before it can boil.*
- *To explain why boiling point temperature for a liquid changes with changing external pressure acting on the liquid.*
- *To explain why different substances boil at different temperatures.*

In this section, you will use your ability to visualize liquid and gaseous particles to understand the mechanics of boiling. This will help you explain why different substances have different temperatures at which they boil and why the boiling point temperature of a specific liquid changes with changes in the external pressure acting on the liquid.

Section 12.3 Particle-Particle Attractions

Goals

- *To describe the different types of attractions that hold particles together in the liquid or solid form.*
- *To describe how to predict the type of attraction holding the particles of a particular substance together in the solid and liquid form.*

- To explain what it means when we say a molecule is polar and show how you can predict whether a molecule is polar or nonpolar.
- To explain why, in general, larger molecules have stronger attractions between them.

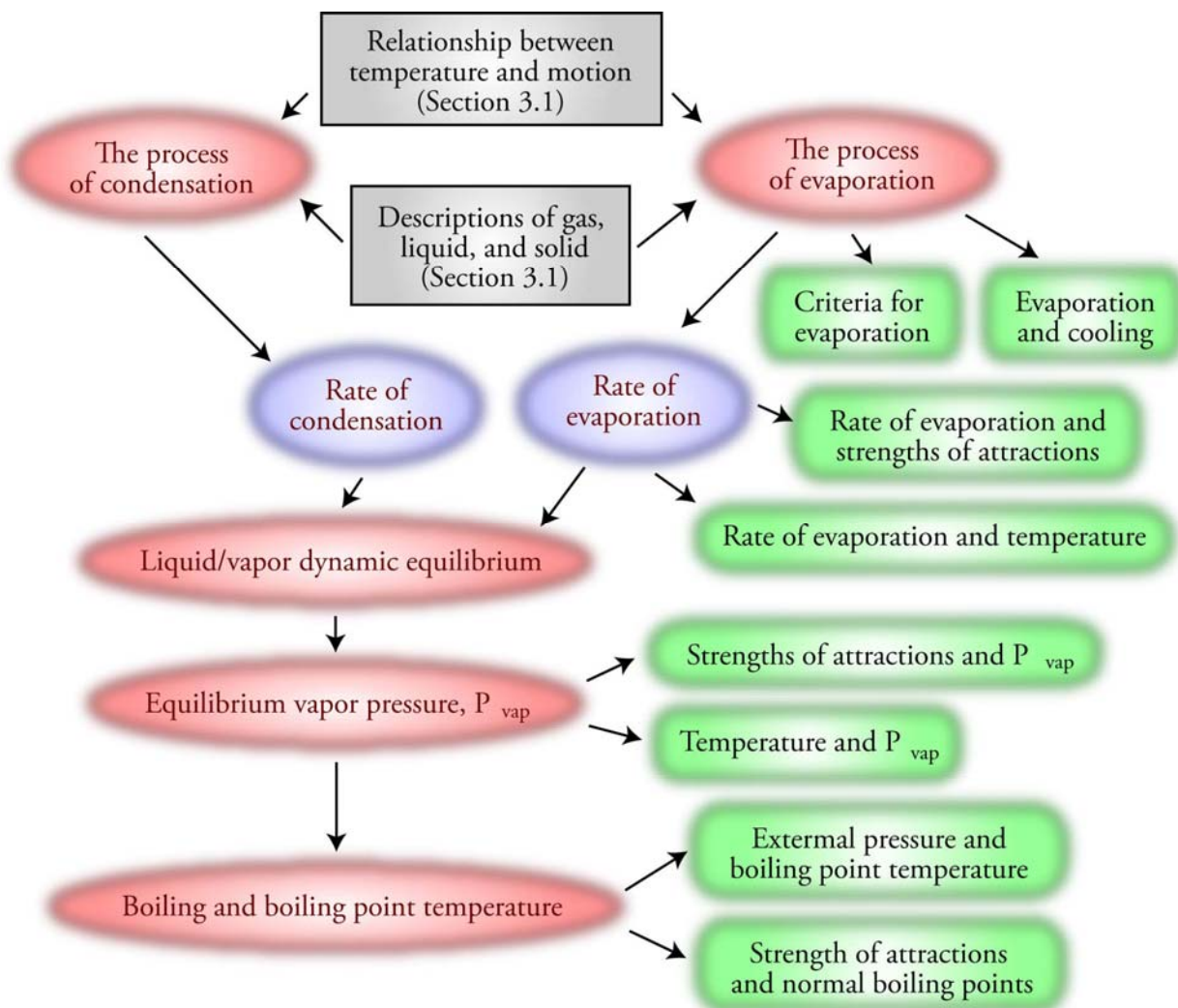
In this section, you get more information about the particles that form the fundamental structure of substances and about the attractions between them. This information will help you understand why certain substances are solids at room temperature, some are liquids, and others are gases; and it will further develop your ability to visualize the changes that take place when substances melt or boil. See the three related sections on our Web site:

