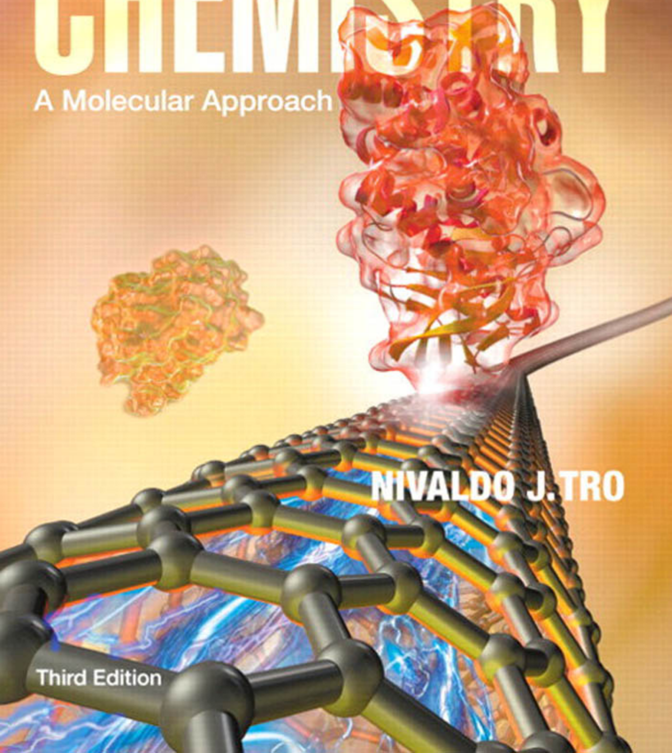
CHEMISTRY

A Molecular Approach



NIVALDO J. TRO

Third Edition

CHEMISTRY

A Molecular Approach

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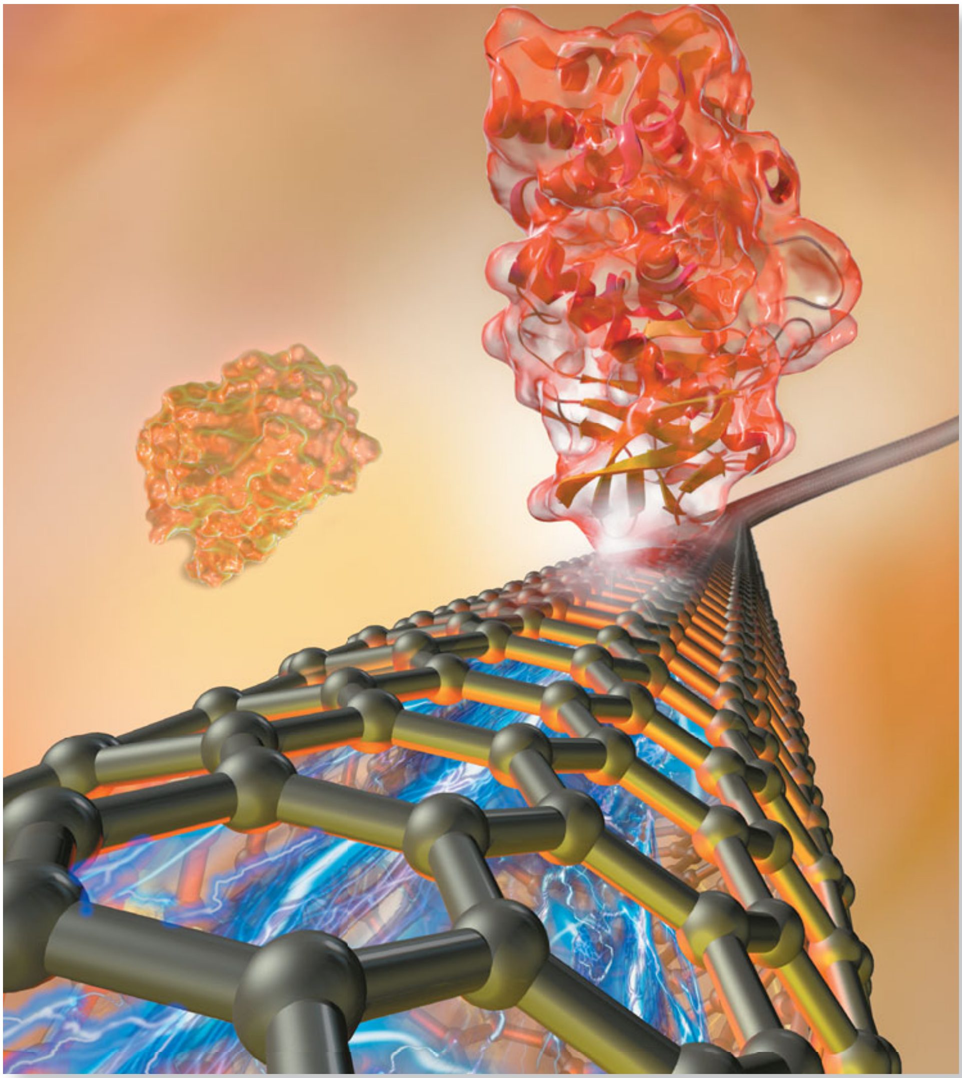

NIVALDO J. TRO

Westmont College

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To Michael, Ali, Kyle, and Kaden

About the Author

NIVALDO TRO is a professor of chemistry at Westmont College in Santa Barbara, California, where he has been a faculty member since 1990. He received his Ph.D. in chemistry from Stanford University for work on developing and using optical techniques to study the adsorption and desorption of molecules to and from surfaces in ultrahigh vacuum. He then went on to the University of California at Berkeley, where he did postdoctoral research on ultrafast reaction dynamics in solution. Since coming to Westmont, Professor Tro has been awarded grants from the American Chemical Society Petroleum Research Fund, from Research Corporation, and from the National Science Foundation to study the dynamics of various processes occurring in thin adlayer films adsorbed on dielectric surfaces. He has been honored as Westmont's outstanding teacher of the year three times and has also received the college's outstanding researcher of the year award. Professor Tro lives in Santa Barbara with his wife, Ann, and their four children, Michael, Ali, Kyle, and Kaden. In his leisure time, Professor Tro enjoys mountain biking, surfing, reading to his children, and being outdoors with his family.

