



Silberberg

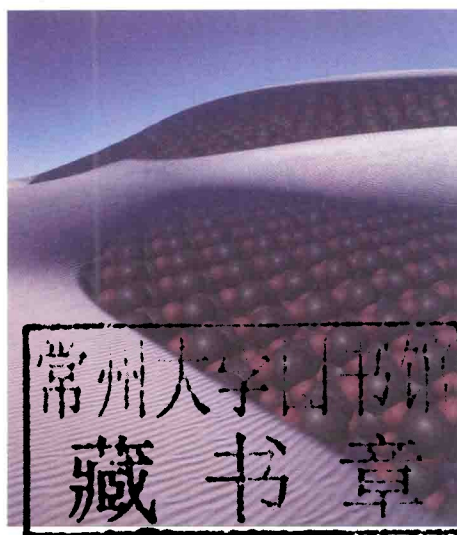
PRINCIPLES OF
GENERAL
CHEMISTRY

second edition

Martin S. Silberberg

Principles of
GENERAL CHEMISTRY

Second Edition



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PRINCIPLES OF GENERAL CHEMISTRY, SECOND EDITION

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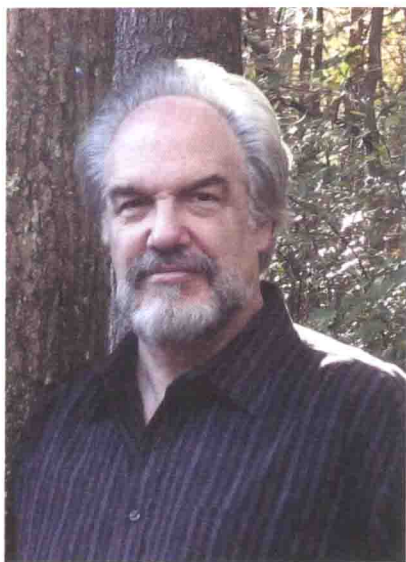
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*To Ruth and Daniel,
with all my love and gratitude*



Martin S. Silberberg received a B.S. in Chemistry from the City University of New York and a Ph.D. in Chemistry from the University of Oklahoma. He then accepted a research position in analytical biochemistry at the Albert Einstein College of Medicine in New York City, where he developed advanced methods to study fundamental brain mechanisms as well as neurotransmitter metabolism in Parkinson's disease. Following his years in research, Dr. Silberberg joined the faculty of Simon's Rock College of Bard, a liberal arts college known for its excellence in teaching small classes of highly motivated students. As Head of the Natural Sciences Major and Director of Premedical Studies, he taught courses in general chemistry, organic chemistry, biochemistry, and liberal arts chemistry. The close student contact afforded him insights into how students learn chemistry, where they have difficulties, and what strategies can help them succeed. Dr. Silberberg applied these insights in a broader context by establishing a text writing, editing, and consulting company. Before writing his own text, he worked as a consulting and developmental editor on chemistry, biochemistry, and physics texts for several major college publishers. He resides with his wife and son in the Pioneer Valley near Amherst, Massachusetts, where he enjoys the rich cultural and academic life of the area and relaxes by cooking, gardening, and hiking.

Preface

Like the science of chemistry, the texts that professors and students rely on to explain the subject are continually evolving. The 1000-page or longer books that most courses use provide a complete survey of the field, with a richness of relevance and content, and *Chemistry: The Molecular Nature of Matter and Change*, the parent text of *Principles of General Chemistry*, stands at the forefront in that category of dynamic, modern textbooks. Yet, extensive market research demonstrates that some professors prefer a more targeted treatment, with coverage confined to the core principles and skills. Such a text allows professors to enrich their course with topics relevant to their own students. Most importantly, the entire book can more easily be covered in one year—including all the material a science major needs to go on to other courses in chemistry, pre-medical studies, engineering, and related fields.

Creating *Principles of General Chemistry* involved assessing the topics that constituted the core of the subject and distilling them from the parent text. Three professors served as content editors, evaluating my proposed changes. It was quite remarkable to find that the four of us defined the essential content of the modern general chemistry course in virtually identical terms.

THE RELATIONSHIP BETWEEN CHEMISTRY AND PRINCIPLES OF GENERAL CHEMISTRY

Principles of General Chemistry is leaner and more concise than its parent, *Chemistry: The Molecular Nature of Matter and Change*, but it maintains the same high standards of accuracy, depth, clarity, and rigor and adopts the same three distinguishing hallmarks:

1. *Visualizing chemical models.* In many discussions, concepts are explained first at the macroscopic level and then from a molecular point of view. Placed near the discussion, the text's celebrated graphics bring the point home for today's visually oriented students, depicting the change at the observable level in the lab, at the molecular level, and, when appropriate, at the symbolic level with the balanced equation.
2. *Thinking logically to solve problems.* The problem-solving approach, based on a four-step method widely approved by chemical educators, is introduced in Chapter 1 and employed consistently throughout the text. It encourages students to first plan a logical approach, and only then proceed to the arithmetic solution. A check step, universally recommended by instructors, fosters the habit of considering the reasonableness and magnitude

of the answer. For practice and reinforcement, each worked problem has a matched follow-up problem, for which an abbreviated, multistep solution—not merely a numerical answer—appears at the end of the chapter.

