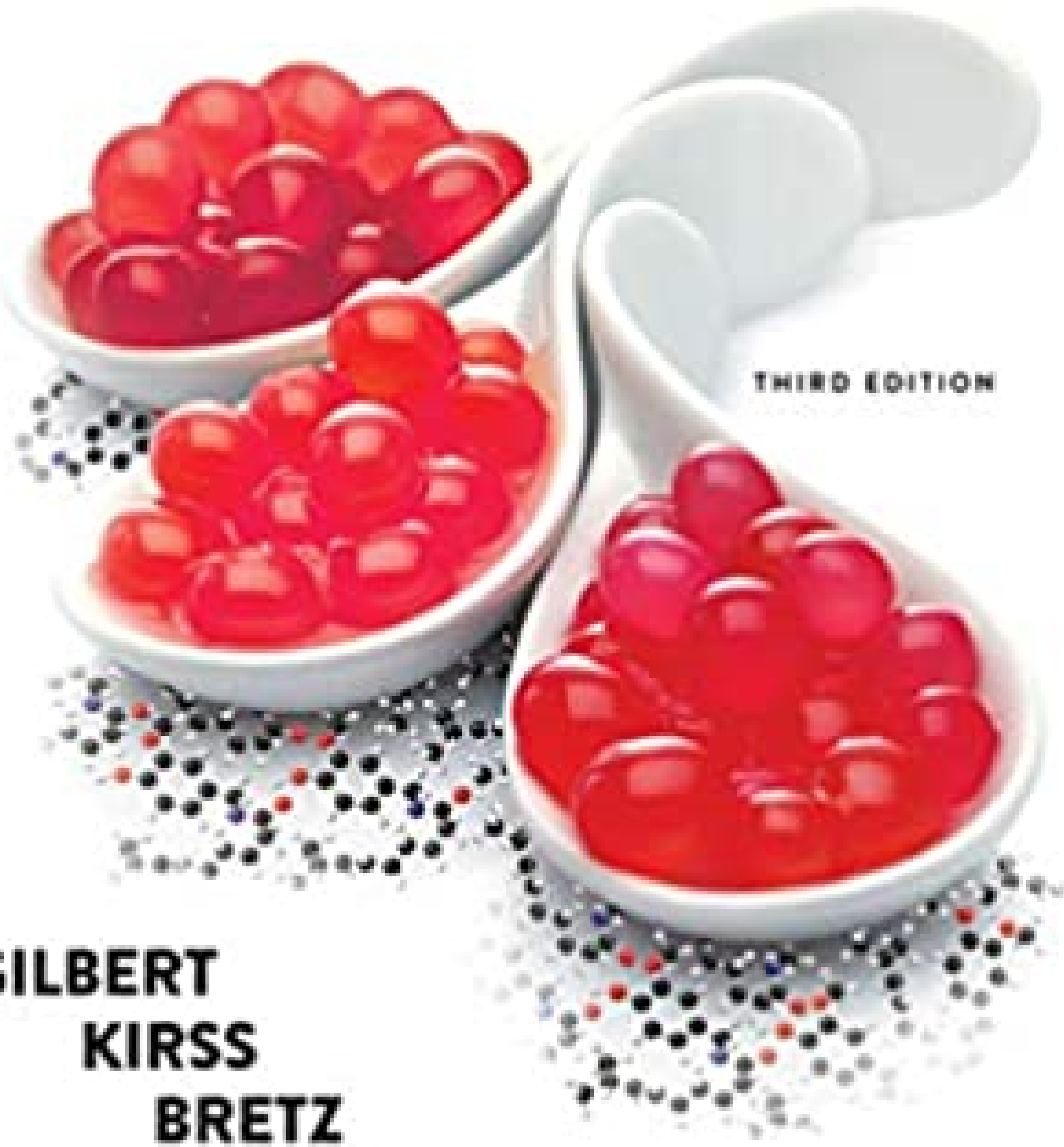
CHEMISTRY

AN ATOMS-FOCUSED APPROACH



THIRD EDITION

GILBERT
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THIRD EDITION

Chemistry

An Atoms-Focused Approach

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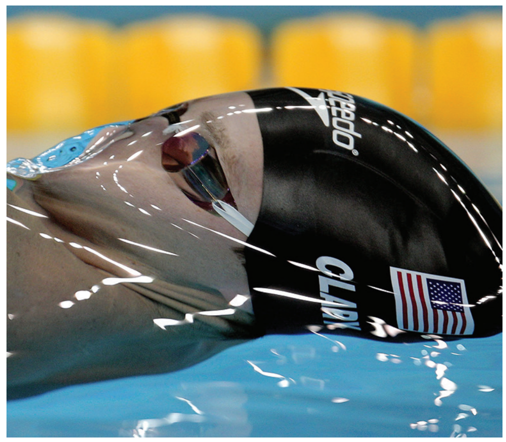


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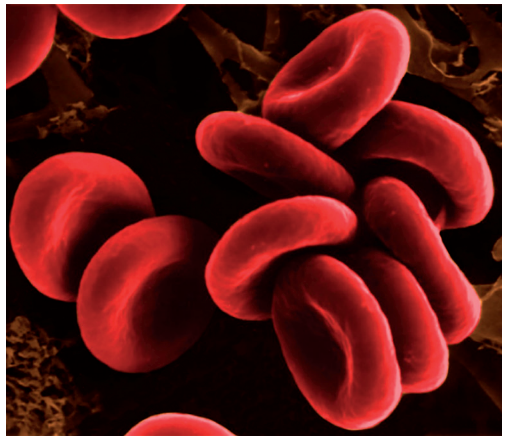

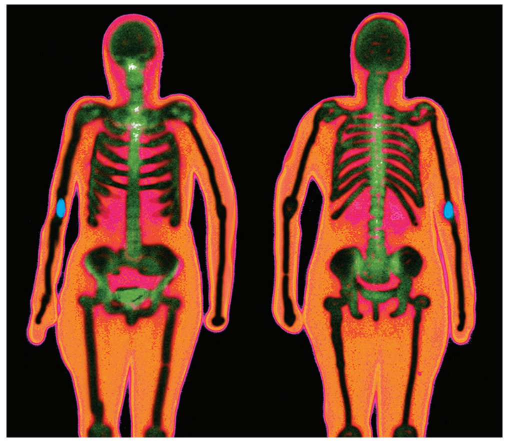

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About the **Authors**

Thomas R. Gilbert has a BS in chemistry from Clarkson and a PhD in analytical chemistry from MIT. After 10 years with the Research Department of the New England Aquarium in Boston, he joined the faculty of Northeastern University, where he is associate professor of chemistry and chemical biology. His research interests are in chemical and science education. He teaches general chemistry and science education courses and conducts professional development workshops for K–12 teachers. He has won Northeastern's Excellence in Teaching Award and Outstanding Teacher of First-Year Engineering Students Award. He is a Fellow of the American Chemical Society and in 2012 was elected to the American Chemical Society's board of directors.

Rein V. Kirss received both a BS in chemistry and a BA in history as well as an MA in chemistry from SUNY Buffalo. He received his PhD in inorganic chemistry from the University of Wisconsin, Madison, where the seeds for this textbook were undoubtedly planted. After two years of postdoctoral study at the University of Rochester, he spent a year at Advanced Technology Materials Inc. before returning to academics at Northeastern University in 1989. He has won the Northeastern University College of Science Excellence in Teaching Award and was the recipient of the John A. Timm Award from the New England Association of Chemistry Teachers in 2019. He is an associate professor of chemistry with an active research interest in organometallic chemistry.