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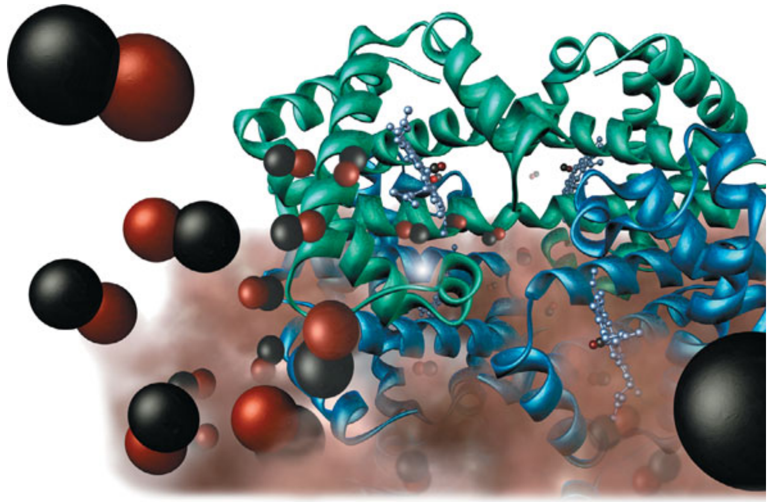

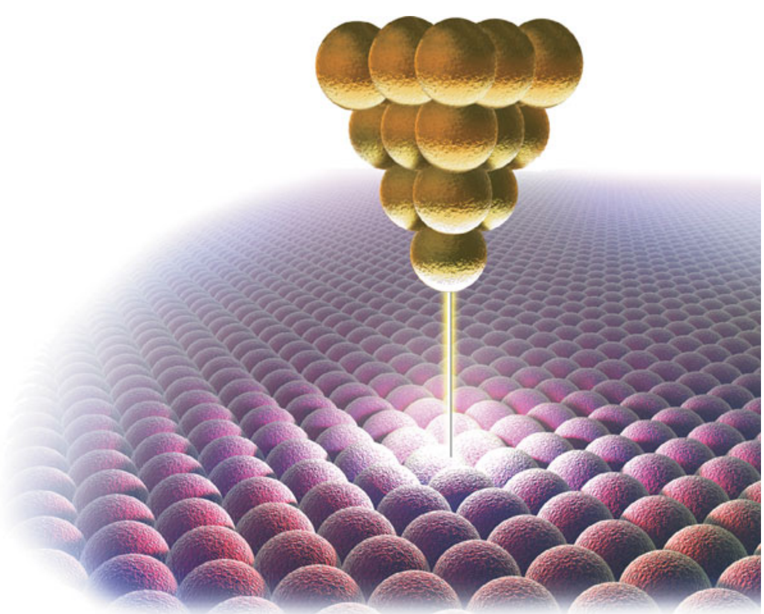

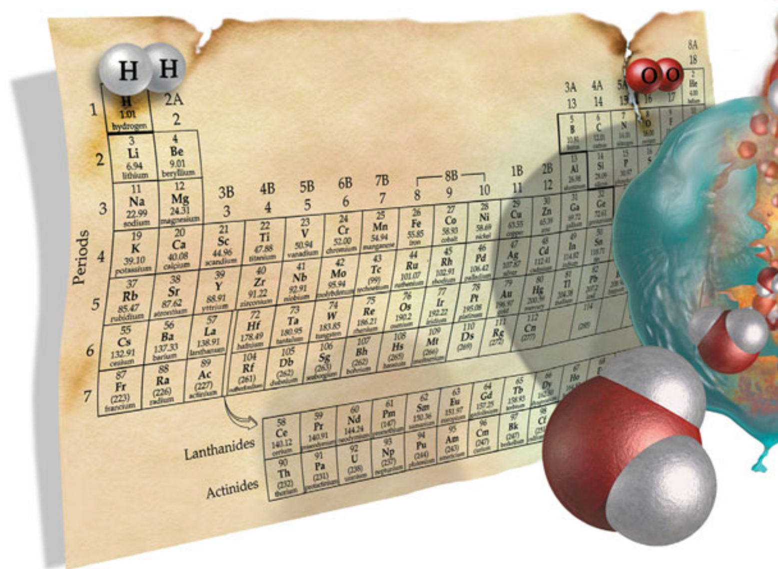

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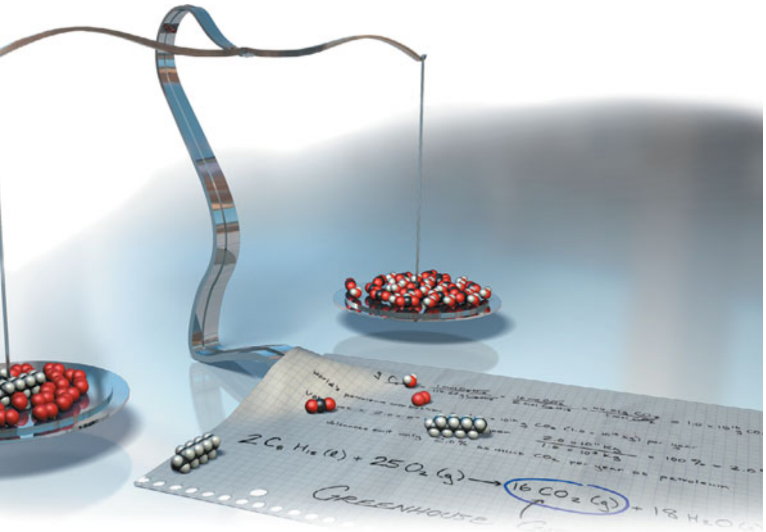


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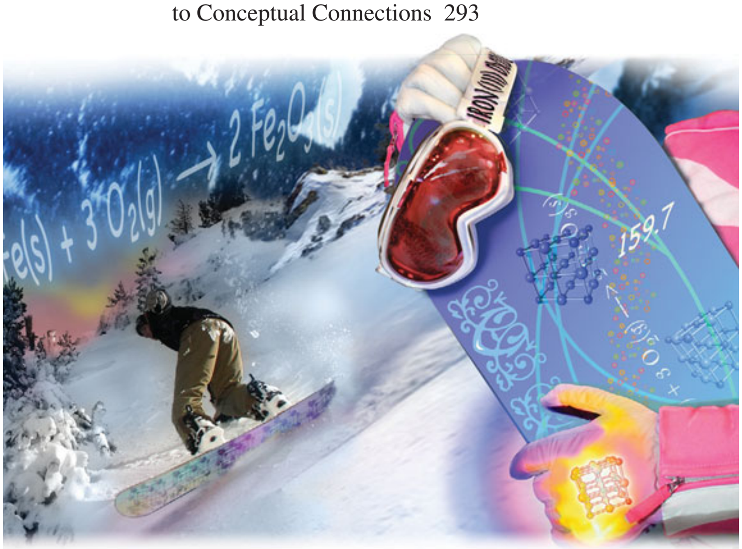
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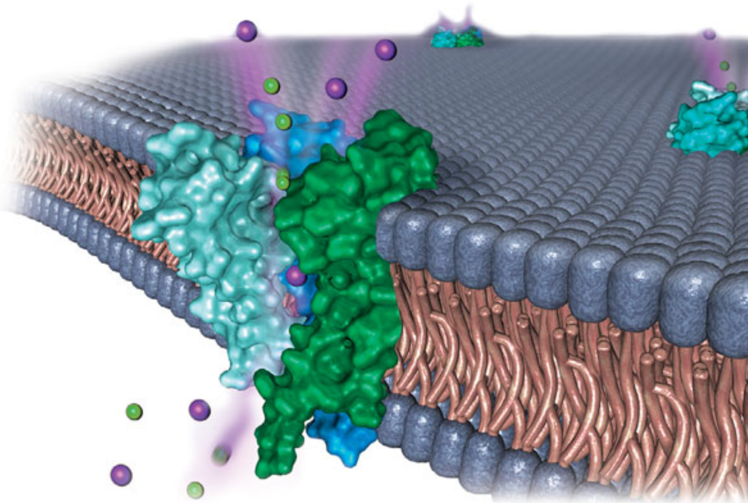