3. *Applying ideas to the real world.* For today's students, who may enter one of numerous chemistry-related fields, especially important applications—such as climate change, enzyme catalysis, industrial production, and others—are woven into the text discussion, and real-world scenarios appear in many worked sample problems and end-of-chapter problems.

HOW CHEMISTRY AND PRINCIPLES OF GENERAL CHEMISTRY ARE DIFFERENT

Principles of General Chemistry presents the authoritative coverage of its parent text in 300 fewer pages, thereby appealing to today's efficiency-minded instructors and value-conscious students. To accomplish this shortening, most of the material in the boxed applications essays and margin notes was removed, which allows instructors to include their own favorite examples.

The content editors and I also felt that several topics, while constituting important fields of modern research, were not central to the core subject matter of general chemistry; these include colloids, green chemistry, and much of advanced materials. Moreover, the chapters on descriptive chemistry, organic chemistry, and transition elements were tightened extensively, and the chapter on the industrial isolation of the elements was removed (except for a few topics that were blended into the chapter on electrochemistry).

The new text includes all the worked sample problems of the parent text but has about two-thirds as many end-of-chapter problems. Nevertheless, there are more than enough representative problems for every topic, and they are packed with relevance and real-world applications.

Principles of General Chemistry is a powerhouse of pedagogy. All the learning aids that students find so useful in the parent text have been retained—Concepts and Skills to Review, Section Summaries, Key Terms, Key Equations, and Brief Solutions to Follow-up Problems. In addition, two aids not found in the parent text give students more help in focusing their efforts:

1. *Key Principles.* At the beginning of each chapter, short paragraphs state the main concepts concisely, using many of the same phrases and terms that will appear in the pages that follow. A student can preview these principles before reading the chapter and then review them afterward.

2. *Problem-Based Learning Objectives.* At the end of each chapter, the list of learning objectives includes the numbers of end-of-chapter problems that relate to each objective. Thus, a student, or instructor, can select problems that relate specifically to a given topic.

Principles provides a thorough introduction to chemistry for science majors. Unlike its parent, which offers almost any topic that *any* instructor could want, *Principles of General Chemistry* offers every topic that *every* instructor needs.

WHAT'S NEW IN THE SECOND EDITION

A new edition always brings a new opportunity to enhance the pedagogy. In the second edition, writing has been clarified wherever readers felt ideas could flow more smoothly. Updates have been made to several rapidly changing areas of chemistry, and a new pedagogic feature has been added. The greatest change, however, is the presence of many new worked sample problems and end-of-chapter problems that use simple molecular scenes to teach quantitative concepts.

Changes to Chapter Content

Both editions of the text have been written to allow rearrangement of the order of topics. For instance, redox balancing (by the half-reaction method in preparation for electrochemistry) is covered in Chapter 21, but it can easily be covered much earlier with other aspects of oxidation-reduction reactions (Chapter 4) if desired. Several chapters can be taught in a different order as well. Gases (Chapter 5), for example, can be covered in the book's chapter sequence to explore the mathematical modeling of physical behavior or, with no loss of continuity, just before liquids and solids (Chapter 12) to show the effects of intermolecular forces on the three states of matter. In fact, based on user feedback, many instructors already move chapters and sections around, for example, covering descriptive chemistry (Chapter 14) and organic chemistry (Chapter 15) in a more traditional place at the end of the course. These or other changes in topic sequence can be made to suit any course.

In the second edition, small content changes have been made to many chapters, but a few sections, and even one whole chapter, have been revised considerably. Among the most important changes are

- Chapter 3 now applies reaction tables to stoichiometry problems involving limiting reactants, just as similar tables are used much later in equilibrium problems.
- Chapter 16 offers an updated discussion of catalysis as it applies to stratospheric ozone depletion.
- Chapter 19 provides an updated discussion of buffering as it applies to the acid-rain problem.

- Chapter 20 has been revised further to clarify the discussion of entropy, with several new pieces of art that illustrate key ideas.
- Chapter 23 has been thoroughly revised to more accurately reflect modern ideas in nuclear chemistry.

"Think of It This Way . . ." with Analogies, Mnemonics, and Insights

An entirely new feature called "Think of It This Way . . ." provides student-friendly analogies for difficult concepts (e.g., "radial probability distribution" of apples around a tree) and amazing quantities (e.g., relative sizes of atom and nucleus), memory shortcuts (e.g., which reaction occurs at which electrode), and new insights into key ideas (e.g., similarities between a saturated solution and a liquid-vapor system).

Molecular-Scene Sample Problems

Many texts include molecular-scene problems in their end-of-chapter sets, but none attempts to explain how to reason toward a solution. In the first edition, five worked-out, molecular-scene sample problems were introduced, using the same multistep problem-solving approach as in other sample problems. Responses from students and teachers alike were very positive, so 17 new molecular-scene sample problems have been included in this edition. With the original five plus an equal number of follow-up problems, 44 molecular-scene problems provide a rich source for learning how to understand quantitative concepts via simple chemical models.