Stacey Lowery Bretz is a University Distinguished Professor in the Department of Chemistry and Biochemistry at Miami University in Oxford, Ohio. She earned her BA in chemistry from Cornell University, an MS from Pennsylvania State University, and a PhD in chemistry education research from Cornell University. She spent one year at the University of California, Berkeley, as a postdoc in the Department of Chemistry. Her research expertise includes the development of assessments to measure chemistry students' thinking with multiple representations (particulate, symbolic, and macroscopic) and to promote meaningful and inquiry learning in the chemistry laboratory. She is a Fellow of the American Chemical Society and a Fellow of the American Association for the Advancement of Science. She has been honored with both of Miami University's highest teaching awards: the E. Phillips Knox Award for Undergraduate Teaching and the Distinguished Teaching Award for Excellence in Graduate Instruction and Mentoring. Stacey won the prestigious, international award from the American Chemical Society for Achievement in Research on Teaching and Learning of Chemistry in 2020.

Natalie Foster is emerita professor of chemistry at Lehigh University in Bethlehem, Pennsylvania. She received a BS in chemistry from Muhlenberg College and MS, DA, and PhD degrees from Lehigh University. Her research interests included studying poly(vinyl alcohol) gels by nuclear magnetic resonance as part of a larger interest in porphyrins and phthalocyanines as candidate contrast enhancement agents for magnetic resonance imaging. She taught both semesters of the introductory chemistry class to engineering, biology, and other nonchemistry majors and a spectral analysis course at the graduate level. She is the recipient of the Christian R. and Mary F. Lindback Foundation Award for distinguished teaching and a Fellow of the American Chemical Society.

Preface

Dear Student,

At first glance you may have thought that the cover of your book showed three spoonfuls of caviar. However, the cover has a clue that would help you realize that those red beads are actually Sriracha pearls made through a cooking technique called cold oil spherification, which uses some of the chemistry you will learn in this course. Each of those tiny spheres will burst in your mouth and release an explosion of flavor—in this case, the spicy hot sauce extracted from red chili peppers. The primary compound responsible for the burning sensation is capsaicin, which is represented by the molecular structure on the cover.

Our cover illustrates a central message of this book: the properties of substances are directly linked to their atomic and molecular structures. We start with the smallest particles of matter and assemble them into more elaborate structures: from subatomic particles to single atoms to monatomic ions and polyatomic ions, and from atoms to small molecules to bigger ones to truly gigantic polymers. By constructing this layered particulate view of matter, we hope our book helps you visualize the structure and properties of substances and the changes they undergo during chemical reactions. We believe, because education research shows, that being able to visualize chemistry at the macro, particulate, and symbolic levels will help you better understand the material and apply that understanding when you're solving a problem.

With that in mind, we begin each chapter with a **Particulate Review** and **Particulate Preview**. The goal of these tools is to prepare you for the material in the chapter. The Particulate Review assesses important prior knowledge that you need to interpret particulate images in the chapter. The Particulate Preview asks you to expand your prior knowledge and to speculate about the new concepts you will see in the chapter. It is also designed to focus your reading by asking you to look out for key terms and concepts.

As you develop your ability to visualize atoms and molecules, you will find that you don't have to resort to memorizing formulas and reactions as a strategy for surviving general chemistry. Instead,

PARTICULATE **REVIEW**

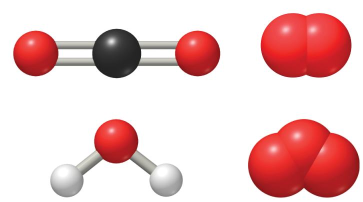
Polar Bonds versus Polar Molecules

In Chapter 6, we explore the connections between the structure of molecules and how they interact with each other. Here are representations of four molecules: carbon dioxide, oxygen, water, and ozone.

- Which molecule is polar and contains polar bonds?
- Which molecule is nonpolar despite containing polar bonds?
- Which molecule is polar despite containing nonpolar bonds?

(Review Section 5.3 if you need help.)

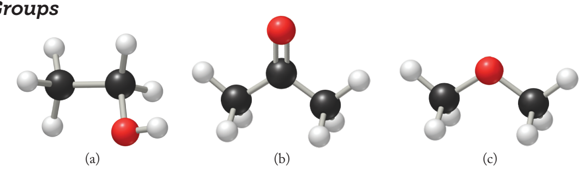
(Answers to Particulate Review questions are in the back of the book.)



PARTICULATE **PREVIEW**

Bonds and Functional Groups

Each molecule shown here contains one or two carbon–oxygen bonds. As you read Chapter 6, look for ideas that will help you answer these questions:



- What is the functional group in each molecule?
- What intermolecular forces exist between molecules of (a)? Between molecules of (b)? Between molecules of (c)?
- Rank these three compounds from lowest to highest boiling point.

you will be able to understand why elements combine to form compounds with particular formulas and why substances react with each other the way they do.

Context

Although our primary goal is for you to be able to interpret, explain, and even predict the physical and chemical properties of substances on the basis of their atomic and molecular structures, we would also like you to understand how chemistry is linked to other disciplines as well as your life. We illustrate these connections by using contexts drawn from biology, medicine, environmental science, materials science, and engineering. We hope that this approach helps you better understand how, for example, chefs use chemistry in their kitchens, and scientists apply the principles of chemistry to treat and cure diseases, to make more efficient use of natural resources, and to minimize the negative impact of human activity on our planet and its people. We also hope you will see how chemistry is all around you, in the air you breathe and the food you eat, and how understanding chemistry will help you solve problems in this course and beyond.

Problem-Solving Strategies

Building on that theme, another primary goal of this book is to help you improve your problem-solving skills. To do this, you first need to recognize the connections between the information provided in a problem and the answer you are asked to find. Sometimes the hardest part of solving a problem is distinguishing between information that is relevant and information that is not. Once you are clear on where you are starting and where you are going, planning for and carrying out a solution become much easier.

To help you hone your problem-solving skills, we have developed a framework that we introduce in Chapter 1. It is a four-step approach we call COAST, which is our acronym for (1) **C**ollect and **O**rganize, (2) **A**nalyze, (3) **S**olve, and (4) **T**hink About It. We use these four steps in *every* Sample Exercise and in the solutions to *odd-numbered* problems in the *Student Solutions Manual*. They are also used in the hints and feedback embedded in the Smartwork5 online homework program. To summarize the four steps:

Collect and Organize helps you understand where to begin to solve the problem. In this step, we often rephrase the problem and what we are trying to find, and we identify the relevant information given in the problem statement or available elsewhere in the book.

Analyze is where we map out a strategy for solving the problem. As part of that strategy, we often estimate what a reasonable answer might be.

Solve applies our strategy from the second step to the information and relationships identified in the first step to actually solve the problem. We walk you through each step in the solution so that you can follow the logic and the math, and we use dimensional analysis consistently throughout the book.

SAMPLE EXERCISE 6.5 Interpreting Phase Diagrams **LO4**

Describe the phase changes that take place when the pressure on a sample of water is increased from 0.0001 to 100 atm at a constant temperature of −25°C, and the sample is then warmed from −25°C to 350°C at a constant pressure of 100 atm.

Collect and Organize We are asked to describe the phase changes that a sample of water undergoes as its pressure increases at constant temperature and its temperature increases at constant pressure. Figure 6.25 shows which phases of water are stable at various combinations of temperature and pressure.

Analyze The change in pressure at constant temperature defines two points on the phase diagram of water with the coordinates (−25°C, 0.0001 atm) and (−25°C, 100 atm). Connecting those points will give us a vertical line. If the line crosses a phase boundary, a change in physical state will occur. The change in temperature at constant pressure defines a third point (350°C, 100 atm) on the phase diagram, which will connect to the second point with a horizontal line.