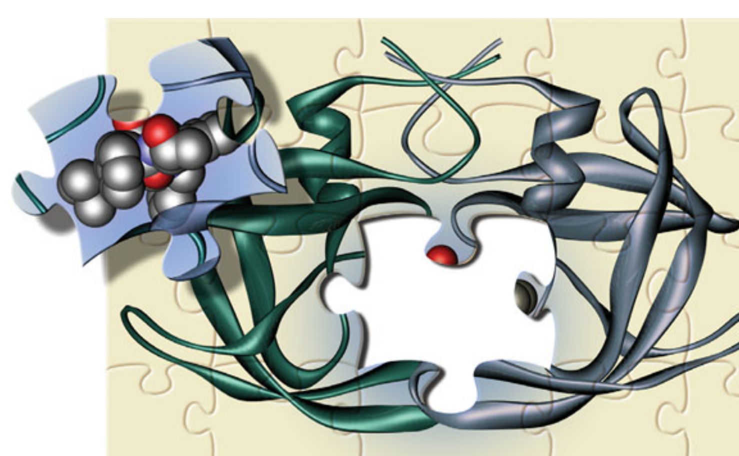

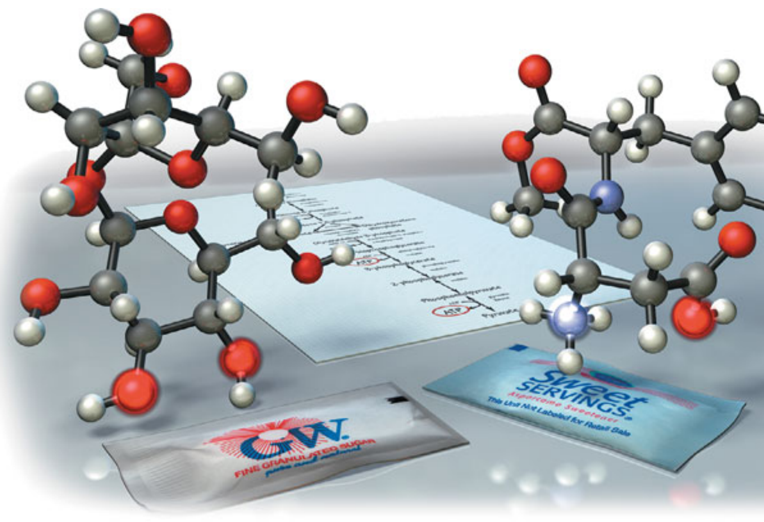

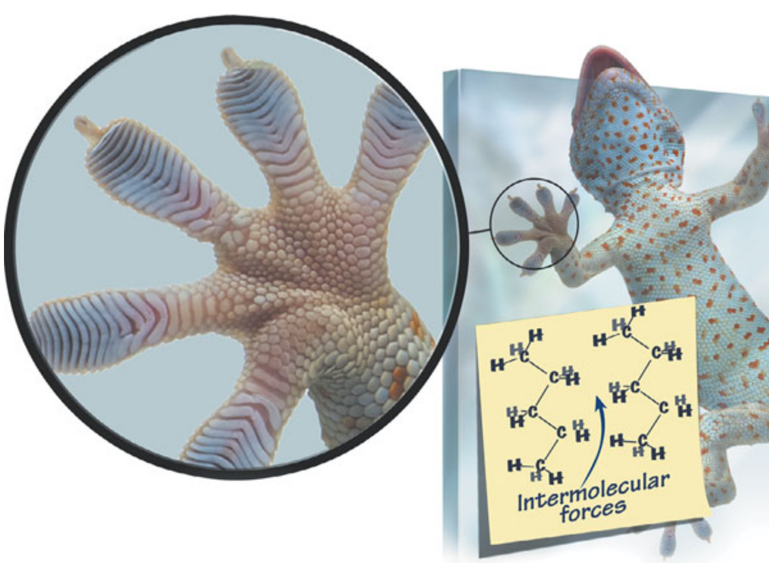
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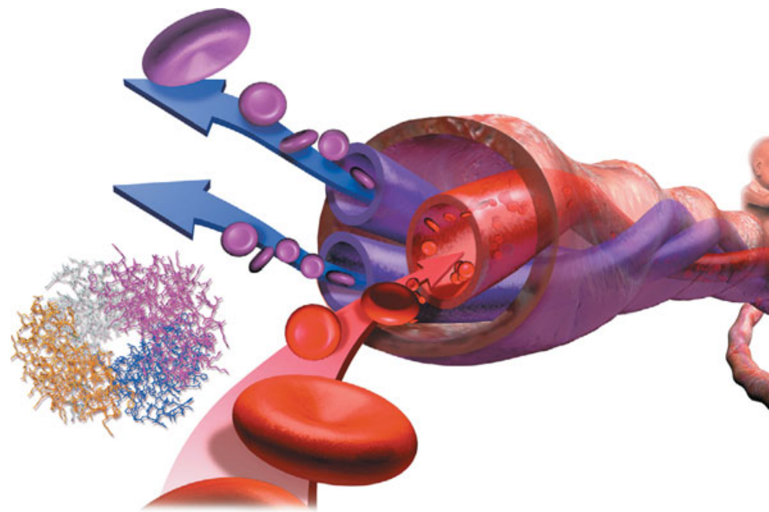

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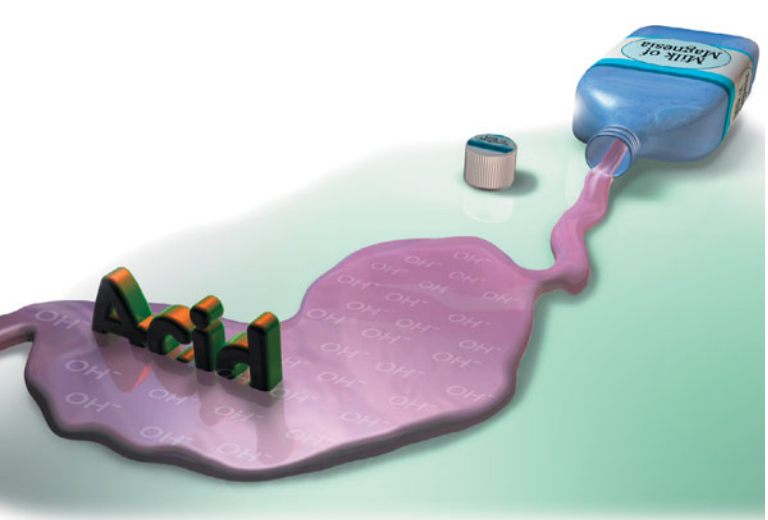