End-of-Chapter Problems

In each edition, a special effort is made to create new problems that are relevant to pedagogic needs and real applications. In the second edition, many problems have been revised quantitatively, and over 125 completely new end-of-chapter problems appear. Of these, over 85 are molecular-scene problems, which, together with the more than 50 carried over from the first edition, offer abundant practice in using visualization to solve chemistry problems. The remaining new problems incorporate realistic, up-to-date, biological, organic, environmental, or engineering/industrial scenarios.

ACKNOWLEDGMENTS

For the second edition of *Principles of General Chemistry*, I am once again very fortunate that Patricia Amateis of Virginia Tech prepared the *Instructors' Solutions Manual* and *Student Solutions Manual* and Libby Weberg the *Student Study Guide*. Amina El-Ashmawy of Collin County Community College–Plano updated the *PowerPoint Lecture Outlines* available on the ARIS website for this text.

And, once again, I very much appreciate the efforts of all the professors who reviewed portions of the new edi-

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Expert freelancers made indispensable contributions as well. My superb copyeditor, Jane Hoover, continued to improve the accuracy and clarity of my writing, and proofreaders Katie Aiken and Janelle Pregler gave their consistent polish to the final manuscript. My friend Michael Goodman helped to create the exciting new cover.

As always, my wife Ruth was involved every step of the way, from helping with early style decisions to checking and correcting content and layout in page proofs. And my son Daniel contributed his artistic skill in helping choose photos, as well as helping to design the cover and several complex pieces of interior artwork.

ORGANIZING AND FOCUSING

Chapter Outline

The chapter begins with an outline that shows the sequence of topics and subtopics.

Key Principles

The main principles from the chapter are given in concise, separate paragraphs so you can keep them in mind as you study. You can also review them when you are finished.

17

Equilibrium: The Extent of Chemical Reactions



Belonging To and For As you'll learn in this chapter, the constant back and forth flow of leaf-cutter ants mimics the forward and reverse steps of a chemical reaction in a state of dynamic equilibrium.

Key Principles

to focus on while studying this chapter

- The principles of equilibrium and kinetics apply to different aspects of a chemical change: the extent (yield) of a reaction is not related to its rate (introduction).
- All reactions are reversible. When the forward and reverse reaction rates are equal, the system has reached equilibrium. After this point, there is no further observable change. The ratio of the rate constants equals the equilibrium constant, K . The size of K is directly related to the extent of the reaction at a given temperature (Section 17.1).
- The reaction quotient, Q , is a specific ratio of product and reactant concentration terms. The various ways to write Q are all based directly on the balanced equation. The value of Q changes continually until the system reaches equilibrium, at which point $Q = K$ (Section 17.2).
- The ideal gas law is used to quantitatively relate an equilibrium constant based on concentrations, K_c , to one based on pressures, K_p (Section 17.3).
- At any point in a reaction, we can learn its direction by comparing Q and K :
 - If $Q < K$, the reaction is forming more product; if $Q > K$, the reaction is forming more reactant; if $Q = K$, the reaction is at equilibrium (Section 17.4).
- If the initial concentration of a reactant, $[A]_0$, is much larger than the change in its concentration to reach equilibrium, x , we make the simplifying assumption that x can be neglected in calculations (Section 17.5).
- If a system at equilibrium is disturbed by a change in conditions (concentration, pressure, or temperature), it will temporarily not be at equilibrium, but will then undergo a net reaction to reach equilibrium again (Le Châtelier's principle). A change in concentration, pressure, or the presence of a catalyst does not affect K , but a change in temperature does (Section 17.6).

Outline

- 17.1 The Equilibrium State and the Equilibrium Constant
- 17.2 The Reaction Quotient and the Equilibrium Constant
 - Writing the Reaction Quotient, Q
 - Variables in the Form of Q
- 17.3 Expressing Equilibria with Pressure Terms: Relation Between K_c and K_p

Our study of kinetics in the last chapter addressed a different aspect of reaction chemistry than our upcoming study of equilibrium:

- Kinetics applies to the *speed* (or rate) of a reaction, the concentration of product that appears (or of reactant that disappears) per unit time.
- Equilibrium applies to the *extent* (or yield) of a reaction, the concentrations of reactant and product present after an unlimited time, or once no further change occurs.

Just as reactions vary greatly in their speed, they also vary in their extent. A fast reaction may go almost completely or barely at all toward products. Consider the dissociation of an acid in water. In 1 M HCl, virtually all the hydrogen chloride molecules are dissociated into ions. In contrast, in 1 M CH₃COOH, fewer than 1% of the acetic acid molecules are dissociated at any given time. Yet both reactions take less than a second to reach completion. Similarly, some slow reactions eventually yield a large amount of product, whereas others yield very little. After a few years at ordinary temperatures, a steel water-storage tank will rust, and it will do so completely given enough time; but no matter how long you wait,

Concepts & Skills to Review before studying this chapter

- equilibrium vapor pressure (Section 12.2)
- equilibrium nature of a saturated solution (Section 13.3)
- dependence of rate on concentration (Sections 16.2 and 16.6)
- rate laws for elementary reactions (Section 16.7)
- function of a catalyst (Section 16.8)

Concepts and Skills to Review

This unique feature helps you prepare for the upcoming chapter by referring to key material from earlier chapters that you should understand *before* you start reading this one.