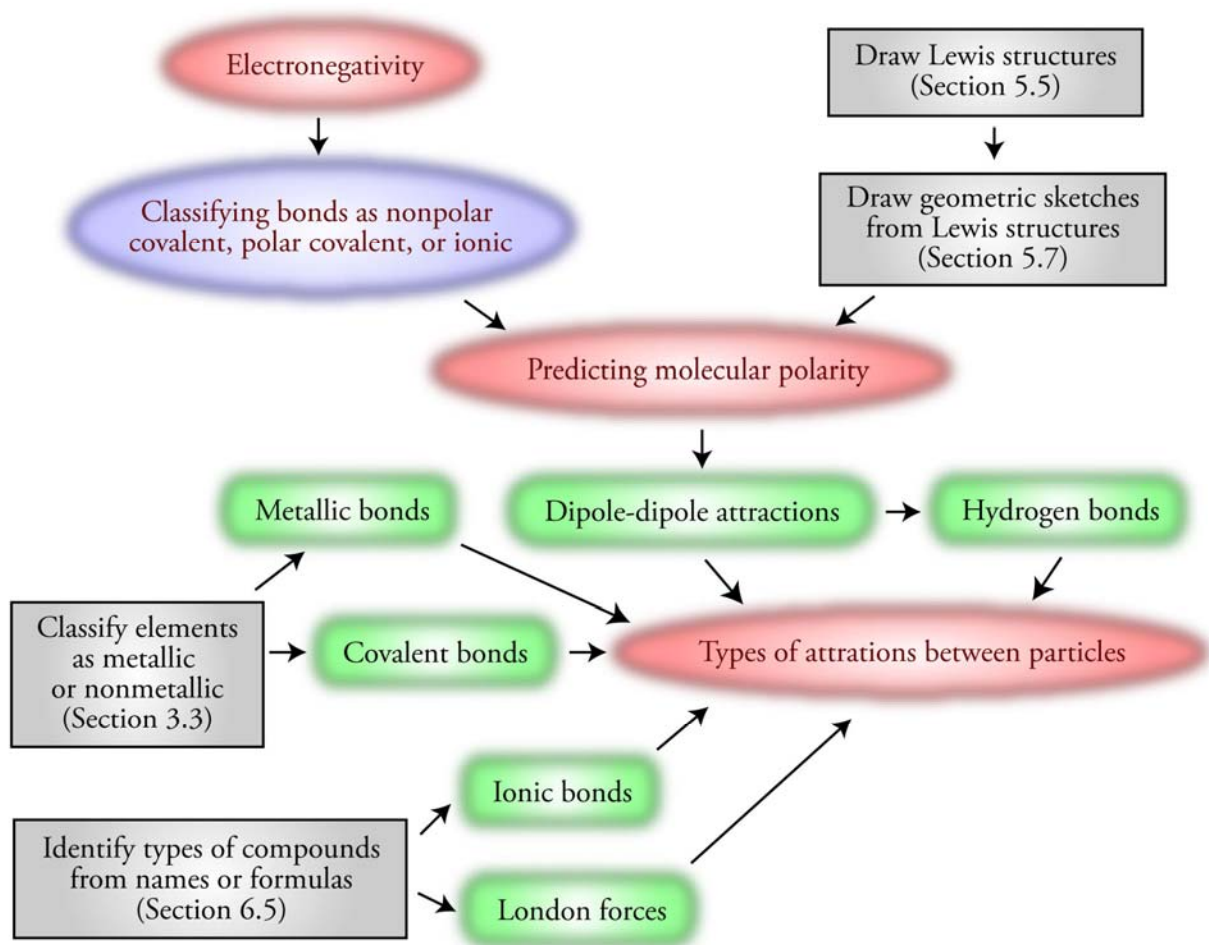
Internet: Molecular Polarity

Internet: London Forces and Polar Molecules

Internet: Relative Strengths of Attractions

Chapter 12 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
- This chapter has logic sequences in Figures 12.3, 12.4, 12.8, 12.9, 12.14, and 12.16. Convince yourself that each of the statements in these sequences logically lead to the next statement.
- Study all of the Chapter Objectives. You might want to write a description of how you will meet each objective. (Although it is best to master all of the objectives, the following objectives are especially important because they pertain to skills that you will need while studying other chapters of this text: 11, 22 and 30.)