Solve **Figure 6.29** shows a plot of our sample's changes in pressure and temperature. At the bottom end of vertical line 1, water is a gas (vapor). As pressure increases along line 1, it crosses the boundary between gas and solid (point A), which means that vapor turns directly into solid ice, which is stable beyond 100 atm at −25°C (point B). As the temperature of the ice increases along horizontal line 2, it intersects the solid–liquid boundary (point C) and the ice melts. At even higher temperatures, just below 350°C, the line intersects the liquid–gas boundary (point D) and the liquid water vaporizes.

Think About It The solid-to-liquid and liquid-to-gas transitions with increasing temperature along line 2 are what we would expect when a solid substance is warmed to its melting point and then the liquid is heated to its boiling point at a given pressure. The transition along line 1 is less familiar because it is caused by increasing the pressure on a gas at a temperature below the triple point temperature, so the vapor never condenses. Instead, it is deposited as a solid.

Practice Exercise Describe the phase changes that occur when the temperature of CO_2 is increased from −100°C to 50°C at a pressure of 25 atm and the pressure is then increased to 100 atm.

Think About It reminds us that an answer is not the last step in solving a problem. We should check the accuracy of the solution and think about the value of a quantitative answer. Is it realistic? Are the units correct? Is the number of significant figures appropriate? How does it compare with our estimate from the Analyze step?

Sample Exercises that require a single-step solution are often streamlined by combining Collect, Organize, and Analyze steps, but the essential COAST features are always maintained.

Many students use the **Sample Exercises** more than any other part of the book. Sample Exercises start with the concepts being discussed and model how to apply them to solve problems. We think that consistently using the COAST framework will help you refine your problem-solving skills, and we hope that the approach will become habit-forming for you. After you finish each Sample Exercise, you'll find a **Practice Exercise** to try on your own. The next few pages describe how to use the tools built into each chapter to gain a conceptual understanding of chemistry and to connect the microscopic structure of substances to their observable physical and chemical properties.

Chapter Structure

As mentioned earlier, each chapter begins with the Particulate Review and Particulate Preview to help you prepare for the material ahead.

If you are trying to decide what is most important in a chapter, check the **Learning Outcomes** listed on the first page. Whether you are reading the chapter from first page to last or reviewing it for an exam, the Learning Outcomes will help you focus on the key information you need and the skills you should develop. Please notice how Learning Outcomes are linked to Sample Exercises in the chapter.

As you study each chapter, you will find **key terms** in boldface in the text and in a running glossary in the margin. All key terms are also defined in the glossary in the back of the book. We have deliberately duplicated these definitions so that you can continue reading without interruption but quickly refer to them when doing homework or studying.

Many concepts build on others described earlier in the book. We point out these relationships with **Connection** icons in the margins. We hope they enable you to draw your own connections between major themes covered in the book.

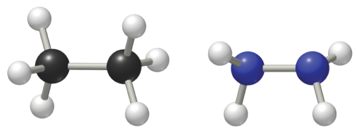
CONNECTION Isomers are introduced and defined in Section 5.6.

To help you develop your own microscale view of matter, we use **molecular art** to enhance photos and figures and to illustrate what is happening at the atomic and molecular levels.

If you're looking for additional help visualizing a concept, we have approximately 140 animations and simulations denoted by the ChemTour and Stepwise Animation icons in the book, and available online at https://digital.wwnorton.com/atoms3. Both the ChemTours and Stepwise Animations demonstrate dynamic processes and chemical concepts and help you visualize events at the molecular level. Many of the ChemTours allow you to manipulate variables and observe the resulting changes.

CONCEPT TEST

Ethane and hydrazine have similar molecular structures (**Figure 6.11**), yet the boiling point of hydrazine (387 K) is more than 200 K greater than that of ethane (184 K). What intermolecular interactions account for this huge difference in boiling points?



Ethane
CH_3CH_3
Boiling point, 184 K

Hydrazine
NH_2NH_2
Boiling point, 387 K

FIGURE 6.11 Ethane and hydrazine have similar structures but different boiling points.

Concept Tests are short, conceptual questions that serve as self-checks by asking you to stop and answer questions related to what you just read. We designed them to help you see for yourself whether you have grasped a key concept and can apply it. We have included an average of one Concept Test per section, and many have visual components. The answers to all the Concept Tests are in the back of the book.

At the end of each chapter is a special Sample Exercise that draws on several key concepts from the chapter and occasionally others from preceding chapters to solve a problem that is framed in the context of a real-world scenario or incident. We call these **Integrated Sample Exercises**. You may find them more challenging than most of the exercises that precede them in each chapter, but please invest your time in working through them because they represent authentic, real-world scenarios that will enhance your problem-solving skills.

Also at the end of each chapter are a thematic **Summary** and a **Problem-Solving Summary**. The first is a synopsis of the chapter, organized by learning outcomes and connected to sections of the chapter. Key figures provide visual cues as you review. The Problem-Solving Summary is unique to this general chemistry book—it outlines the types of problems you should be able to solve, indicates where to find examples of them in the Sample Exercises, and reminds you of key concepts and equations.

PROBLEM-SOLVING SUMMARY

Type of Problem	Concepts and Equations	Sample Exercises
Identifying intermolecular forces	All atoms and molecules experience London dispersion forces. Ions in aqueous solution interact with water molecules through ion–dipole interactions. Molecules with permanent dipoles interact through a combination of London dispersion forces and dipole–dipole interactions. The strongest dipole–dipole interactions are hydrogen bonds, which form between H atoms bonded to N, O, and F atoms and other N, O, and F atoms.	**6.1**
Explaining differences and trends in boiling points of liquids	Because of London dispersion forces, substances made of large molecules usually have higher boiling points than those with smaller molecules. Because of dipole–dipole interactions, polar compounds have higher boiling points than nonpolar compounds of similar molar mass. Compounds whose molecules form hydrogen bonds have even higher boiling points because H bonds are especially strong dipole–dipole interactions.	**6.2**
Predicting solubility in water	Polar molecules are more soluble in water than nonpolar molecules. Molecules that form hydrogen bonds are more soluble in water than molecules that cannot form these bonds. Like dissolves like.	**6.3**
Explaining solubility trends for ionic compounds	The solubility of any compound in a solvent depends on the relative strengths of the solute–solute, solvent–solvent, and solute–solvent interactions.	**6.4**
Interpreting phase diagrams	Locate the combination of temperature and pressure of interest on the phase diagram, and determine which physical state exists at that point. Changes in pressure at constant temperature are represented by vertical paths, and changes in temperature at constant pressure are represented by horizontal paths. If a path crosses a phase boundary line, a change in phase occurs.	**6.5**

After the summaries are groups of questions and problems. The first group consists of **Visual Problems**. In many of them, you are asked to interpret a molecular view of a sample or a graph of experimental data. The last Visual Problem in each chapter contains a **Visual Problem Matrix**. This grid consists of nine images followed by questions that will test your ability to identify the similarities and differences among the macroscopic, particulate, and symbolic images.