Section Summaries

Concise summary paragraphs conclude each section, immediately restating the major ideas just covered.

STEP-BY-STEP PROBLEM SOLVING

Using this clear and thorough problem-solving approach, you'll learn to think through chemistry problems logically and systematically.

Sample Problems

A worked-out problem appears whenever an important new concept or skill is introduced. The step-by-step approach is shown consistently for every sample problem in the text. **Problem-solving roadmaps** specific to the problem and shown alongside the plan lead you visually through the needed calculation steps.

- **Plan** analyzes the problem so that you can use what is known to find what is unknown. This approach develops the habit of thinking through the solution *before* performing calculations.
- **Solution** shows the calculation steps *in the same order* as they are discussed in the plan and shown in the roadmap.
- **Check** fosters the habit of going over your work quickly to make sure that the answer is reasonable, chemically and mathematically—a great way to avoid careless errors.
- **Comment** provides an additional insight, alternative approach, or common mistake to avoid.
- **Follow-up Problem** gives you immediate practice by presenting a similar problem.

SECTION 17.1 SUMMARY

Kinetics and equilibrium are distinct aspects of a chemical reaction, thus the rate and extent of a reaction are not related. • When the forward and reverse reactions occur at the same rate, the system has reached dynamic equilibrium and concentrations no longer change. • The equilibrium constant (K) is a number based on a particular ratio of product and reactant concentrations: K is small for reactions that reach equilibrium with a high concentration of reactant(s) and large for reactions that reach equilibrium with a low concentration of reactant(s).

SAMPLE PROBLEM 3.2 Calculating the Moles and Number of Formula Units in a Given Mass of a Compound

Problem Ammonium carbonate is a white solid that decomposes with warming. Among its many uses, it is a component of baking powder, fire extinguishers, and smelling salts. How many formula units are in 41.6 g of ammonium carbonate?

Plan We know the mass of compound (41.6 g) and need to find the number of formula units. As we saw in Sample Problem 3.1(b), to convert grams to number of entities, we have to find number of moles first, so we must divide the grams by the molar mass (M). For this, we need M , so we determine the formula (see Table 2.5) and take the sum of the elements' molar masses. Once we have the number of moles, we multiply by Avogadro's number to find the number of formula units.

Solution The formula is (NH₄)₂CO₃. Calculating molar mass:

$$M = (2 \times M \text{ of N}) + (8 \times M \text{ of H}) + (1 \times M \text{ of C}) + (3 \times M \text{ of O}) \\ = (2 \times 14.01 \text{ g/mol}) + (8 \times 1.008 \text{ g/mol}) + 12.01 \text{ g/mol} + (3 \times 16.00 \text{ g/mol}) \\ = 96.09 \text{ g/mol}$$

Converting from grams to moles:

$$\text{Moles of (NH}_4\text{)}_2\text{CO}_3 = 41.6 \text{ g (NH}_4\text{)}_2\text{CO}_3 \times \frac{1 \text{ mol (NH}_4\text{)}_2\text{CO}_3}{96.09 \text{ g (NH}_4\text{)}_2\text{CO}_3} = 0.433 \text{ mol (NH}_4\text{)}_2\text{CO}_3$$

Converting from moles to formula units:

$$\text{Formula units of (NH}_4\text{)}_2\text{CO}_3 = 0.433 \text{ mol (NH}_4\text{)}_2\text{CO}_3 \\ \times \frac{6.022 \times 10^{23} \text{ formula units (NH}_4\text{)}_2\text{CO}_3}{1 \text{ mol (NH}_4\text{)}_2\text{CO}_3} \\ = 2.61 \times 10^{23} \text{ formula units (NH}_4\text{)}_2\text{CO}_3$$

Check The units are correct. The mass is less than half the molar mass ($\sim 42/96 < 0.5$), so the number of formula units should be less than half Avogadro's number ($\sim 2.6 \times 10^{23} / 6.0 \times 10^{23} < 0.5$).

Comment A common mistake is to forget the subscript 2 outside the parentheses in (NH₄)₂CO₃, which would give a much lower molar mass.

FOLLOW-UP PROBLEM 3.2 Tetraphosphorus decoxide reacts with water to form phosphoric acid, a major industrial acid. In the laboratory, the oxide is used as a drying agent.

- What is the mass (in g) of 4.65×10^{22} molecules of tetraphosphorus decoxide?
- How many P atoms are present in this sample?

Mass (g) of (NH₄)₂CO₃

divide by M (g/mol)

Amount (mol) of (NH₄)₂CO₃

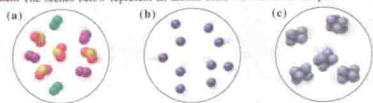
multiply by 6.022×10^{23}

formula units/mol

Number of (NH₄)₂CO₃ formula units

SAMPLE PROBLEM 2.1 Distinguishing Elements, Compounds, and Mixtures at the Atomic Scale

Problem The scenes below represent an atomic-scale view of three samples of matter:

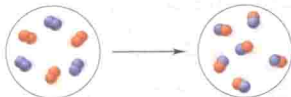


Describe each sample as an element, compound, or mixture.