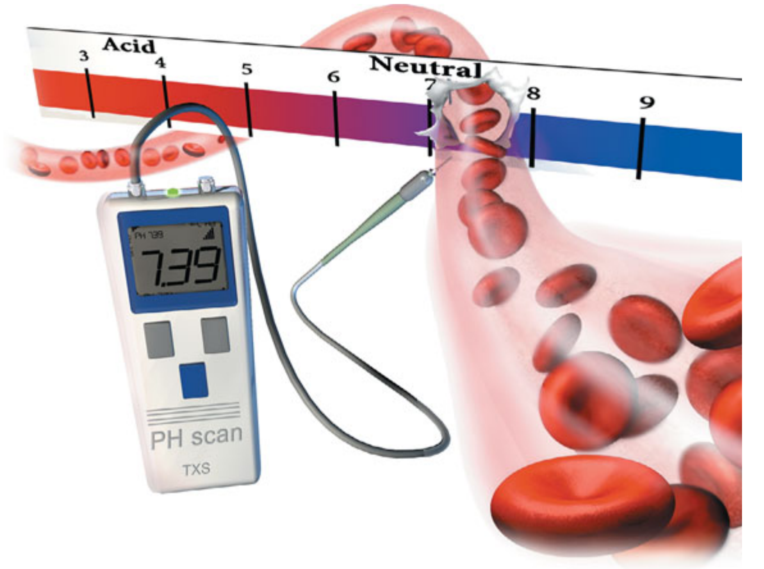
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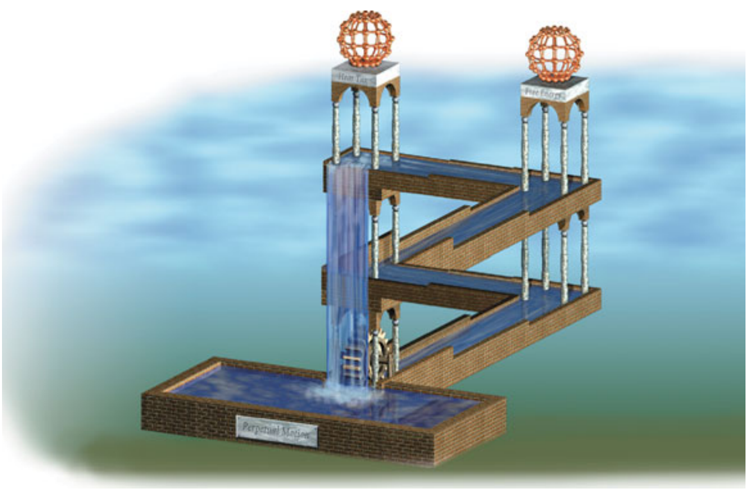


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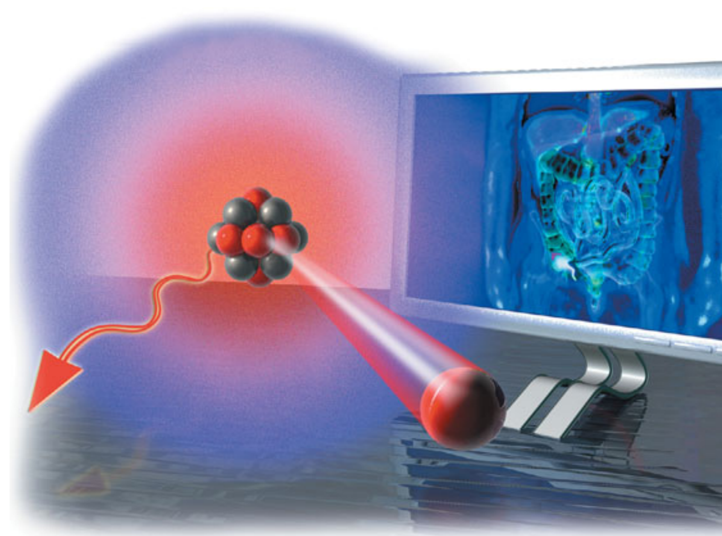

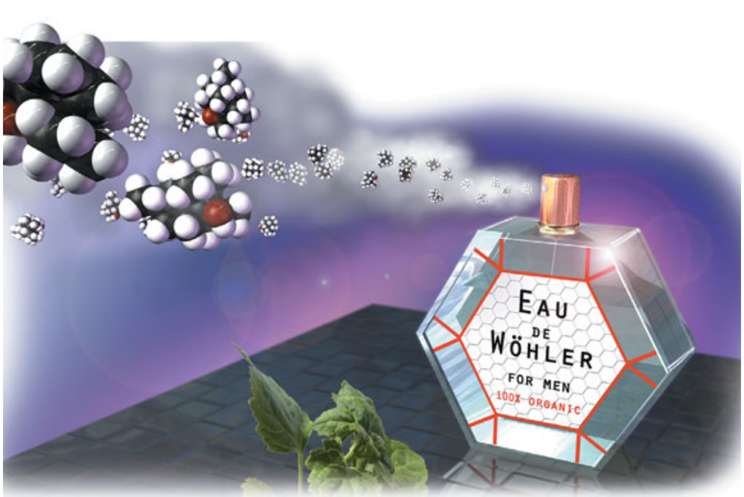
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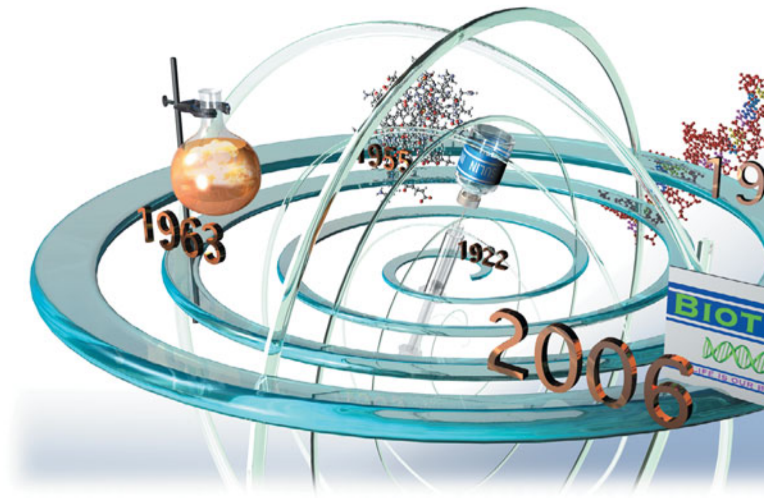
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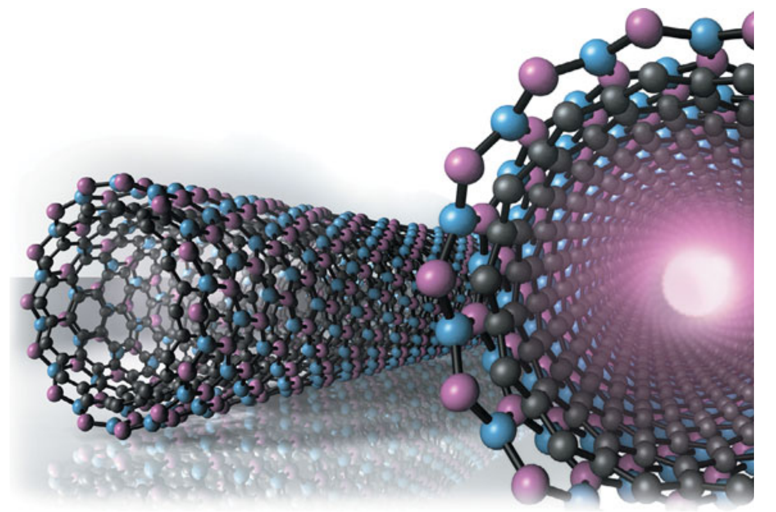


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Preface

To the Student

As you begin this course, I invite you to think about your reasons for enrolling in it. Why are you taking general chemistry? More generally, why are you pursuing a college education? If you are like most college students taking general chemistry, part of your answer is probably that this course is required for your major and that you are pursuing a college education so you can get a good job some day. While these are good reasons, I would like to suggest a better one. I think the primary reason for your education is to prepare you to *live a good life*. You should understand chemistry—not for what it can *get* you—but for what it can *do* to you. Understanding chemistry, I believe, is an important source of happiness and fulfillment. Let me explain.