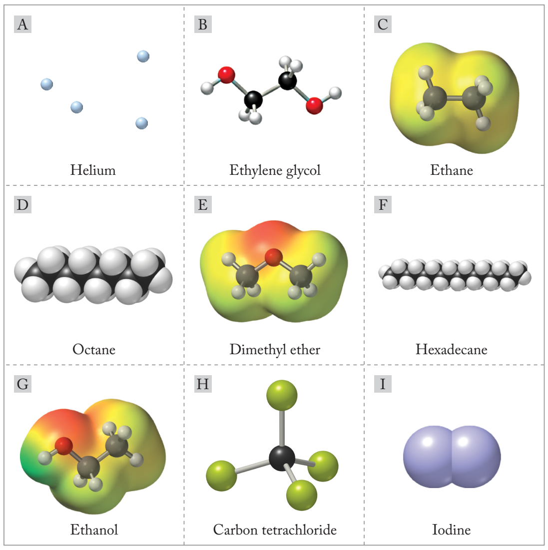


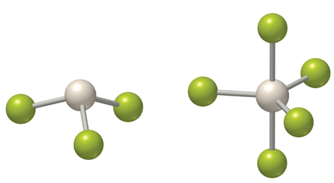
FIGURE P6.16

6.16. Use representations [A] through [I] in Figure P6.16 to answer questions a–f.
   a. What are the intermolecular forces between the molecules in representations C, E, and G?
   b. Which of the nine substances has the lowest boiling point?
   c. Which representations are isomers of one another?
   d. Which is more soluble in water: ethylene glycol or iodine? Which is more soluble in carbon tetrachloride? Explain your answers in terms of the intermolecular forces involved.
   e. Which hydrocarbon has the higher boiling point?
   f. Which substance does not form hydrogen bonds between its molecules but can form hydrogen bonds to another molecule?

Concept Review Questions and Problems come next, arranged by topic in the same order as they appear in the chapter. Concept Reviews are qualitative and often ask you to explain why or how something happens. Problems are paired and can be quantitative, conceptual, or both. **Contextual Problems** have a title that describes the context in which the problem is placed. Finally, **Additional Problems** can come from any section or combination of sections in the chapter. Some problems incorporate concepts from previous chapters. Problems marked with an asterisk (*) are more challenging and often take multiple steps to solve.

We want you to have confidence in using the answers in the back of the book as well as the *Student Solutions Manual*, so we used a rigorous triple-check accuracy program for this book. Each end-of-chapter question or problem was solved independently by the *Solutions Manual* author, Karen Brewer, and by two additional PhD chemistry instructors. Karen compared her solutions with those from the two reviewers and resolved any discrepancies. This process is designed to ensure clearly written problems and accurate answers in the appendices and *Solutions Manual*.

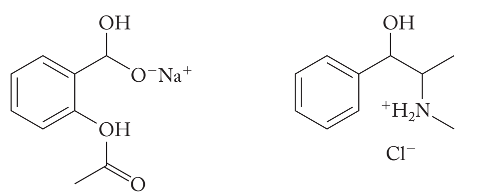
***6.27.** The compound with the molecular structure in Figure P6.27 (b) melts at a higher temperature than the compound in (a). Explain why, using the different types and strengths of the intermolecular forces experienced by the molecules.



(a) (b)

FIGURE P6.27

***6.57.** **Improving the Solubility of Drugs** Many common over-the-counter medications such as pseudoephedrine and acetylsalicylic acid are formulated with either sodium cations or chloride anions to improve their water solubility. Why would the structures in Figure P6.57 have improved solubility in water?



Sodium acetylsalicylate Pseudoephedrine hydrochloride

FIGURE P6.57

Dear Instructor,

This book adopts what has traditionally been called an atoms-first approach to teaching chemistry. Consequently, the sequence of chapters in the book and the sequence of topics in many of the chapters differ, on the basis of our experience in the classroom, from some other atoms-first general chemistry textbooks, thus our subtitle, *An Atoms-Focused Approach*. For example, we devote the early chapters to giving students an in-depth view of the particulate nature of matter, including the structure of atoms and molecules and how the properties of substances link directly to their structures.

After two chapters on the nature of chemical bonding, molecular shape, and theories to explain both, we build on those topics as we explore the intermolecular forces that strongly influence the form and function of molecules, particularly those of biological importance.

Once this theoretical foundation has been developed, we examine chemical reactivity and the energetics of chemical reactions. Most general chemistry books don't complete their coverage of chemistry and energy until late in the book. We examine thermodynamics in Chapter 12, which means that students already understand the roles of energy and entropy in chemical reactions before they encounter chemical kinetics and the question of how quickly reactions happen. The kinetics chapter is followed by several chapters on chemical equilibrium, which introduce the phenomenon in terms of what happens when reactions proceed to a measurable extent in both forward and reverse directions, and how interactions between and within particles influence chemical changes.

Changes in the Third Edition

As authors of a textbook, we are often asked: "Why is a new edition necessary? Has the chemistry changed that much since the previous edition?" Although chemistry is a vigorous and dynamic field, most basic concepts presented in an introductory course have not changed dramatically. However, two areas that are tightly intertwined in this text—pedagogy and context—have changed significantly, and those areas drive this new edition. Here are some of the most noteworthy changes we made throughout this edition:

- Adopters enthusiastically embraced the visualization pedagogy introduced in the second edition and then asked for additional tools to help them use this research-based pedagogy to assess students. The teaching tools accompanying the third edition include:
  - In-class activities, often including premade handouts, help you facilitate active learning with a focus on visualization, in any size classroom.
  - Projected visualization questions help you assess students on their understanding and support the Particulate Review, Particulate Preview, and Visual Matrix problems in the book by providing color images you can project in your class, accompanied by questions you can use on your exam or for in-class quizzes.
  - The new *Interactive Instructor's Guide* (IIG) is an easily searchable online resource containing all the teaching resources for the third edition. Instructors can search by chapter, phrase, topic, or learning objective to find activities, animations, simulations, and visualization questions to use in class.

- On the basis of her chemistry education research, Stacey Lowery Bretz evaluated and revised the art in the book and the media to be more pedagogically effective and address student misconceptions.
- In Chapter 5, we've removed any reference to *d* orbital hybridization when discussing molecular geometry, updating our explanations for molecules with more than an octet of electrons around a central atom to be grounded in molecular orbital theory.
- The gases chapter, now Chapter 9, is introduced before thermochemistry. We believe this will allow instructors to develop the concept of pressure in Chapter 9 and then build on that understanding to discuss pressure–volume work in Chapter 10.
- Several new Sample Exercises were added to the acid–base and equilibria chapters on the basis of reviewer feedback and to provide more detailed discussions of titrations and buffers.
- End-of-chapter problems have been refined to better align with the text's Learning Outcomes and provide a more balanced selection in terms of level and concept coverage. We estimate that 10% to 15% of the end-of-chapter problems have been replaced or revised.
- More than 600 problems have been added to the Smartwork5 course, including additional end-of-chapter, algorithmic, and pooled problems to provide more than 5000 problems in the third edition course.
- Powered by Knewton, adaptive functionality in Smartwork5 has been continually improved, resulting in more intuitive experiences for students as they work through personalized learning paths and the availability of better data for instructors to review their students' mastery of chosen learning objectives.
- Revised ChemTour Animations, also found in the ebook and Smartwork5, are now easier to navigate and assign individual sections and have been revised to reflect Stacey Lowery Bretz's visualization pedagogy. ChemTours are available streaming in the ebook, in Smartwork5 questions, as remediation in adaptive assignments, and in the *Interactive Instructor's Guide*, which includes discussion questions and activity ideas for each.
- Our new partnership with the Squarecap classroom response system gives you book-specific clicker questions in an easy-to-use system for a low cost to students.

Teaching and Learning Resources

Smarkwork5 Online Homework For General Chemistry

digital.wwnorton.com/atoms3

Smartwork5 is the most intuitive online tutorial and homework management system available for general chemistry. The many question types, including graded molecule drawing, math and chemical equations, ranking tasks, and interactive figures, help students develop and apply their understanding of fundamental concepts in chemistry. Adaptive functionality, powered by Knewton, gives students personalized coaching, allowing them to master assigned concepts at their own pace.