Plan From depictions of the samples, we have to determine the type of matter by examining the component particles. If a sample contains only one type of particle, it is either an element or a compound; if it contains more than one type, it is a mixture. Particles of an element have only one kind of atom (one color), and particles of a compound have two or more kinds of atoms.

Solution (a) This sample is a mixture; there are three different types of particles, two types contain only one kind of atom, either green or purple, so they are elements, and the third type contains two red atoms for every one yellow, so it is a compound. (b) This sample is an element; it consists of only blue atoms. (c) This sample is a compound; it consists of molecules that each have two black and six blue atoms.

FOLLOW-UP PROBLEM 2.1 Describe this reaction in terms of elements, compounds, and mixtures.



Unique to Principles of General Chemistry: Molecular Scene Sample Problems

These problems apply the same stepwise strategy to help you interpret molecular scenes and solve problems based on them.

Brief Solutions to Follow-up Problems

These provide multistep solutions at the end of the chapter, not just a one-number answer at the back of the book. This fuller treatment is an excellent way for you to reinforce your problem-solving skills.

Molecular equation
 $2\text{AgNO}_3(\text{aq}) + \text{K}_2\text{CrO}_4(\text{aq}) \rightarrow \text{Ag}_2\text{CrO}_4(\text{s}) + 2\text{KNO}_3(\text{aq})$
 Silver nitrate Potassium dichromate Silver chromate Potassium nitrate

Total ionic equation
 $2\text{Ag}^+(\text{aq}) + 2\text{NO}_3^-(\text{aq}) + 2\text{K}^+(\text{aq}) + \text{CrO}_4^{2-}(\text{aq}) \rightarrow \text{Ag}_2\text{CrO}_4(\text{s}) + 2\text{K}^+(\text{aq}) + 2\text{NO}_3^-(\text{aq})$

Net ionic equation
 $2\text{Ag}^+(\text{aq}) + \text{CrO}_4^{2-}(\text{aq}) \rightarrow \text{Ag}_2\text{CrO}_4(\text{s})$

Cutting-Edge Molecular Models

Author and artist worked side by side and employed the most advanced computer-graphic software to provide accurate molecular-scale models and vivid scenes.