Understanding chemistry helps you to live life to its fullest for two basic reasons. The first is *intrinsic*: through an understanding of chemistry, you gain a powerful appreciation for just how rich and extraordinary the world really is. The second reason is *extrinsic*: understanding chemistry makes you a more informed citizen—it allows you to engage with many of the issues of our day. In other words, understanding chemistry makes *you* a deeper and richer person and makes your country and the world a better place to live. These reasons have been the foundation of education from the very beginnings of civilization.

How does chemistry help prepare you for a rich life and conscientious citizenship? Let me explain with two examples. My first one comes from the very first page of Chapter 1 of this book. There, I ask the following question: What is the most important idea in all of scientific knowledge? My answer to that question is this: **the behavior of matter is determined by the properties of molecules and atoms**. That simple statement is the reason I love chemistry. We humans have been able to study the substances that compose the world around us and explain their behavior by reference to particles so small that they can hardly be imagined. If you have never realized the remarkable sensitivity of the world we *can* see to the world we *cannot*, you have missed out on a fundamental truth about our universe. To have never encountered this truth is like never having read a play by Shakespeare or seen a sculpture by Michelangelo—or, for that matter, like never having discovered that the world is round. It robs you of an amazing and unforgettable experience of the world and the human ability to understand it.

My second example demonstrates how science literacy helps you to be a better citizen. Although I am largely sympathetic to the environmental movement, a lack of science literacy within some sectors of that movement, and the resulting anti-environmental backlash, creates confusion that impedes real progress and opens the door to what could be misinformed policies. For example, I have heard conservative pundits say that volcanoes emit more carbon dioxide—the most significant greenhouse gas—than does petroleum combustion. I have also heard a liberal environmentalist say that we have to stop using hairspray because it is causing holes in the ozone layer that will lead to global warming. Well, the claim about volcanoes emitting more carbon dioxide than petroleum combustion can be refuted by the basic tools you will learn to use in Chapter 4 of this book. We can easily show that volcanoes emit only 1/50th as much carbon dioxide as petroleum combustion. As for hairspray depleting the ozone layer and thereby leading to global warming, the chlorofluorocarbons that deplete ozone have been banned from hairspray since 1978, and ozone depletion has nothing to do with global warming anyway. People with special interests or axes to grind can conveniently distort the truth before an ill-informed public, which is why we all need to be knowledgeable.

So this is why I think you should take this course. Not just to satisfy the requirement for your major, and not just to get a good job some day, but to help you to lead a fuller life and to make the world a little better for everyone. I wish you the best as you embark on the journey to understand the world around you at the molecular level. The rewards are well worth the effort.

To the Professor

First and foremost, thanks to all of you who adopted this book in its first and second editions. You helped to make this book one of the most popular general chemistry textbooks in the world. I am grateful beyond words. Second, I have listened carefully to your feedback on the previous edition. The changes you see in this edition are the direct result of your input, as well as my own experience using the book in my general chemistry courses. If you have acted as a reviewer or have contacted me directly, you will likely see your suggestions reflected in the changes I have made. Thank you.

In spite of the changes I just mentioned, the goal of the book remains the same: *to present a rigorous and accessible treatment of general chemistry in the context of relevance.* Teaching general chemistry would be much easier if all of our students had exactly the same level of preparation and ability. But alas, that is not the case. Even though I teach at a relatively selective institution, my courses are populated with students with a range of backgrounds and abilities in chemistry. The challenge of successful teaching, in my opinion, is therefore figuring out how to instruct and challenge the best students while not losing those with lesser backgrounds and abilities. My strategy has always been to set the bar relatively high, while at the same time providing the motivation and support necessary to reach the high bar. That is exactly the philosophy of this book. We do not have to compromise away rigor in order to make chemistry accessible to our students. In this book, I have worked hard to combine rigor with accessibility—to create a book that does not dilute the content, yet can be used and understood by any student willing to put in the necessary effort.

Chemistry: A Molecular Approach is first and foremost a *student-oriented book*. My main goal is to motivate students and get them to achieve at the highest possible level. As we all know, many students take general chemistry because it is a requirement; they do not see the connection between chemistry and their lives or their intended careers. *Chemistry: A Molecular Approach* strives to make those connections consistently and effectively. Unlike other books, which often teach chemistry as something that happens only in the laboratory or in industry, this book teaches chemistry in the context of relevance. It shows students *why* chemistry is important to them, to their future careers, and to their world.

Chemistry: A Molecular Approach is secondly a *pedagogically driven book*. In seeking to develop problem-solving skills, a consistent approach (Sort, Strategize, Solve, and Check) is applied, usually in a two- or three-column format. In the two-column format, the left column shows the student how to analyze the problem and devise a solution strategy. It also lists the steps of the solution, explaining the rationale for each one, while the right column shows the implementation of each step. In the three-column format, the left column outlines the general procedure for solving an important category of problems that is then applied to two side-by-side examples. This strategy allows students to see both the general pattern and the slightly different ways in which the procedure may be applied in differing contexts. The aim is to help students understand both the *concept of the problem* (through the formulation of an explicit conceptual plan for each problem) and the *solution to the problem.*

Chemistry: A Molecular Approach is thirdly a *visual book.* Wherever possible, images are used to deepen the student's insight into chemistry. In developing chemical principles, multipart images help to show the connection between everyday processes visible to the unaided eye and what atoms and molecules are actually doing. Many of these images have three parts: macroscopic, molecular, and symbolic. This combination helps students to see the relationships between the formulas they write down on paper (symbolic), the world they see around them (macroscopic), and the atoms and molecules that compose that world (molecular). In addition, most figures are designed to teach rather than just to illustrate. They are rich with annotations and labels intended to help the student grasp the most important processes and the principles that underlie them. The resulting images are rich with information but also uncommonly clear and quickly understood.

Chemistry: A Molecular Approach is fourthly a *"big picture" book*. At the beginning of each chapter, a short paragraph helps students to see the key relationships between the different topics they are learning. Through a focused and concise narrative, I strive to make the basic ideas of every chapter clear to the student. Interim summaries are provided at selected spots in the narrative, making it easier to grasp (and review) the main points of important discussions. And to make sure that students never lose sight of the forest for the trees, each chapter includes several *Conceptual Connections,* which ask them to think about concepts and solve problems without doing any math. I want students to learn the concepts, not just plug numbers into equations to churn out the right answer.