Every problem in Smartwork5 includes response-specific feedback and general hints often organized by the steps in COAST. Links to the ebook version of *Chemistry: An Atoms-Focused Approach,* Third Edition, take students to the specific place in the text where the concept is explained. All problems in Smartwork5 use the same language and notation as the textbook.

Smartwork5 also features Tutorial Problems. If students ask for help in a Tutorial Problem, the system breaks the problem down into smaller steps, coaching them with hints, answer-specific feedback, and probing questions within each part. At any point in a Tutorial, students can return to and answer the original problem.

Assigning, editing, and administering homework within Smartwork5 is easy. Smartwork5 allows the instructor to search for problems by text section, learning objectives, question type, difficulty, and Bloom's taxonomy. Instructors can use premade assignment sets provided by Norton authors, modify those assignments, or create their own. Instructors can also make changes in the problems at the question level. All instructors have access to our WYSIWYG (what you see is what you get) authoring tools—the same ones Norton authors use. Those intuitive tools make it easy to modify existing problems or to develop content that meets the specific needs of your course.

Wherever possible, Smartwork5 uses algorithmic variables so that students see slightly different versions of the same problem. Assignments are graded automatically, and Smartwork5 includes sophisticated yet flexible tools for managing class data. Instructors can use the class activity report to assess students' performance on specific problems within an assignment. Instructors can also review individual students' work on problems.

Smartwork5 for *Chemistry*: *An Atoms-Focused Approach*, Third Edition, features the following problem types:

- End-of-Chapter Problems. These problems, which use algorithmic variables when appropriate, all have hints and answer-specific feedback to coach students through mastering single- and multiconcept problems based on chapter content. They use all of Smartwork5's answer-entry tools.
- ChemTour Problems. Many of our ChemTour animations have been redesigned to make them easier than ever to navigate, making it simple to assign Smartwork5 questions on specific interactives.
- Visual and Graphing Problems. These problems challenge students to identify chemical phenomena and to interpret graphs by using Smartwork5's Drag-and-Drop functionality.
- Ranking Task Problems. These problems ask students to make comparative judgments between items in a set.
- Nomenclature Problems. New matching and multiple-choice problems help students master course vocabulary.
- Multistep Tutorials. These problems offer students who demonstrate a need for help a series of linked, step-by-step subproblems to work. They are based on the Concept Review problems at the end of each chapter.
- Math Review Problems. These problems can be used by students for practice or by instructors to diagnose the mathematical ability of their students.

Ebook

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An affordable and convenient alternative to the print text, the Norton Ebook lets students access the entire book and much more: they can search, highlight, and take notes with ease. The Norton Ebook allows instructors to share their notes with students. And the ebook can be viewed on most devices—laptop, tablet, even a public computer—and will stay synced between devices.

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by Karen Brewer, Hamilton University

The *Instructor's Solutions Manual* gives instructors fully worked solutions to every end-of-chapter Concept Review and Problem. Each solution uses the COAST four-step method (**C**ollect and **O**rganize, **A**nalyze, **S**olve, and **T**hink About It).

Interactive Instructor's Guide

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by Spencer Berger, Western Washington University, Thomas Pentecost, Grand Valley State University, and Elizabeth Raymond, Western Washington University

The *Interactive Instructor's Guide* will help instructors use our unique visualization pedagogy in class and for assessment by compiling the many valuable teaching resources available with *Chemistry: An Atoms-Focused Approach*, Third Edition, in an easily searchable online format. In-class activities, backed by chemical education research and written by active learning experts who teach atoms first, emphasize visualization and are designed to promote collaboration. New projected visualization problems, developed based on how Stacey Lowery Bretz gives her own exams, allow instructors to ask exam questions that use full-color images. The ChemTours are also accompanied by new activity ideas, discussion questions, and clicker questions, making them easier than ever to use. All resources are searchable by chapter, keyword, or learning objective.

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by Margaret Asirvatham, University of Colorado, Boulder

This instructor-oriented resource describes implementing clickers in general chemistry courses. *Clickers in Action* contains more than 250 class-tested, lecture-ready questions, with histograms showing student responses, as well as insights and suggestions for implementation. Question types include macroscopic observation, symbolic representation, and atomic/molecular views of processes.

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- Lecture PowerPoints are available.
- All ChemTours are included.
- Test bank is available in PDF, Word, and ExamView Assessment Suite formats.
- *Solutions Manual* is offered in PDF and Word so that instructors may edit solutions.
- All end-of-chapter Questions and Problems are available in Word along with the key equations.
- Labeled and unlabeled photographs, drawn figures, and tables from the text are available in PowerPoint and JPEG formats.
- Clicker questions, including those from *Clickers in Action,* are included.
- Course cartridges: Available for the most common learning management systems, course cartridges include access to the ChemTours and Stepwise animations as well as links to the ebook and Smartwork5.

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Chemistry

An Atoms-Focused Approach

1

Matter and Energy

An Atomic Perspective

TENNIS RACKET TECHNOLOGY
This tennis racket is both lightweight and exceptionally stiff and strong. Its frame is reinforced by graphene, a form of carbon.

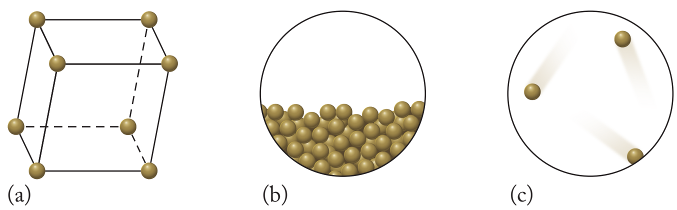
PARTICULATE **REVIEW**

Solids, Liquids, and Gases

In Chapter 1, we explore the particulate nature of matter. Throughout this book, colored spheres represent the fundamental particles of matter known as atoms. (*Note*: This book's inside back cover shows the colors that represent the atoms of different elements.) The spheres in these three images represent atoms of the element mercury, which is a liquid at room temperature but turns into a solid at low temperatures and into a vapor (or gas) at high temperatures.

- Which representation depicts liquid mercury?
- Which representation depicts solid mercury?
- Which representation depicts mercury vapor?

(Answers to Particulate Review questions are in the back of the book.)

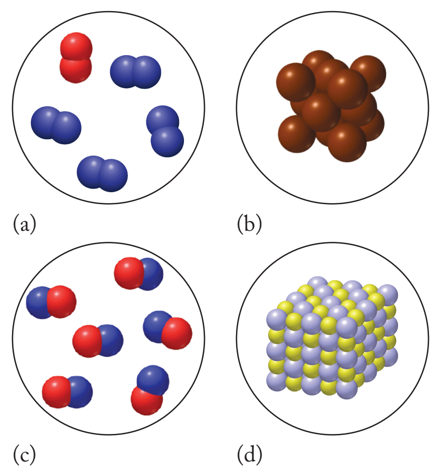


PARTICULATE **PREVIEW**

Elements versus Compounds

The tennis player on this page is using a racket whose frame is strengthened by graphene, which is composed of two-dimensional arrays of atoms of the element carbon. As you read Chapter 1, look for ideas that will help you answer these questions:

- Which representation depicts molecules of a compound?
- Which representation depicts a mixture of molecular elements?
- Which representation depicts a compound consisting of an array of ions?
- Which representation depicts an element consisting of an array of atoms?