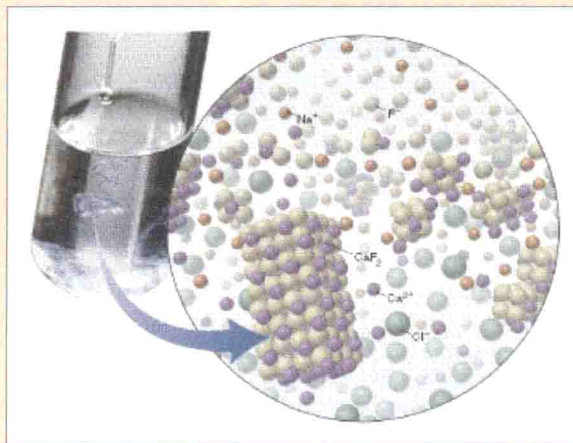
BRIEF SOLUTIONS TO FOLLOW-UP PROBLEMS

- 2.1** There are two types of particles reacting (left circle), one with two blue atoms and the other with two orange, so the depiction shows a mixture of two elements. In the product (right circle), all the particles have one blue atom and one orange; this is a compound.
- 2.2** Mass (t) of pitchblende
 $= 2.3 \text{ t uranium} \times \frac{84.2 \text{ t pitchblende}}{71.4 \text{ t uranium}} = 2.7 \text{ t pitchblende}$
- Mass (t) of oxygen
 $= 2.7 \text{ t pitchblende} \times \frac{(84.2 - 71.4 \text{ t oxygen})}{84.2 \text{ t pitchblende}} = 0.41 \text{ t oxygen}$
- 2.3** Sample B. Two bromine-fluorine compounds appear. In one, there are three fluorine atoms for each bromine; in the other, there is one fluorine for each bromine. Therefore, in the two compounds, the ratio of fluorines combining with one bromine is 3/1.
- 2.4** (a) Q = Ca; 5p², 6s⁰, 5c⁰
 (b) X = Ca; 20p², 21n⁰, 20e⁻
 (c) Y = I; 53p², 78n⁰, 53e⁻
- 2.5** $10.0129x + [11.0093(1-x)] = 10.81$; $0.9964x = 0.1993$; $x = 0.2000$ and $1-x = 0.8000$; % abundance of ¹⁰B = 20.00%; % abundance of ¹¹B = 80.00%
- 2.6** (a) S²⁻; (b) Rb⁺; (c) Ba²⁺
- 2.7** (a) Zinc [Group 2B(12)] and oxygen [Group 6A(16)]
 (b) Silver [Group 1B(11)] and bromine [Group 7A(17)]
 (c) Lithium [Group 1A(1)] and chlorine [Group 7A(17)]
 (d) Aluminum [Group 3A(13)] and sulfur [Group 6A(16)]
- 2.8** (a) ZnO; (b) AgBr; (c) LiCl; (d) Al₂S₃
- 2.9** (a) PbO₂; (b) copper(I) sulfide (cuprous sulfide); (c) iron(II) bromide (ferrous bromide); (d) HgCl₂
- 2.10** (a) Cu(NO₃)₂·3H₂O; (b) Zn(OH)₂; (c) lithium cyanide
- 2.11** (a) (NH₄)₂PO₄; ammonium is NH₄⁺ and phosphate is PO₄³⁻.
 (b) Al(OH)₃; parentheses are needed around the polyatomic ion OH⁻.
 (c) Magnesium hydrogen carbonate; Mg²⁺ is magnesium and can have only a 2+ charge, so it does not need (II); HCO₃⁻ is hydrogen carbonate (or bicarbonate).
 (d) Chromium(III) nitrate; the -ic ending is not used with Roman numerals; NO₃⁻ is nitrate.
- (e) Calcium nitrate; Ca²⁺ is calcium and NO₃⁻ is nitrate.
- 2.12** (a) HClO₄; (b) hydrofluoric acid; (c) CH₃COOH (or HC₂H₃O₂); (d) H₂SO₄; (e) hypobromous acid
- 2.13** (a) Sulfur trioxide; (b) silicon dioxide; (c) N₂O; (d) SeF₆
- 2.14** (a) Disulfur dichloride; the -ous suffix is not used.
 (b) NO₂; the name indicates one nitrogen.
 (c) Bromine trichloride; Br is in a higher period in Group 7A(17), so it is named first.
- 2.15** (a) H₂O₂; 34.02 amu; (b) C₂Cl₄; 168.4 amu; (c) H₂SO₄; 98.09 amu; (d) K₂SO₄; 174.27 amu
- 2.16** (a) Na₂O. This is an ionic compound, so the name is sodium oxide.
 Formula mass
 $= (2 \times \text{atomic mass of Na}) + (1 \times \text{atomic mass of O})$
 $= (2 \times 22.99 \text{ amu}) + 16.00 \text{ amu} = 61.98 \text{ amu}$
 (b) NO₂. This is a covalent compound, and N has the lower group number, so the name is nitrogen dioxide.
 Molecular mass
 $= (1 \times \text{atomic mass of N}) + (2 \times \text{atomic mass of O})$
 $= 14.01 \text{ amu} + (2 \times 16.00 \text{ amu}) = 46.01 \text{ amu}$

VISUALIZING CHEMISTRY

Three-Level Illustrations

A Silberberg hallmark, these illustrations provide macroscopic and molecular views of a process that help you connect these two levels of reality with each other and with the chemical equation that describes the process in symbols.



REINFORCING THE LEARNING PROCESS

Chapter Review Guide

A rich catalog of study aids ends each chapter to help you review its content:

- **Learning Objectives** are listed, with section, sample problem, and end-of-chapter problem numbers, to help you focus on key concepts and skills.
- **Key Terms** are boldfaced within the chapter and listed here by section (with page numbers); they are defined again in the Glossary.
- **Key Equations and Relationships** are highlighted and numbered within the chapter and listed here with page numbers.

CHAPTER REVIEW GUIDE

The following sections provide many aids to help you study this chapter. (Numbers in parentheses refer to pages, unless noted otherwise.)

• **LEARNING OBJECTIVES** These are concepts and skills to review after studying this chapter.

Related section (§), sample problem (SP), and end-of-chapter problem (EP) numbers are listed in parentheses.

1. Explain how gases differ from liquids and solids (§ 5.1) (EPs 5.1, 5.2)
2. Understand how a barometer works and interconvert units of pressure (§ 5.2) (SP 5.1) (EPs 5.3–5.10)
3. Describe Boyle's, Charles's, and Avogadro's laws, understand how they relate to the ideal gas law, and apply them in calculations (§ 5.3) (SPs 5.2–5.6) (EPs 5.11–5.25)
4. Apply the ideal gas law to determine the molar mass of a gas, the density of a gas at different temperatures, and the partial pres-

sure (or mole fraction) of each gas in a mixture (Dalton's law) (§ 5.4) (SPs 5.7–5.10) (EPs 5.26–5.42)

5. Use stoichiometry and the gas laws to calculate amounts of reactants and products (§ 5.5) (SPs 5.11, 5.12) (EPs 5.43–5.52)
6. Understand the kinetic-molecular theory and how it explains the gas laws, average molecular speed and kinetic energy, and the processes of effusion and diffusion (§ 5.6) (SP 5.13) (EPs 5.53–5.64)
7. Explain why intermolecular attractions and molecular volume cause real gases to deviate from ideal behavior and how the van der Waals equation corrects for the deviations (§ 5.7) (EPs 5.65–5.68)

• **KEY TERMS** These important terms appear in boldface in the chapter and are defined again in the Glossary.