- Reread the Study Sheet in this chapter and decide whether you will use it or some variation on it to complete the tasks it describes.

Sample Study Sheet 12.1: Electronegativity, Types of Chemical Bonds, and Bond Polarity

- Memorize the following.

Be sure to check with your instructor to determine how much you are expected to know of the following.

- The information on Table 12.1

Type of Substance	Particles	Examples	Attraction in Solid or Liquid
Elements			
Metal	Cations in a sea of electrons	Au	Metallic Bond
Noble Gases	Atoms	Xe	London Forces
Carbon (diamond)	Carbon Atoms	C(dia)	Covalent Bonds
Other Nonmetal Elements	Molecules	H ₂ , N ₂ , O ₂ , F ₂ , Cl ₂ , Br ₂ , I ₂ , S ₈ , Se ₈ , P ₄	London Forces
Ionic Compounds	Cations and Anions	NaCl	Ionic Bond
Molecular Compounds			
Nonpolar Molecular	Molecules	CO ₂ and Hydrocarbons	London Forces
Polar molecules without H-F, O-H, or N-H bond	Molecules	HF, HCl, HBr, and HI	Dipole-Dipole Forces
Molecules with H-F, O-H or N-H bond	Molecules	HF, H ₂ O, alcohols, NH ₃	Hydrogen Bonds

- 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: Molecular Polarity

Internet: London Forces and Polar Molecules

Internet: Relative Strengths of Attractions

Internet: Glossary Quiz

Exercises Key

Exercise 12.1 - Using Electronegativities: Classify the following bonds as nonpolar covalent, polar covalent, or ionic. If a bond is polar covalent, identify which atom has the partial negative charge and which has the partial positive charge. If a bond is ionic, identify which atom is negative and which is positive. (*Obj 22*)

- N bonded to H **polar covalent N is partial negative, and H is partial positive.**
- N bonded to Cl **nonpolar covalent**
- Ca bonded to O **ionic O is negative, and Ca is positive.**
- P bonded to F **polar covalent F is partial negative, and P is partial positive.**

Exercise 12.2 - Comparing Bond Polarities: Which bond would you expect to be more polar, P–H or P–F? Why? (*Obj 22*)

P–F bond; greater difference in electronegativity

Exercise 12.3 - Types of Particles and Types of Attractions:

For (a) iron, (b) iodine, (c) CH₃OH, (d) NH₃, (e) hydrogen chloride, (f) KF, and (g) carbon in the diamond form, specify (1) the type of particle that forms the substance's basic structure and (2) the name of the type of attraction that holds these particles in the solid and liquid form. (*Obj 30*)

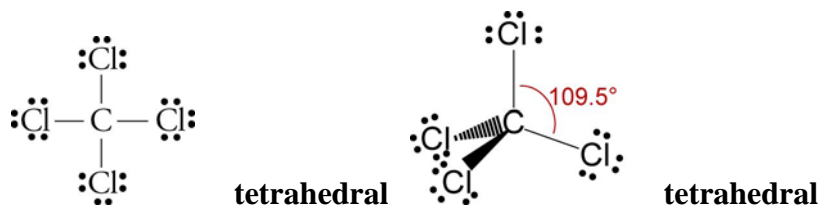
Substance	Particles to visualize	Type of attraction
iron	Fe cations in a sea of electrons	Metallic bonds
iodine	I ₂ molecules	London forces
CH ₃ OH	CH ₃ OH molecules	Hydrogen bonds
NH ₃	NH ₃ molecules	Hydrogen bonds
hydrogen chloride	HCl molecules	Dipole-dipole attractions
KF	Cations and anions	Ionic bonds
C (diamond)	Atoms	Covalent bonds

Review Questions Key

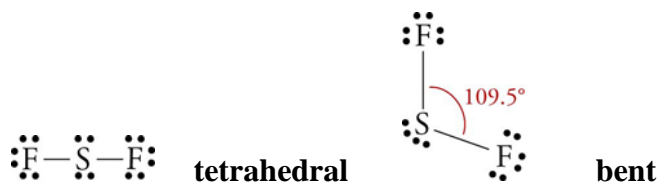
- For each of the following pairs of elements, decide whether a bond between them would be covalent or ionic.
 - Ni and F *Metal-nonmetal combinations usually lead to ionic bonds.*
 - S and O *Nonmetal-nonmetal combinations lead to covalent bonds.*
- Classify each of the following as either a molecular compound or an ionic compound.
 - oxygen difluoride **OF₂ all nonmetallic elements (no ammonium), so molecular**
 - Na₂O **metal-nonmetal, so ionic**
 - calcium carbonate **CaCO₃ metal-polyatomic ion, so ionic**
 - C₃H₈ **all nonmetallic elements (no ammonium), so molecular**