Learning Outcomes

LO1 Describe scientific methods

LO2 Apply the COAST approach to solving problems
Sample Exercises 1.1–1.12

LO3 Distinguish between the classes of matter and between the physical and chemical properties of pure substances
Sample Exercises 1.1, 1.2

LO4 Describe the states of matter and how their physical properties can be explained by the particulate nature of matter
Sample Exercise 1.3

LO5 Distinguish between heat, work, potential energy, and kinetic energy, and describe the law of conservation of energy

LO6 Use molecular formulas and molecular models to describe the elemental composition and three-dimensional arrangement of the atoms in compounds

LO7 Distinguish between exact and uncertain values and express uncertain values with the appropriate number of significant figures
Sample Exercises 1.4–1.6

LO8 Accurately convert values from one set of units to another
Sample Exercises 1.7–1.10

LO9 Analyze and express experimental results to convey their certainty, that is, how precisely and with what accuracy they are known
Sample Exercises 1.11, 1.12

1.1 Exploring the Particulate Nature of Matter

The tennis racket in this chapter's opening photograph is both lightweight and exceptionally stiff and strong. Those properties are linked to the chemical composition of its frame, which is reinforced by a substance called graphene. Viewed at the particle level, graphene consists of sheets of carbon atoms bonded together. The strength of the carbon–carbon bonds and the rigidity of the resulting network contribute to the racket's notable strength and stiffness. Graphene was discovered only recently, but carbon networks like those in its structure have existed in nature for billions of years. Modern scientists can characterize the properties of graphene because they understand the carbon–carbon bonds that form its structure.

In this chapter we begin an exploration of how the properties of materials are linked to their particulate structure. As we do, we need to go back in time and acknowledge the philosophers of ancient Greece who espoused *atomism*, a belief that all forms of matter are composed of extremely tiny, indestructible building blocks called **atoms**. Atomism is an example of a natural philosophy; it is not a **scientific theory**. The difference between the two is that although both seek to explain natural phenomena, scientific theories do so through concise, testable explanations based on observation and experimentation. An important quality of a valid scientific theory is that it accurately predicts the results of experiments and can even serve as a guide to designing those experiments. The ancient Greeks did not have the technology to test whether matter really is made of atoms—but now we do.

Consider the images in **Figure 1.1**. On the bottom is a photograph of silicon wafers, the material used to make computer chips and photovoltaic cells. Above the photograph is a magnified view of a silicon wafer produced by an instrument called a scanning tunneling microscope.[1] The fuzzy spheres are individual atoms of silicon.

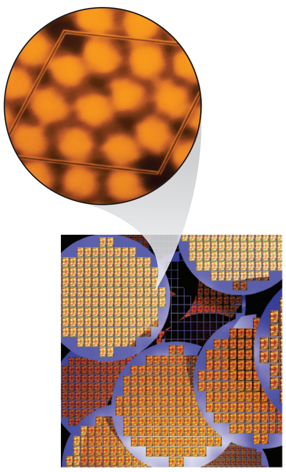


FIGURE 1.1 Silicon wafers are widely used to make computer chips and photovoltaic cells for solar panels. Since the 1980s, scientists have been able to image individual atoms by using an instrument called a scanning tunneling microscope (STM). In the STM image (top), the irregular shapes are individual silicon atoms. The radius of each atom is 117 picometers (pm), or 117 trillionths of a meter.

[1]German physicist Gerd Binnig (b. 1947) and Swiss physicist Heinrich Rohrer (1933–2013) shared the 1986 Nobel Prize in Physics for developing scanning tunneling microscopy.

Atomic Theory: Scientific Methods in Action

Scanning tunneling microscopes have been used to image atoms since the early 1980s, but the scientific theory that matter was composed of atoms evolved two centuries earlier, when chemists in France and England made enormous advances in our understanding of the composition of matter. Among those researchers was French chemist Antoine Lavoisier (1743–1794), who published the first modern chemistry textbook in 1789. That book contained a list of substances that he believed could not be separated into simpler substances. Today we call such "simple" substances **elements** (**Figure 1.2**). The silicon (Si) in Figure 1.1 is an element, as is carbon (C). Every element has a one- or two-letter symbol, shown in the periodic table of the elements inside this book's front cover.

Lavoisier and other scientists conducted experiments that examined patterns in how elements combined with other elements to form **compounds**. Those experiments followed systematic approaches known as **scientific methods** to investigate and understand natural phenomena (**Figure 1.3**). When such investigations reveal consistent patterns and relationships, they may be used to formulate concise descriptions of fundamental scientific truths. Those descriptions are known as **scientific laws**.

When French chemist Joseph Louis Proust (1754–1826) studied the composition of compounds containing different metals and oxygen, he concluded that those compounds always contained the same proportions of their component elements. His **law of definite proportions** applies to all compounds. An equivalent law, known as the **law of constant composition**, states that a compound always has the same *elemental composition* by mass no matter what its source. Thus, the composition of pure water is always the same: 11.2% by mass hydrogen and 88.8% by mass oxygen.

When Proust published his law of definite proportions, some leading chemists of the time refused to believe it. Their own experiments seemed to show, for example, that in samples of the compound that tin formed with oxygen, the content of tin varied. Those scientists did not realize that their samples were actually

atom the smallest particle of an element that cannot be chemically or mechanically divided into smaller particles.

scientific theory a concise, extensively tested explanation of widely observed natural phenomena.

element a pure substance that cannot be separated into simpler substances.

compound a pure substance composed of two or more elements that are chemically bonded in fixed proportion.

scientific methods approaches to acquiring knowledge by observing phenomena, developing a testable hypothesis, and carrying out additional experiments that test the validity of the hypothesis.

scientific law a concise and generally applicable statement of a fundamental scientific principle.

law of definite proportions the principle that a compound always contains the same proportion of its component elements.

law of constant composition the principle that all samples of a given compound have the same elemental composition.

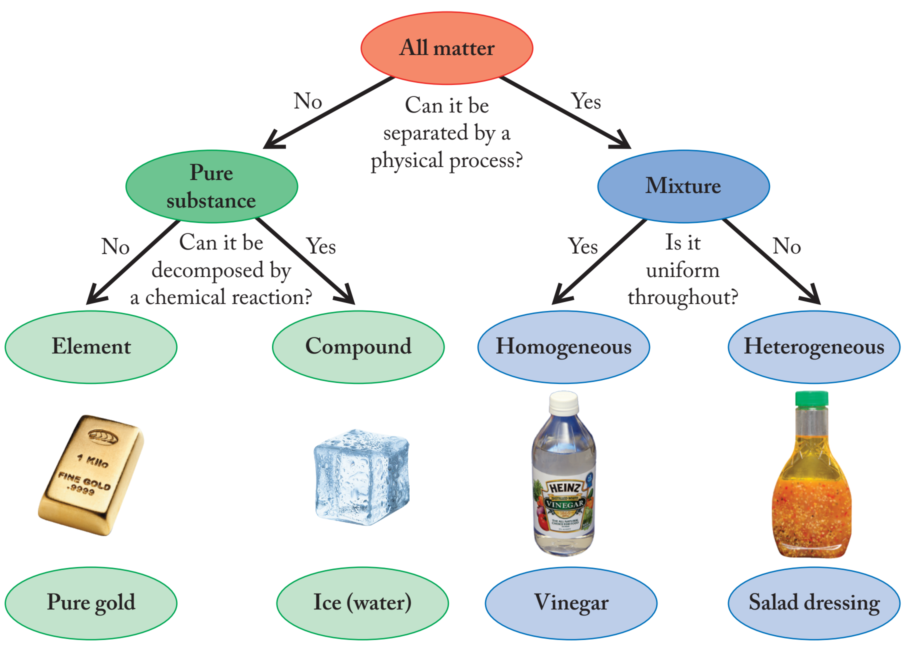


FIGURE 1.2 Matter is classified as shown in this diagram. The two principal categories are pure substances and mixtures. A pure substance may be a compound (such as water) or an element (such as gold). When the substances making up a mixture are distributed uniformly, as in vinegar (a mixture of acetic acid and water), the mixture is homogeneous. When the substances making up a mixture are not distributed uniformly, as in salad dressing, the mixture is heterogeneous. We explore those categories in Section 1.3.