Section 5.2 pressure (<i>P</i>) (147) barometer (148) pascal (Pa) (148) standard atmosphere (atm) (148) millimeter of mercury (mmHg) (149) torr (149)	Section 5.3 ideal gas (150) Boyle's law (151) Charles's law (152) Avogadro's law (154) standard temperature and pressure (STP) (154) standard molar volume (154)	ideal gas law (155) universal gas constant (<i>R</i>) (155) Section 5.4 partial pressure (162) Dalton's law of partial pressures (162) mole fraction (<i>X</i>) (163)	Section 5.6 kinetic-molecular theory (167) rms speed (<i>u_{rms}</i>) (171) effusion (172) Graham's law of effusion (172) diffusion (173) Section 5.7 van der Waals equation (176)
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• **KEY EQUATIONS AND RELATIONSHIPS** Numbered and screened concepts are listed for you to refer to or memorize.

5.1 Expressing the volume-pressure relationship (Boyle's law) (151):

$$V \propto \frac{1}{P} \quad \text{or} \quad PV = \text{constant} \quad [T \text{ and } n \text{ fixed}]$$

5.2 Expressing the volume-temperature relationship (Charles's law) (152):

$$V \propto T \quad \text{or} \quad \frac{V}{T} = \text{constant} \quad [P \text{ and } n \text{ fixed}]$$

5.3 Expressing the pressure-temperature relationship (Amontons's law) (153):

$$P \propto T \quad \text{or} \quad \frac{P}{T} = \text{constant} \quad [V \text{ and } n \text{ fixed}]$$

5.4 Expressing the volume-amount relationship (Avogadro's law) (154):

$$V \propto n \quad \text{or} \quad \frac{V}{n} = \text{constant} \quad [P \text{ and } T \text{ fixed}]$$

5.5 Defining standard temperature and pressure (154):

$$\text{STP: } 0^\circ\text{C (273.15 K) and 1 atm (760 torr)}$$

5.6 Defining the volume of 1 mol of an ideal gas at STP (154):
Standard molar volume = 22.414 L = 22.4 L [3 sf]

5.7 Relating volume to pressure, temperature, and amount (ideal gas law) (155):

$$PV = nRT \quad \text{and} \quad \frac{P_1V_1}{n_1T_1} = \frac{P_2V_2}{n_2T_2}$$

5.8 Calculating the value of *R* (155):

$$R = \frac{PV}{nT} = \frac{1 \text{ atm} \times 22.414 \text{ L}}{1 \text{ mol} \times 273.15 \text{ K}} = 0.082058 \frac{\text{atm} \cdot \text{L}}{\text{mol} \cdot \text{K}} = 0.0821 \frac{\text{atm} \cdot \text{L}}{\text{mol} \cdot \text{K}} \quad [3 \text{ sf}]$$

5.9 Rearranging the ideal gas law to find gas density (160):

$$PV = \frac{m}{M}RT \quad \text{so} \quad \frac{m}{V} = d = \frac{M \times P}{RT}$$

5.10 Rearranging the ideal gas law to find molar mass (161):

$$n = \frac{m}{M} = \frac{PV}{RT} \quad \text{so} \quad M = \frac{mRT}{PV} \quad \text{or} \quad M = \frac{dRT}{P}$$

5.11 Relating the total pressure of a gas mixture to the partial pressures of the components (Dalton's law of partial pressures) (162):

$$P_{\text{total}} = P_1 + P_2 + P_3 + \dots$$

5.12 Relating partial pressure to mole fraction (163):

$$P_A = X_A \times P_{\text{total}}$$

5.13 Defining rms speed as a function of molar mass and temperature (171):

$$u_{\text{rms}} = \sqrt{\frac{3RT}{M}}$$

5.14 Applying Graham's law of effusion (172):

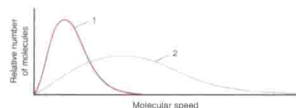
$$\frac{\text{Rate}_A}{\text{Rate}_B} = \frac{\sqrt{M_B}}{\sqrt{M_A}} = \sqrt{\frac{M_B}{M_A}}$$

energy, (c) diffusion rate after the valve is opened, (d) total kinetic energy of the molecules, and (e) density.

5.36 What is the ratio of effusion rates for the lightest gas, H₂, and the heaviest known gas, UF₆?

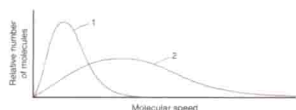
5.37 What is the ratio of effusion rates for O₂ and Kr?

5.38 The graph below shows the distribution of molecular speeds for argon and helium at the same temperature.



- Does curve 1 or 2 better represent the behavior of argon?
- Which curve represents the gas that effuses more slowly?
- Which curve more closely represents the behavior of fluorine gas? Explain.

5.39 The graph below shows the distribution of molecular speeds for a gas at two different temperatures.



- Does curve 1 or 2 better represent the behavior of the gas at the lower temperature?
- Which curve represents the gas when it has a higher *E_k*?
- Which curve is consistent with a higher diffusion rate?

5.60 At a given pressure and temperature, it takes 4.85 min for a 1.5-L sample of He to effuse through a membrane. How long does it take for 1.5 L of F₂ to effuse under the same conditions?

5.61 A sample of an unknown gas effuses in 11.1 min. An equal volume of H₂ in the same apparatus at the same temperature and pressure effuses in 2.42 min. What is the molar mass of the unknown gas?

5.62 Solid white phosphorus melts and then vaporizes at high temperature. Gaseous white phosphorus effuses at a rate that is 0.404 times that of neon in the same apparatus under the same conditions. How many atoms are in a molecule of gaseous white phosphorus?