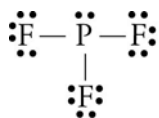
3. Classify each of the following compounds as (1) a binary ionic compound, (2) an ionic compound with polyatomic ion(s), (3) a binary covalent compound, (4) a binary acid, (5) an alcohol, or (6) an oxyacid. Write the chemical formula that corresponds to each name.
- magnesium chloride **ionic** MgCl_2
 - hydrogen chloride **binary covalent** HCl
 - sodium nitrate **ionic with polyatomic ion** NaNO_3
 - methane **binary covalent (hydrocarbon)** CH_4
 - ammonia **binary covalent** NH_3
 - hydrochloric acid **binary acid** $\text{HCl}(aq)$
 - nitric acid **oxyacid** HNO_3
 - ethanol **alcohol** $\text{C}_2\text{H}_5\text{OH}$
4. Classify each of the following compounds as (1) a binary ionic compound, (2) an ionic compound with polyatomic ion(s), (3) a binary covalent compound, (4) a binary acid, (5) an alcohol, or (6) an oxyacid. Write the name that corresponds to each chemical formula.
- HF **binary covalent** **hydrogen fluoride**
 - CH_3OH **alcohol** **methanol**
 - LiBr **ionic** **lithium bromide**
 - NH_4Cl **ionic with polyatomic ion** **ammonium chloride**
 - C_2H_6 **binary covalent (hydrocarbon)** **ethane**
 - BF_3 **binary covalent** **boron trifluoride**
 - H_2SO_4 **oxyacid** **sulfuric acid**
5. For each of the formulas listed below,
- Draw a reasonable Lewis structure.
 - Write the name of the electron group-geometry around the central atom.
 - Draw the geometric sketch of the molecule, including bond angles.
 - Write the name of the molecular geometry around the central atom.

a. CCl_4

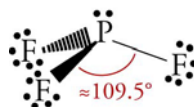


b. SF_2

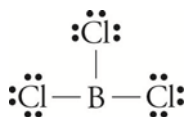


c. PF₃

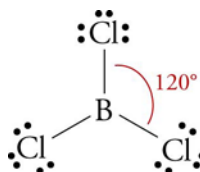
tetrahedral



trigonal pyramid

d. BCl₃

trigonal planar



trigonal planar

Key Ideas Answers

6. Gases can be converted into liquids by a decrease in temperature. At a high temperature, there are no **significant** attractions between particles of a gas. As the temperature is lowered, attractions between particles lead to the formation of very small clusters that **remain** in the gas phase. As the temperature is lowered further, the particles move slowly enough to form clusters so **large** that they drop to the bottom of the container and combine to form a liquid.
8. During the evaporation of a liquid, the **more rapidly** moving particles escape, leaving the particles left in the liquid with a lower average velocity, and lower average velocity means **lower** temperature.
10. Greater surface area means **more** particles at the surface of a liquid, which leads to a greater rate of evaporation.
12. Increased temperature increases the average velocity and momentum of the particles. As a result, a greater **percentage** of particles will have the minimum momentum necessary to escape, so the liquid will evaporate more quickly.
14. For a dynamic equilibrium to exist, the rates of the two **opposing** changes must be equal, so that there are constant changes between state A and state B but no **net** change in the components of the system.
16. The **weaker** the attractions between particles of a substance, the higher the equilibrium vapor pressure for that substance at a given temperature.
18. As a liquid is heated, the vapor pressure of the liquid increases until the temperature gets high enough to make the pressure within the bubbles that form equal to the **external pressure**. At this temperature, the bubbles can maintain their volume, and the liquid boils.
20. If the external pressure acting on a liquid changes, then the **internal vapor pressure** needed to preserve a bubble changes, and therefore the boiling-point temperature changes.
22. We know that increased strength of attractions leads to decreased rate of evaporation, decreased rate of condensation at equilibrium, decreased concentration of vapor, and decreased vapor pressure at a given temperature. This leads to a(n) **increased temperature** necessary to reach a vapor pressure of one atmosphere.
24. A dipole-dipole attraction is an attraction between the **partial positive** end of one molecule and the **partial negative** end of another molecule.