Chemistry: A Molecular Approach is lastly a book that delivers the depth of coverage faculty want. We do not have to cut corners and water down the material in order to get our students interested. We simply have to meet them where they are, challenge them to the highest level of achievement, and then support them with enough pedagogy to allow them to succeed.

I hope that this book supports you in your vocation of teaching students chemistry. I am increasingly convinced of the importance of our task. Please feel free to email me with any questions or comments about the book.

Nivaldo J. Tro
tro@westmont.edu

What's New in This Edition?

The book has been extensively revised and contains more small changes than can be detailed here. I have detailed the most significant changes to the book and its supplements below.

- I have added a 10–15 question multiple-choice end-of-chapter Self Assessment Quiz to each chapter. Since many colleges and universities utilize multiple-choice exams, and because standardized final exams are often multiple choice, these quizzes are meant for students to self test their basic knowledge and skills for each chapter.
- I have added approximately 50 new Conceptual Connection questions throughout the book. I have also moved the answers to all Conceptual Connections from within the chapter to the end-of-chapter material.
- I have updated all data throughout the book to reflect the most recent measurements available. These updates include *Figure 4.2 Carbon Dioxide in the Atmosphere; Figure 4.3 Global Temperatures; Figure 4.25 U.S. Energy Consumption; Table 13.4 Change in Pollutant Levels*; *Figure 13.19 Ozone Depletion in the Antarctic Spring; Figure 15.15 Sources of U.S. Energy; Figure 15.16 Acid Rain;* and *Figure 15.18 U.S. Sulfur Dioxide Pollutant Levels*.
- I have added a new *Chemistry in Your Day: Evolving Atomic Masses* box to Section 2.9 to address the recent changes in IUPAC atomic masses. I have modified the atomic masses of Li, S, and Ge throughout the book to reflect these changes.
- I have added new material in which students must interpret mass spectra to Section 2.8. This material includes a new unnumbered figure and new end-of-chapter problems.
- I have added a new section (Section 3.7 *Summary of Inorganic Nomenclature*) that includes a new in-chapter figure (Figure 3.10) and a new example (Example 3.11). This new material summarizes nomenclature and allows the student to learn how to name a compound without the compound being pre-classified.
- I have added a new example (Example 3.24) on balancing chemical equations containing ionic compounds with polyatomic ions.
- I have replaced Section 7.1 with a new chapter opener entitled *Schrödinger's Cat*. The opener includes new art depicting Erwin Schrödinger's desk.

- I have expanded and clarified the description of the photoelectric effect and the particle nature of light in Section 7.2, including a new figure (Figure 7.9) that depicts a graph of the rate of electron ejection from a metal versus the frequency of light used.
- I have moved the introduction of the fourth quantum number, m_s, the spin quantum number, from Chapter 8 to Section 7.5.
- I have added a new example to Chapter 9 (Example 9.9).
- I have changed the wedge notation used to draw 3D structures (first introduced in Section 10.4) to reflect current trends in this notation.
- I have added electrostatic potential maps for a number of molecules in Chapter 11 to help students better visualize polarity and interactions between polar molecules.
- I have updated all of the energy statistics in Section 15.12.
- I have added information about the Fukushima nuclear accident added to Section 19.7. I have also updated the content about the proposed nuclear waste storage facility in Yucca Mountain, Nevada.
- I have revised the Key Concepts end-of-chapter material so that it is now in a bulleted list format for all chapters for easy student review.
- I have added or modified approximately 60 end-of-chapter problems.
- I have enlarged many key figures throughout text.

Supplements

For the Instructor

MasteringChemistry® is the best adaptive-learning online homework and tutorial system. Instructors can create online assignments for their students by choosing from a wide range of items, including end-of-chapter problems and research-enhanced tutorials. Assignments are automatically graded with up-to-date diagnostic information, helping instructors pinpoint where students struggle either individually or as a class as a whole.

Instructor Resource DVD (0-321-81363-4) This DVD provides an integrated collection of resources designed to help instructors make efficient and effective use of their time. It features four pre-built PowerPoint™ presentations. The first presentation contains all the images/figures/tables from the text embedded within the PowerPoint slides, while the second includes a complete modifiable lecture outline. The final two presentations contain worked "in-chapter" sample exercises and questions to be used with Classroom Response Systems. This DVD also contains movies and animations, as well as the TestGen version of the Test Bank, which allows instructors to create and tailor exams to their needs.

Solutions Manual (0-321-81376-6) Prepared by MaryBeth Kramer of the University of Delaware and Kathleen Thrush Shaginaw, this manual contains step-by-step solutions to all complete, end-of-chapter exercises. The Solutions Manual to accompany the second edition has been extensively revised. All problems have been accuracy checked and the design has been upgraded to improve clarity and ease of use. With instructor permission, this manual may be made available to students.

Instructor Resource Manual (0-321-81354-5) Organized by chapter, this useful guide includes objectives, lecture outlines, references to figures and solved problems, as well as teaching tips.

Printed Test Bank (0-321-81367-7) Prepared by Christine Hermann of Radford University. The printed test bank contains more than 2000 multiple choice, true/false, and short-answer questions. The third edition also contains more than 1400 algorithmic questions.

Blackboard® and WebCT® All test questions are available formatted for either Blackboard or WebCT. These are available for download at www.pearsonhighered.com/chemistry.

For the Student

MasteringChemistry® provides students with two learning systems: an extensive self-study area with an interactive eBook and the most widely used chemistry homework and tutorial system (if an instructor chooses to make online assignments part of the course).

Pearson eText The integration of Pearson eText within MasteringChemistry® gives students, with new books, easy access to the electronic text when they are logged into MasteringChemistry. Pearson eText pages look exactly like the printed text, offering powerful new functionality for students and instructors. Users can create notes, highlight text in different colors, create bookmarks, zoom, view in single-page or two-page view, etc.

Selected Solutions Manual (0-321-81364-2) Prepared by MaryBeth Kramer of the University of Delaware and Kathleen Thrush Shaginaw, this manual for students contains complete, step-by-step solutions to selected odd-numbered end-of-chapter problems. The Selected Solutions Manual to accompany the third edition has been extensively revised. All problems have been accuracy checked and the design has been upgraded to improve clarity and ease of use.

Study Guide (0-321-81362-6) Prepared by Jennifer Shanoski of Merritt College. This Study Guide was written specifically to assist students using the third edition of *Chemistry: A Molecular Approach*. It presents the major concept, theories, and applications discussed in the text in a comprehensive and accessible manner for students. It contains learning objectives, chapter summaries, and outlines, as well as examples, self test, and concept questions.

Laboratory Manual (0-321-81377-4) Prepared by John B. Vincent and Erica Livingston, both of the University of Alabama. This manual contains 29 experiments with a focus on real-world applications. Each experiment contains a set of pre-laboratory questions, an introduction, a step-by-step procedure (including safety information), and a report section featuring post-laboratory questions. Additional features include a section on laboratory safety rules, an overview on general techniques and equipment, and a detailed tutorial on graphing data in Excel.