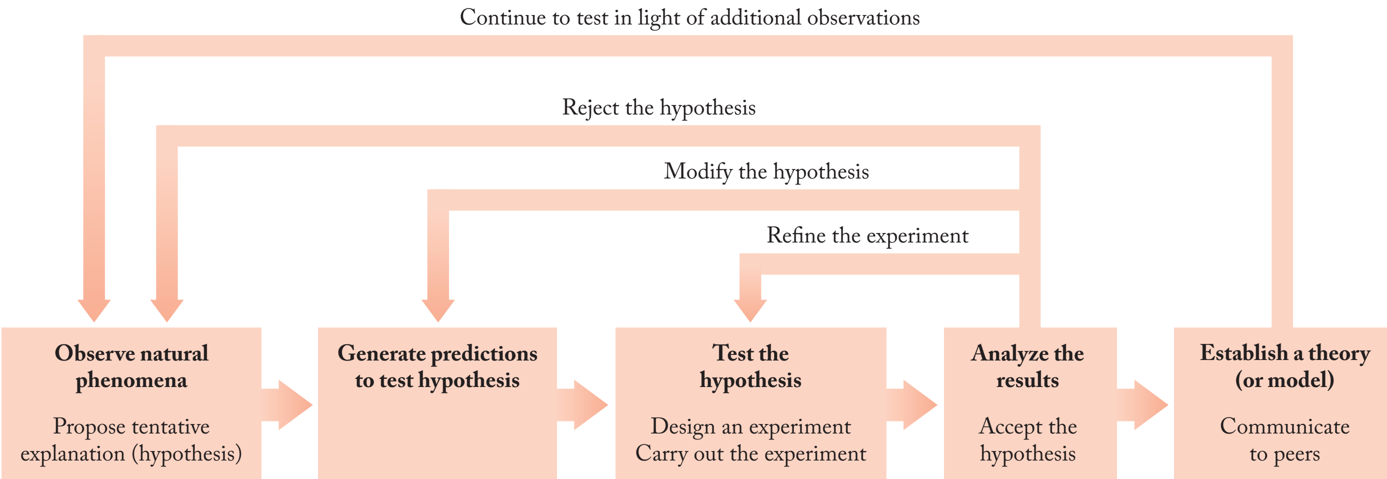


FIGURE 1.3 Using scientific methods, observations lead to a tentative explanation, or hypothesis, which leads to more observations and testing, which in turn may lead to the formulation of a succinct, comprehensive explanation called a theory. That process is rarely linear; it often involves looping back because the results of one test lead to additional tests and a revised hypothesis. Science, when done right, is a dynamic and self-correcting process.

mixtures of two compounds with different compositions, which Proust was able to demonstrate. Still, accepting Proust's law required more than corroborating results from other scientists; the law also needed to be explained by a scientific theory. That is, scientists needed a convincing argument that explained *why* the composition of a compound is always the same, no matter its source.

Scientific laws and theories complement each other in that scientific laws describe natural phenomena and relationships, and scientific theories explain *why* those phenomena and relationships are always observed. Scientific theories usually start out as tentative explanations of why a set of experimental results was obtained or why a particular phenomenon is consistently observed. Such a tentative explanation is called a **hypothesis**. An important feature of a hypothesis is that it can be tested through additional observations and experiments. A hypothesis also enables scientists to accurately predict the likely outcomes of observations and experiments. Further testing and observation might support a hypothesis, disprove it, or require that it be modified. A hypothesis that withstands the tests of many experiments, accurately explaining further observations and accurately predicting the results of additional experimentation, may be elevated to the rank of scientific theory.

In 1803, English chemist John Dalton (1746–1844) proposed a scientific theory explaining Proust's law of definite proportions. Dalton observed that when two elements react to form gaseous compounds, they may form two or more compounds with different compositions. Dalton's findings with gaseous compounds agreed with findings from Proust's experiments with solid compounds. Proust had discovered that tin (Sn) and oxygen (O) combined to form one compound that was 88.1% by mass Sn and 11.9% O, and a second compound that was 78.8% Sn and 21.2% O. Dalton realized that the ratio of oxygen to tin in the second compound,

$$\frac{21.2\%\ \text{O}}{78.8\%\ \text{Sn}} = 0.269$$

was very close to twice what it was in the first compound,

$$\frac{11.9\%\ \text{O}}{88.1\%\ \text{Sn}} = 0.135$$

Similar results were obtained with other sets of compounds also formed by pairs of elements. Sometimes their compositions would differ by a factor of 2, as with oxygen and tin, and sometimes their compositions differed by other factors—but

Dalton showed that the compositions always differed *by ratios of small whole numbers*. That pattern led Dalton to formulate the **law of multiple proportions**: when two elements combine to make two (or more) compounds, the ratio of the masses of one of the elements that combine with a given mass of the second element is always a ratio of small whole numbers. For example, 15 grams of oxygen combines with 10 grams of sulfur under one set of reaction conditions, whereas only 10 grams of oxygen combines with 10 grams of sulfur to form a different compound under a different set of reaction conditions. The ratio of the two masses of oxygen

$$\frac{15 \cancel{\text{ g oxygen}}}{10 \cancel{\text{ g oxygen}}} = \frac{3}{2}$$

is indeed a ratio of two small whole numbers and is consistent with Dalton's law of multiple proportions.

To explain the laws of definite proportions and multiple proportions, Dalton proposed the scientific theory that *elements are composed of atoms*. Thus, Proust's compound with the O:Sn ratio of 0.135 contains one atom of oxygen for each atom of tin, whereas his compound with twice that O:Sn ratio (0.269) contains *two* atoms of O per atom of Sn. Those atomic ratios are reflected in the **chemical formulas** of the two compounds: SnO and SnO_2, in which the subscripts after the symbols represent the relative number of atoms of each element in the substance. The absence of a subscript means the formula contains one atom of the preceding element. Similarly, the two compounds that sulfur and oxygen form have an oxygen ratio of 3:2 because their chemical formulas are SO_3 and SO_2, respectively.

Since the early 1800s, scientists have learned much more about the atomic, and even subatomic, structure of the matter that makes up our world and the universe that surrounds us. Although the laws developed two centuries ago are still useful, Dalton's atomic theory, like many theories, has undergone revisions as new discoveries have been made. Dalton assumed, for example, that all the atoms of a particular element were the same. However, we will learn in Chapter 2 that atoms have internal components and structures, only some of which are the same for all the atoms of a given element. Atoms can differ in other ways, too, that the scientists of centuries ago could not have observed or even imagined.

hypothesis a tentative and testable explanation for an observation or a series of observations.

law of multiple proportions the principle that, when two masses of one element react with a given mass of another element to form two compounds, the two masses of the first element have a ratio of two small whole numbers.

chemical formula a notation that uses the symbols of the elements to represent the elemental composition of a pure substance; subscripts indicate the relative number of atoms of each element in the substance.

1.2 COAST: A Framework for Solving Problems

Throughout this chapter and book, you will find Sample Exercises designed to help you better understand chemical concepts and develop your problem-solving skills. Each Sample Exercise follows a systematic approach to problem solving and is followed by a Practice Exercise that can be solved using a similar approach. We also encourage you to apply that approach to the end-of-chapter problems. We use the acronym COAST (**C**ollect and **O**rganize, **A**nalyze, **S**olve, and **T**hink about the answer) to represent the four steps in our problem-solving approach. As you read about it here and use it later, keep in mind that COAST is merely a *framework* for solving problems, not a recipe. Use it as a guide to develop your own approach to solving problems.