26. The higher an element's electronegativity, the greater its ability to **attract** electrons from other elements.
28. If the difference in electronegativity (ΔEN) between two atoms is between 0.4 and 1.7, we expect the bond between them to be a(n) **polar** covalent bond.
30. The atom with the higher electronegativity has the partial **negative** charge. The atom with the lower electronegativity has the partial **positive** charge.
32. When comparing two covalent bonds, the bond with the greater **difference** in electronegativity (ΔEN) between the atoms in the bond is likely to be the more polar bond.
34. When there are no polar bonds in a molecule, there is no permanent charge difference between one part of the molecule and another, and the molecule is **nonpolar**.
36. **Hydrogen** bonds are attractions that occur between a nitrogen, oxygen, or fluorine atom of one molecule and a hydrogen atom bonded to a nitrogen, oxygen, or fluorine atom in another molecule.
38. The larger the molecules of a substance, the **stronger** the London forces between them. A larger molecule has more electrons and a greater **chance** of having its electron cloud distorted from its nonpolar shape. Thus instantaneous dipoles are more likely to form in larger molecules. The electron clouds in larger molecules are also larger, so the average distance between the nuclei and the electrons is greater; as a result, the electrons are held less **tightly** and shift more easily to create a dipole.

Problems Key

Section 12.1 Change from Gas to Liquid and from Liquid to Gas – An Introduction to Dynamic Equilibrium

40. Why is dew more likely to form on a lawn at night than in the day? Describe the changes that take place as dew forms.

At the lower temperature during the night, the average velocity of the water molecules in the air is lower, making it more likely that they will stay together when they collide. They stay together long enough for other water molecules to collide with them forming clusters large enough for gravity to pull them down to the grass where they combine with other clusters to form the dew.
42. Consider two test tubes, each containing the same amount of liquid acetone. A student leaves one of the test tubes open overnight and covers the other one with a balloon so that gas cannot escape. When the student returns to the lab the next day, all of the acetone is gone from the open test tube, but most of it remains in the covered tube.
 - a. Explain why the acetone is gone from one test tube and not from the other.

In the closed test tube, the vapor particles that have escaped from the liquid are trapped in the space above the liquid. The concentration of acetone 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 test tube.

In the open test tube, the acetone vapor escapes into the room. The concentration of vapor never gets high enough to balance the rate of evaporation, so all of the liquid finally disappears.

- b. Was the initial rate at which liquid changed to gas (the rate of evaporation) greater in one test tube than in the other? Explain your answer.

No, the rate of evaporation is dependent on the strengths of attractions between particles in the liquid, the liquid's surface area, and temperature. All of these factors are the same for the two systems, so the initial rate of evaporation is the same for each.

- c. Consider the system after 30 minutes, with liquid remaining in both test tubes. Is condensation (vapor to liquid) taking place in both test tubes? Is the rate of condensation the same in both test tubes? Explain your answer.

There will be some vapor above both liquids, so some vapor molecules will collide with the surface of the liquid and return to the liquid state. Thus there will be condensation in both test tubes. The concentration of acetone vapor above the liquid in the closed container will be higher, so the rate of collision between the vapor particles and the liquid surface will be higher. Thus the rate of condensation in the closed container will be higher.

- d. Describe the submicroscopic changes in the covered test tube that lead to a constant amount of liquid and vapor. (Obj 10)

The liquid immediately begins to evaporate with a rate of evaporation that is dependent on the surface area of the liquid, the strengths of attractions between the liquid particles, and temperature. If these three factors remain constant, the rate of evaporation will be constant. If we assume that the container initially holds no vapor particles, there is no condensation of vapor when the liquid is first added. As the liquid evaporates, the number of vapor particles above the liquid increases, and the condensation process begins. As long as the rate of evaporation of the liquid is greater than the rate of condensation of the vapor, the concentration of vapor particles above the liquid will increase. As the concentration of vapor particles increases, the rate of collisions of vapor particles with the liquid increases, increasing the rate of condensation. If there is enough liquid in the container to avoid all of it evaporating, the rising rate of condensation eventually becomes equal to the rate of evaporation. At this point, for every particle that leaves the liquid, a particle somewhere else in the container returns to the liquid. Thus there is no net change in the amount of substance in the liquid form or the amount of substance in the vapor form.