Acknowledgments

The book you hold in your hands bears my name on the cover, but I am really only one member of a large team that carefully crafted the first edition, the second edition, and now the third edition of this book. Most importantly, I thank my new editor on this edition, Terry Haugen. Terry is a great editor and friend. He gives me the right balance of freedom and direction and always supports me in my endeavors. Thanks Terry for all you have done for me and for general chemistry courses throughout the world. I am just as grateful for my project editor, Jennifer Hart, who has now worked with me on multiple editions of several books. Jennifer, your guidance, organizational skills, and wisdom are central to the success of my projects, and I am eternally grateful. New to this edition is Jessica Moro. Although we have only worked together a short while, I am already indebted to her helpfulness. I am also grateful to Erin Kneuer, who helped with organizing reviews, as well as numerous other tasks associated with keeping the team running smoothly. I also thank Erin Mulligan, who has now worked with me on several projects. Erin is an outstanding developmental editor who not only worked with me on crafting and thinking through every word, but also became a friend and fellow foodie in the process. I am also grateful to Adam Jaworski. His skills and competence have led the chemistry team since he took over as editor-in-chief. And of course, I am continually grateful for Paul Corey, with whom I have now worked for over 12 years and 9 projects. Paul is a man of incredible energy and vision, and it is my great privilege to work with him. Paul told me many years ago (when he first signed me on to the Pearson team) to dream big, and then he provided the resources I needed to make those dreams come true. *Thanks, Paul.* I would also like to thank my first editor at Pearson, Kent Porter-Hamann. Kent and I spent many good years together writing books, and I continue to miss her presence in my work.

New to the team is my marketing manager, Jonathan Cottrell, and although we have worked together for only a short while, I am already impressed by his energy in marketing this book. I continue to owe a special word of thanks to Glenn and Meg Turner of Burrston House, ideal collaborators whose contributions to the first edition of the book were extremely important and much appreciated. Quade and Emiko Paul, who make my ideas come alive with their art, have been with us from the beginning, and I owe a special debt of gratitude to them. I am also grateful to Mark Ong and Emily Friel for their creativity and hard work in crafting the design of this text; to Michelle Durgerian, Shari Toron, and Gina Cheselka, whose skill and diligence gave this book its physical existence; and to Connie Long who managed the extensive art program. Finally, I would like to thank my copyeditor and proofreader from the GEX Publishing Services editorial team for their dedication and professionalism, and Erin Schrader for his exemplary photo research. The team at Pearson is a first-class operation—this text has benefited immeasurably from their talents and hard work.

I acknowledge the great work of my colleague Mary Beth Kramer from the Chemistry Department at University of Delaware, who has been a co-author on the solutions manual for this book. Mary Beth Kramer worked tirelessly to ensure that the solutions manual was accurate and useful to students. Sadly, Professor Kramer passed away shortly before this book went to press. We will all miss her and her excellent work.

I acknowledge the help of my colleagues Allan Nishimura, Kristi Lazar, David Marten, Stephen Contakes, Michael Everest, and Carrie Hill who have supported me in my department while I worked on this book. I am also grateful to Gayle Beebe, the president of Westmont College, who has allowed me the time and space to work on my books. Thank you, Gayle, for allowing me to pursue my gifts and my vision. I am also grateful to those who have supported me personally. First on that list is my wife, Ann. Her patience and love for me are beyond description, and without her, this book would never have been written. I am also indebted to my children, Michael, Ali, Kyle, and Kaden, whose smiling faces and love of life always inspire me. I come from a large Cuban family whose closeness and support most people would envy. Thanks to my parents, Nivaldo and Sara; my siblings, Sarita, Mary, and Jorge; my siblings-in-law, Jeff, Nachy, Karen, and John; my nephews and nieces, Germain, Danny, Lisette, Sara, and Kenny. These are the people with whom I celebrate life.

I would like to thank all of the general chemistry students who have been in my classes throughout my 22 years as a professor at Westmont College. You have taught me much about teaching that is now in this book. I am especially grateful to Michael Tro who put in many hours proofreading my manuscript, working problems and quiz questions, and organizing art codes and appendices. Michael, you are an amazing kid—it is my privilege to have you work with me on this project. I would also like to express my appreciation to Josh Alamillo, Catherine Olson, Hannah Sievers, and Rose Corcoran, who were a tremendous help with the new self assessment quizzes.

I would like to thank Brian Woodfield from Brigham Young University, the students at the University of Kentucky, and the Pearson Student Advisory Board for helping me create the interactive worked examples.

Lastly, I am indebted to the many reviewers, listed on the following pages, whose ideas are imbedded throughout this book. They have corrected me, inspired me, and sharpened my thinking on how best to teach this subject we call chemistry. I deeply appreciate their commitment to this project. I am particularly grateful to Bob Boikess for his important contributions to the book. Thanks also to Frank Lambert for his review of the entropy sections in the first edition of the book, and to Diane K. Smith for her review of and input on the electrochemistry chapter. Last but by no means least, I would like to thank Nancy Lee for her suggestions on the origin of elements box, and Alyse Dilts, Tracey Knowles, Gary Mines, and Alison Soult for their help in reviewing page proofs.

Reviewers

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> —Matthew Joshua Buhr, Student, *University of South Dakota*

Telling the Story of Chemistry with

Chemistry is **relevant to every process** occurring around us, at every second. Niva Tro helps you understand this connection by weaving specific, vivid examples throughout the text that tell the story of chemistry. Every chapter begins with a brief story showing chemistry is relevant to all people, at every moment.

Relevant Stories and Examples

Tro opens each chapter by giving a specific example of the concept to grab students' attention, stepping back to make a more general and relatable analogy, and then going back into specifics. This style is reinforced by both his own classroom experiences and other successful science writers.

Problem Solving Reinforced by

A consistent **step-by-step framework** encourages thinking logically through the problem-solving process rather than simply memorizing formulas.

NEW! **40 Interactive Worked Examples** have been created for viewing on mobile devices. Interactive examples instruct you in breaking down problems with Tro's proven 'Sort, Strategize, Solve, and Check" technique and include questions asking students to predict the outcome.

Two-Column Example

The **left column** explains how the problem is solved.

A four-part structure (**"Sort, Strategize, Solve, Check"**) provides you with a framework for analyzing and solving problems.

Icons appear next to examples indicating that a digital version is available. See the ways to access listed on the facing page.

Many problems are solved with a **conceptual plan** that provides a visual outline of the steps leading from the given information to the solution.

The **right column** shows the implementation of the steps explained in the left column.

Every Worked Example is followed by "For Practice" Problems that you can try to solve on your own. Answers to "For Practice" Problems are in Appendix IV.

EXAMPLE 6.5 Measuring ΔE_{rxn} in a Bomb Calorimeter

When 1.010 g of sucrose ($C_{12}H_{22}O_{11}$) undergoes combustion in a bomb calorimeter, the temperature rises from 24.92 °C to 28.33 °C. Find ΔE_{rxn} for the combustion of sucrose in kJ/mol sucrose. The heat capacity of the bomb calorimeter, determined in a separate experiment, is 4.90 kJ/°C. (You can ignore the heat capacity of the small sample of sucrose because it is negligible compared to the heat capacity of the calorimeter.)