5.63 Helium is the lightest noble gas component of air, and xenon is the heaviest. [For this problem, use *R* = 8.314 J/(mol·K) and *M* in kg/mol.]

- Calculate the rms speed of helium in winter (0°C) and in summer (30°C).
- Compare *u_{rms}* of helium with that of xenon at 30°C.
- Calculate the average kinetic energy per mole of helium and xenon at 30°C.
- Calculate *E_k* per molecule of helium at 30°C.

Problems 181

5.64 A mixture of gaseous disulfur difluoride, dinitrogen tetrafluoride, and sulfur tetrafluoride is placed in an effusion apparatus. (a) Rank the gases in order of increasing effusion rate. (b) Find the ratio of effusion rates of disulfur difluoride and dinitrogen tetrafluoride. (c) If gas X, and it effuses at 0.935 times the rate of sulfur tetrafluoride, find the molar mass of X.

Real Gases: Deviations from Ideal Behavior

5.65 Do intermolecular attractions cause negative or positive deviations from the *PV/RT* ratio of an ideal gas? Use data from Table 5.4 to rank Kr, CO₂, and N₂ in order of increasing magnitude of these deviations.

5.66 Does molecular size cause negative or positive deviations from the *PV/RT* ratio of an ideal gas? Use data from Table 5.4 to rank Cl₂, H₂, and O₂ in order of increasing magnitude of these deviations.

5.67 Does N₂ behave more ideally at 1 atm or at 500 atm? Explain.

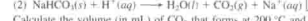
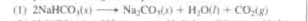
5.68 Does SF₆ (boiling point = 16°C at 1 atm) behave more ideally at 150°C or at 20°C? Explain.

Comprehensive Problems

Problems with an asterisk (*) are more challenging.

5.69 Hemoglobin is the protein that transports O₂ through the blood from the lungs to the rest of the body. In doing so, each molecule of hemoglobin combines with four molecules of O₂. If 1.00 g of hemoglobin combines with 1.53 mL of O₂ at 37°C and 743 torr, what is the molar mass of hemoglobin?

5.70 A baker uses sodium hydrogen carbonate (baking soda) as the leavening agent in a banana-nut quickbread. The baking soda decomposes according to two possible reactions:

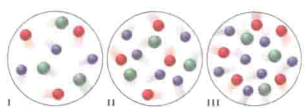


Calculate the volume (in mL) of CO₂ that forms at 200°C and 0.975 atm per gram of NaHCO₃ by each of the reaction processes.

5.71 Chlorine is produced from sodium chloride by the electrochemical chlor-alkali process. During the process, the chlorine is collected in a container that is isolated from the other products to prevent unwanted (and explosive) reactions. If a 1550-L container holds 0.5950 kg of Cl₂ gas at 225°C, calculate

- P_{Cl₂}*
- P_{Cl₂}* (use *R* = 0.08206 $\frac{\text{atm} \cdot \text{L}}{\text{mol} \cdot \text{K}}$)

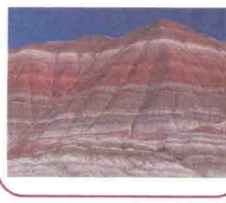
5.72 Three equal volumes of gas mixtures, all at the same *T*, are depicted below (with gas A red, gas B green, and gas C blue):



- Which sample, if any, has the highest partial pressure of A?
- Which sample, if any, has the lowest partial pressure of B?
- In which sample, if any, do the gas particles have the highest average kinetic energy?

End-of-Chapter Problems

An exceptionally large number of problems ends each chapter. These are sorted by section, and many are grouped in similar pairs, with one of each pair answered in Appendix E. Following these section-based problems is a large group of comprehensive problems, which are based on concepts and skills from any section and/or earlier chapter and are filled with applications from related sciences. Especially challenging problems have an asterisk.

THINK OF IT THIS WAY
Environmental Flow

The environment demonstrates beautifully the varying abilities of substances in the three states to flow and diffuse. Atmospheric gases mix so well that the 80 km of air closest to Earth's surface has a uniform composition. Much less mixing occurs in the oceans, and seawater differs in composition with depth, supporting different species. Rocky solids (see photo) intermingle so little that adjacent strata remain separated for millions of years.

Types of Phase Changes Phase changes are also determined by the interplay between kinetic energy and intermolecular forces. As the temperature increases, the average kinetic energy increases as well, so the faster moving particles can overcome attractions more easily; conversely, lower temperatures allow the forces to draw the slower moving particles together.

What happens when gaseous water is cooled? A mist appears as the particles form tiny microdroplets that then collect into a bulk sample of liquid with a single surface. The process by which a gas changes into a liquid is called **con-**

Think of It This Way

Analogies, memory shortcuts, and new insights into key ideas are provided in "Think of It This Way" paragraphs.

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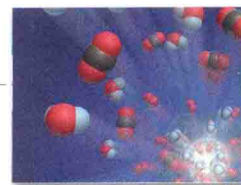
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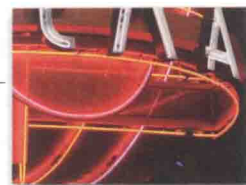
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