- e. The balloon expands slightly after it is placed over the test tube, suggesting an initial increase in pressure in the space above the liquid. Why? After this initial expansion, the balloon stays inflated by the same amount. Why doesn't the pressure inside the balloon change after the initial increase? (Obj 12)

While the rate of evaporation is greater than the rate of condensation, there is a steady increase in the amount of vapor above the liquid. This increases the total pressure of gas above the liquid, so the balloon expands. When the rates of evaporation and condensation become equal, the amount of vapor and the total gas pressure remain constant, so the balloon maintains the same degree of inflation.

- f. If the covered test tube is heated, the balloon expands. Part of this expansion is due to the increase in gas pressure that results from the rise in temperature of the gas, but the increase is greater than expected from this factor alone. What other factor accounts for the increase in pressure? Describe the submicroscopic changes that take place that lead to this other factor. (*Obj 14*)

The rate of evaporation is dependent on the temperature of the liquid. Increased temperature increases the average velocity and momentum of the particles in the liquid. This increases the percentage of particles that have the minimum velocity necessary to escape and increases the rate of evaporation. More particles escape per second, and the partial pressure due to the vapor above the liquid increases.

43. The attractions between ethanol molecules, C_2H_5OH , are stronger than the attractions between diethyl ether molecules, $CH_3CH_2OCH_2CH_3$.

- a. Which of these substances would you expect to have the higher rate of evaporation at room temperature? Why?

The weaker attractions between diethyl ether molecules are easier to break, allowing a higher percentage of particles to escape from the surface of liquid diethyl ether than from liquid ethanol. If the surface area and temperature is the same for both liquids, more particles will escape per second from the diethyl ether than from the ethanol.

- b. Which of these substances would you expect to have the higher equilibrium vapor pressure? Why? (*Obj 13*)

Because the attractions between diethyl ether molecules are weaker than those between ethanol molecules, it is easier for a diethyl ether molecule to break them and move into the vapor phase. Therefore, the rate of evaporation from liquid diethyl ether is greater than for ethanol at the same temperature. When the dynamic equilibrium between evaporation and condensation for the liquids is reached and the two rates become equal, the rate of condensation for the diethyl ether is higher than for ethanol. Because the rate of condensation is determined by the concentration of vapor above the liquid, the concentration of diethyl ether vapor at equilibrium is higher than for the ethanol. The higher concentration of diethyl ether particles leads to a higher equilibrium vapor pressure.

45. Picture a half-empty milk bottle in the refrigerator. The water in the milk will be constantly evaporating into the gas-filled space above the liquid, and the water molecules in this space will be constantly colliding with the liquid and returning to the liquid state. If the milk is tightly closed, a dynamic equilibrium forms between the rate of evaporation and the rate of condensation. If the bottle is removed from the refrigerator and left out in the room with its cap still on tightly, what happens to the rates of evaporation and condensation? An hour later when the milk has reached room temperature, will a dynamic equilibrium exist between evaporation and condensation?

As the temperature of the liquid milk increases, its rate of evaporation increases. This will disrupt the equilibrium, making the rate of evaporation greater than the rate of condensation. This leads to an increase in the concentration of water molecules in the gas space above the liquid, which increases the rate of condensation until it increases enough to once again become equal to the rate of evaporation. At this new dynamic equilibrium, the rates of evaporation and condensation will both be higher.

Section 12.2 Boiling Liquids

47. The normal boiling point of ethanol, $\text{C}_2\text{H}_5\text{OH}$, is $78.3\text{ }^\circ\text{C}$.

- a. Describe the submicroscopic events that occur when a bubble forms in liquid ethanol. (*Obj 15*)

Ethanol molecules are moving constantly, sometimes at very high velocity. When they collide with other particles, they push them out of their positions, leaving small spaces in the liquid. Other particles move across the spaces and collide with other particles, and the spaces grow in volume. These spaces can be viewed as tiny bubbles.

The surface of each of these tiny bubbles is composed of a spherical shell of liquid particles. Except for shape, this surface is the same as the surface at the top of the liquid. Particles can escape from the surface (evaporate) into the vapor phase in the bubble, and when particles in the vapor phase collide again with the surface of the bubble, they return to the liquid state (condense). A dynamic equilibrium between the rate of evaporation and the rate of condensation is set up in the bubble just like the liquid-vapor equilibrium above the liquid in the closed container.

- b. Consider heating liquid ethanol in a system where the external pressure acting on the liquid is 1 atm. Explain why bubbles cannot form and escape from the liquid until the temperature reaches $78.3\text{ }^\circ\text{C}$. (*Obj 16*)

Each time a particle moves across a bubble and collides with the surface of the bubble, it exerts a tiny force pushing the wall of the bubble out. All of the collisions with the shell of the bubble combine to yield a gas pressure inside the bubble. This pressure is the same as the equilibrium vapor pressure for the vapor above the liquid in a closed container.