Collect and Organize The first step in solving a problem is to decide how to use the given information. Identify the key concepts of the problem and define the key terms used to express those concepts. Restating the problem in your own words might be useful. Sort through the information given in the problem to separate what is relevant from what is not. Then assemble the relevant information along with any supplemental information that may be needed, such as equations, definitions, and the values of constants.

Analyze The next step is to analyze the information you have collected to determine how to connect it to the answer you seek. Sometimes working backward to create the relationships may be easier: consider the nature of the answer first and think about how you might get to it from the information given in the problem and other sources. That approach might mean finding some intermediate quantity to use in a later step. If the problem is quantitative and requires a numerical answer, the units of the initial values and the final answer may help you identify how they are connected and which equation(s) may be useful. Consider rearranging equations to solve for an unknown.

For some problems, drawing a sketch based on molecular models or on an experimental setup may help you visualize how the starting points and final answer can be connected. You also should look at the numbers involved and estimate an answer. Having an order-of-magnitude ("ballpark") estimate of your final answer before entering numbers into your calculator can serve as a check on the accuracy of your calculated answer.

Some Sample Exercises test your understanding of a single concept or require only a single-step calculation. In those exercises we may combine the Collect and Organize with the Analyze steps.

Solve For most conceptual questions, the solution flows directly from your analysis of the problem. To solve quantitative problems, you need to insert the starting values and the appropriate constants into the relevant equations and then calculate the answer. Make sure that units are consistent and cancel as needed and that the certainty of the answer is reflected by an appropriate number of *significant figures* (we discuss significant figures in Section 1.7 and conversion factors in Section 1.8).

Think About It Finally, you need to think about your result. Does your answer make sense in the context of your own experience and what you have just learned? Is the value for a quantitative answer reasonable—is it close to your estimate from the Analyze step? Are the units correct and the number of significant figures appropriate? Then ask yourself how confident you are that you could solve another problem, perhaps drawn from another context but based on the same chemical concept. You may also think about how the problem relates to other observations you may have made about matter in your daily life.

The COAST approach should help you solve problems logically and avoid certain pitfalls, such as grabbing an equation that seems to have the right variables and simply plugging numbers into it or resorting to trial and error. As you study the steps in each Sample Exercise, try to answer these questions: **What** is done in this step? **How** is it done? **Why** is it done? After answering those questions, you will be ready to solve the Practice Exercises and end-of-chapter problems systematically.

1.3 Classes and Properties of Matter

Everything that we can see, touch, smell, or feel—from the air we breathe to the ground we walk on—is a form of matter. Scientists define **matter** as everything in the universe that has **mass (*m*)** and occupies space. **Chemistry** is the study of the composition, structure, and properties of matter and the changes it undergoes.

matter anything that has mass and occupies space.

mass (*m*) the property that defines the quantity of matter in an object.

chemistry the study of the composition, structure, and properties of matter and of the energy consumed or given off when matter undergoes a change.

pure substance matter that has a constant composition and cannot be broken down to simpler matter by any physical process.

physical process a transformation of a sample of matter, such as a change in its physical state, that does not alter the chemical identity of any substance in the sample; also called *physical change*.

intensive property a property that is independent of the amount of substance.

extensive property a property that varies with the amount of substance.

physical property a property of a substance that can be observed without changing the substance into another substance.

Matter is classified according to its composition, as we saw in Figure 1.2. The simplest forms of matter—elements and compounds—are **pure substances**, such as gold or water, that cannot be separated into simpler substances by any physical process. A **physical process** (or *physical change*) in a sample of matter refers to a transformation that does not alter the chemical identities of any substance in the sample, such as melting ice.

Pure substances have distinctive properties. Pure gold, for example (**Figure 1.4a**), has a characteristic color, is a soft metal, is malleable (it can be hammered into very thin sheets called gold leaf), is ductile (it can be drawn into thin wires), and melts at 1064°C. Those properties, which characterize a pure substance but are independent of the amount of the substance in a sample, are called **intensive properties**. Other properties, such as the particular length, width, mass, and volume of an ingot of gold, are called **extensive properties** because they depend on how much of the substance is present in a particular sample.

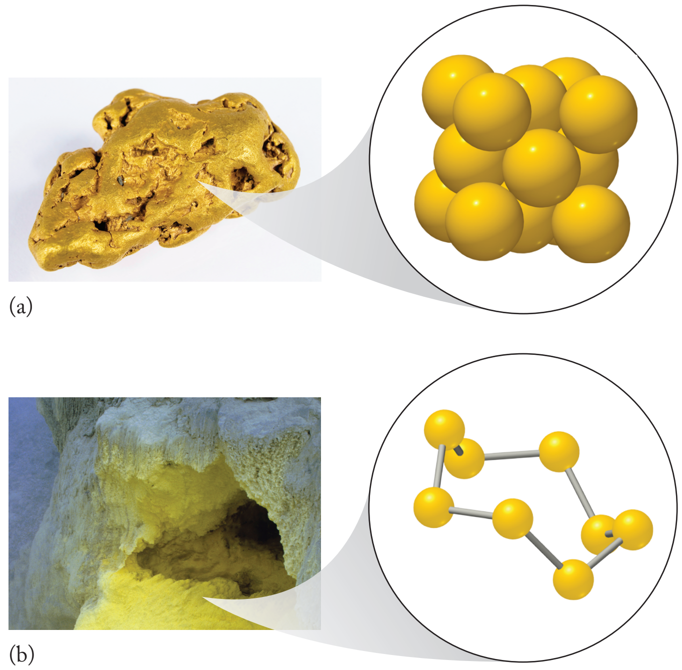


FIGURE 1.4 (a) Gold and (b) sulfur are among the few elements that occur in nature uncombined with other elements.

The properties of substances are either *physical* or *chemical*. **Physical properties**, such as those just described for gold, can be observed or measured without changing the substance into another substance. Another physical property is **density (*d*)**, which is the ratio of the mass (*m*) of a substance or object to its volume (*V*):

$$d = \frac{m}{V} \tag{1.1}$$

CONCEPT TEST

Which properties of a sample of pure iron are intensive? (a) mass; (b) density; (c) volume; (d) hardness

(Answers to Concept Tests are in the back of the book.)

Gold is one of the few elements that occurs in nature uncombined with other elements, as is sulfur (**Figure 1.4b**). The tendencies of most elements to react with other substances—that is, to be transformed in **chemical reactions** into compounds with different chemical identities and properties—represent the **chemical properties** of the elements. Chemical properties include whether or not a particular element reacts with another element or with a particular compound. They also include how rapidly the reactions take place and what products are formed.

Throughout this book we will see many examples of how the properties of substances are linked to the behavior of the particles that form them, including how those particles interact with the particles that form other substances. Those particles may be atoms, but they may also be groups of atoms held together in a characteristic pattern by forces called **chemical bonds**. Many of those groups of atoms are *neutral* **molecules**, meaning that they have no net electrical charge. However, some atoms or molecules acquire a net positive or negative electrical charge, and therefore we refer to them as monatomic (single-atom) or polyatomic (many-atom) **ions**. We will discuss how and why ions form in Chapter 2, but for now the key point is that the particles that make up elements and compounds may be atoms, molecules, or ions.

density (*d*) the ratio of the mass (*m*) of an object to its volume (*V*).

chemical reaction the conversion of one or more substances into one or more different substances; also called *chemical change*.

chemical property a property of a substance that can be observed only by reacting the substance with something else to form another substance.

chemical bond a force that holds two atoms or ions in a molecule or a compound together.

molecule a collection of chemically bonded atoms.

ion a particle consisting of one or more atoms that has a net positive or negative charge.