If the 1 atm of external pressure pushing on the bubble is greater than the vapor pressure of the bubble, the liquid particles are pushed closer together, and the bubble collapses. If the vapor pressure of the bubble is greater than the external pressure, the bubble will grow. If the two pressures are equal, the bubble maintains its volume. The vapor pressure of the bubbles in ethanol does not reach 1 atm until the temperature rises to $78.3\text{ }^\circ\text{C}$.

- c. If the external pressure on the surface of the ethanol is increased to 2 atm, will its boiling-point temperature increase, decrease, or stay the same? Why? (*Obj 17*)

If the external pressure acting on the bubbles in ethanol rises to 2 atm, the vapor pressure inside the bubbles must rise to 2 atm also to allow boiling. This requires an increase in the temperature, so the boiling point increases.

49. At 86 m below sea level, Death Valley is the lowest point in the western hemisphere. The boiling point of water in Death Valley is slightly higher than water's normal boiling point. Explain why.

The pressure of the earth's atmosphere decreases with increasing distance from the center of the earth. Therefore, the average atmospheric pressure in Death Valley is greater than at sea level where it is one atmosphere. This greater external pressure acting on liquid water increases the vapor pressure necessary for the water to maintain bubbles and boil. This leads to a higher temperature necessary to reach the higher vapor pressure. Because the boiling-point temperature of a liquid is the temperature at which the vapor pressure of the liquid reaches the external pressure acting on it, the boiling-point temperature is higher in Death Valley.

51. Explain why liquid substances with stronger interparticle attractions will have higher boiling points than liquid substances whose particles experience weaker interparticle attractions.

(Obj 19)

Increased strength of attractions leads to decreased rate of evaporation, decreased rate of condensation at equilibrium, decreased concentration of vapor, and decreased vapor pressure at a given temperature. This leads to an increased temperature necessary to reach a vapor pressure of one atmosphere.

Section 12.3 Particle-Particle Attractions

54. Complete the following table by classifying each bond as nonpolar covalent, polar covalent, or ionic. If a bond is polar covalent, identify the atom that has the partial negative charge and the atom that has the partial positive charge. If a bond is ionic, identify the ion that has the negative charge and the ion that has the positive charge. *(Obj 22)*

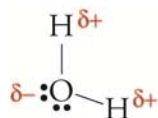
Atoms	Is the bond polar covalent, nonpolar covalent, or ionic?	For polar covalent bonds, which atom is partial negative? For ionic bonds, which atom is negative?
C–N	Polar covalent	N
C–H	Nonpolar covalent	-----
H–Br	Polar covalent	Br
Li–F	Ionic	F
C–Se	Nonpolar covalent	----
Se–S	Nonpolar covalent	----
F–S	Polar covalent	F
O–P	Polar covalent	O
O–K	Ionic	O
F–H	Polar covalent	F

56. Identify the bond in each pair that you would expect to be more polar. *(Obj 22)*

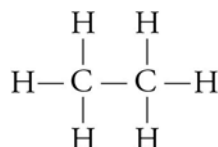
- a. C–O or C–H **C–O**
 b. P–H or H–Cl **H–Cl**

58. Explain why water molecules are polar, why ethane, C_2H_6 , molecules are nonpolar, and why carbon dioxide, CO_2 , molecules are nonpolar. (*Obj 23*)

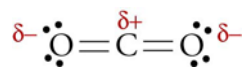
Water molecules have an asymmetrical distribution of polar bonds, so they are polar.



All of the bonds in ethane molecules are nonpolar, so the molecules are nonpolar.



Carbon dioxide molecules have a symmetrical distribution of polar bonds, so they are nonpolar.



60. Ammonia has been used as a refrigerant. In the cooling cycle, gaseous ammonia is alternately compressed into a liquid and allowed to expand back to the gaseous state. What are the particles that form the basic structure of ammonia? What type of attraction holds these particles together? Draw a rough sketch of the structure of liquid ammonia. (*Obj 26*)

Ammonia is composed of NH_3 molecules that are attracted by hydrogen bonds between the partially positive hydrogen atoms and the partially negative nitrogen atoms of other molecules. See Figure 12.24 of the textbook.

The liquid would look much like the image for liquid water shown in Figure 7.5 of the textbook, except with NH_3 molecules in the place of H_2O molecules.

62. Bromine, Br_2 , is used to make ethylene bromide, which is an antiknock additive in gasoline. The Br_2 molecules have nonpolar covalent bonds between the atoms, so we expect isolated Br_2 molecules to be nonpolar. Despite the nonpolar character of isolated Br_2 molecules, attractions form between bromine molecules that are strong enough to hold the particles in the liquid form at room temperature and pressure. What is the nature of these attractions? How do they arise? Describe what you would see if you were small enough to ride on a Br_2 molecule in liquid bromine. (*Obj 27*)

The attractions are London forces. Because the $Br-Br$ bond is nonpolar, the expected distribution of the electrons in the Br_2 molecule is a symmetrical arrangement around the two bromine nuclei, but this arrangement is far from static. Even though the most probable distribution of charge in an isolated Br_2 molecule is balanced, in a sample of bromine that contains many billions of molecules, there is a chance that a few of these molecules will have their electron clouds shifted more toward one bromine atom than the other. The resulting dipoles are often called instantaneous dipoles because they may be short-lived. Remember also that in all states of matter, there are constant collisions between molecules. When Br_2 molecules collide, the repulsion between their electron clouds will distort the clouds and shift them from their nonpolar state. The dipoles that form are also called instantaneous dipoles.

An instantaneous dipole can create a dipole in the molecule next to it. For example, the negative end of one instantaneous dipole will repel the negative electron cloud of a

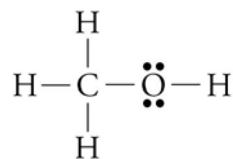
nonpolar molecule next to it, pushing the cloud to the far side of the neighboring molecule. The new dipole is called an induced dipole. The induced dipole can then induce a dipole in the molecule next to it. This continues until there are many polar molecules in the system. The resulting partial charges on these polar molecules lead to attractions between the opposite charges on the molecules. See Figure 12.25 of the textbook.

64. Carbon disulfide, CS_2 , which is used to make rayon, is composed of nonpolar molecules that are similar to carbon dioxide molecules, CO_2 . Unlike carbon dioxide, carbon disulfide is liquid at room temperature. Why?

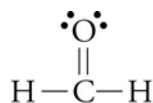
Both of these substances have nonpolar molecules held together by London forces. Because the CS_2 molecules are larger, they have stronger London forces that raise carbon disulfide's boiling point to above room temperature.

66. Methanol, CH_3OH , is used to make formaldehyde, CH_2O , which is used in embalming fluids. The molecules of these substances have close to the same atoms and about the same molecular mass, so why is methanol a liquid at room temperature and formaldehyde a gas?

Because of the O–H bond in methanol, the attractions between CH_3OH molecules are hydrogen bonds. The hydrogen atoms in CH_2O molecules are bonded to the carbon atom, not the oxygen atom, so there is no hydrogen bonding for formaldehyde. The C–O bond in each formaldehyde molecule is polar, and when there is only one polar bond in a molecule, the molecule is polar. Therefore, CH_2O molecules are held together by dipole-dipole attractions. For molecules of about the same size, hydrogen bonds are stronger than dipole-dipole attractions. The stronger hydrogen bonds between CH_3OH molecules raise its boiling point above room temperature, making it a liquid.



methanol



formaldehyde

68. Complete the following table by specifying (1) the name for the type of particle viewed as forming the structure of a solid, liquid, or gas of each substance and (2) the name of the type of attraction that holds these particles in the solid or liquid form. (Obj 30)

Substance	Particles to visualize	Type of attraction
Silver	Ag cations in a sea of electrons	Metallic bonds
HCl	HCl molecules	Dipole-dipole attractions
$\text{C}_2\text{H}_5\text{OH}$	$\text{C}_2\text{H}_5\text{OH}$ molecules	Hydrogen bonds
NaBr	Cations and anions	Ionic bonds
Carbon (diamond)	Carbon atoms	Covalent bonds
C_5H_{12}	C_5H_{12} molecules	London forces
water	H_2O molecules	Hydrogen bonds

70. Have you ever broken a mercury thermometer? If you have, you probably noticed that the mercury forms droplets on the surface on which it falls rather than spreading out and wetting it like water. Describe the difference between liquid mercury and liquid water that explains this different behavior. (*Hint: Consider the attractions between particles.*)

As a liquid spreads out on a surface, some of the attractions between liquid particles are broken. Because the metallic bonds between mercury atoms are much stronger than the hydrogen bonds between water molecules, they keep mercury from spreading out like water.