SORT You are given the mass of sucrose, the heat capacity of the calorimeter, and the initial and final temperatures. You are asked to find the change in internal energy for the reaction.

GIVEN: 1.010 g $C_{12}H_{22}O_{11}$, $T_i = 24.92$ °C, $T_f = 28.33$ °C, $C_{cal} = 4.90$ kJ/°C

FIND: ΔE_{rxn}

STRATEGIZE The conceptual plan has three parts. In the first part, use the temperature change and the heat capacity of the calorimeter to find q_{cal}.

CONCEPTUAL PLAN

$C_{cal}, \Delta T \rightarrow q_{cal}$ ($q_{cal} = C_{cal} \times \Delta T$)

In the second part, use q_{cal} to get q_{rxn} (which just involves changing the sign). Since the bomb calorimeter ensures constant volume, q_{rxn} is equivalent to ΔE_{rxn} for the amount of sucrose burned.

$q_{cal} \rightarrow q_{rxn}$ ($q_{rxn} = -q_{cal}$)

In the third part, divide q_{rxn} by the number of moles of sucrose to get ΔE_{rxn} per mole of sucrose.

$$\Delta E_{rxn} = \frac{q_{rxn}}{\text{mol } C_{12}H_{22}O_{11}}$$

RELATIONSHIPS USED

$q_{cal} = C_{cal} \times \Delta T = -q_{rxn}$

molar mass $C_{12}H_{22}O_{11} = 342.3$ g/mol

SOLVE Gather the necessary quantities in the correct units and substitute these into the equation to calculate q_{cal}.

SOLUTION

$$\Delta T = T_f - T_i = 28.33\ °C - 24.92\ °C = 3.41\ °C$$

$$q_{cal} = C_{cal} \times \Delta T$$

$$q_{cal} = 4.90 \frac{kJ}{°C} \times 3.41\ °C = 16.7\ kJ$$

Find q_{rxn} by taking the negative of q_{cal}.

$$q_{rxn} = -q_{cal} = -16.7\ kJ$$

Find ΔE_{rxn} per mole of sucrose by dividing q_{rxn} by the number of moles of sucrose (calculated from the given mass of sucrose and its molar mass).

$$\Delta E_{rxn} = \frac{q_{rxn}}{\text{mol } C_{12}H_{22}O_{11}} = \frac{-16.7\ kJ}{1.010\ g\ C_{12}H_{22}O_{11} \times \frac{1\ mol\ C_{12}H_{22}O_{11}}{342.3\ g\ C_{12}H_{22}O_{11}}} = -5.66 \times 10^3\ kJ/mol\ C_{12}H_{22}O_{11}$$

CHECK The units of the answer (kJ) are correct for a change in internal energy. The sign of ΔE_{rxn} is negative, as it should be for a combustion reaction that gives off energy.

FOR PRACTICE 6.5

When 1.550 g of liquid hexane (C_6H_{14}) undergoes combustion in a bomb calorimeter, the temperature rises from 25.87 °C to 38.13 °C. Find ΔE_{rxn} for the reaction in kJ/mol hexane. The heat capacity of the bomb calorimeter, determined in a separate experiment, is 5.73 kJ/°C.

FOR MORE PRACTICE 6.5

The combustion of toluene has a ΔE_{rxn} of -3.91×10^3 kJ/mol. When 1.55 g of toluene (C_7H_8) undergoes combustion in a bomb calorimeter, the temperature rises from 23.12 °C to 37.57 °C. Find the heat capacity of the bomb calorimeter.

Interactive Worked Examples

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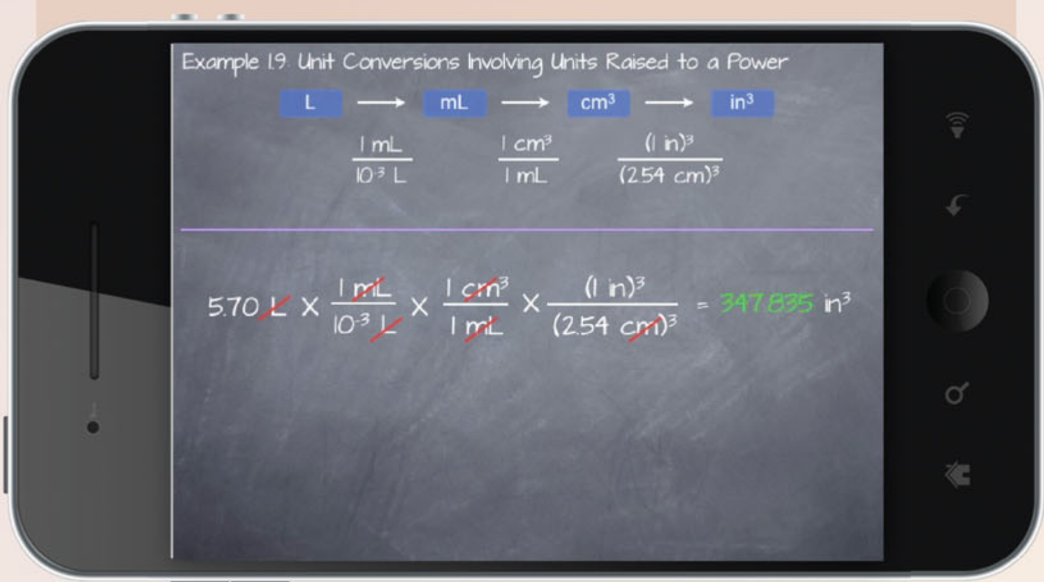


Scan this QR code (located on the back cover of the textbook) with your smartphone to access the Digital Worked Examples.

A Consistent Problem-solving Strategy

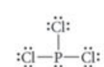
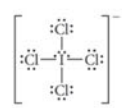
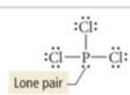
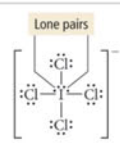
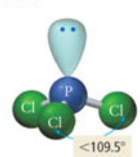
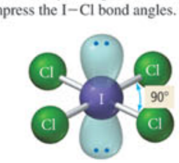
A **consistent approach to problem solving** is used throughout the book and helps students understand the logic and purpose of each step in the problem-solving process.

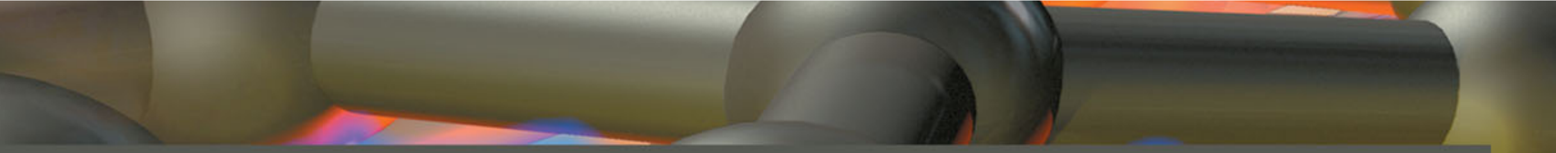
Problem-solving Procedure Boxes for important categories of problems enable you to see how the same reasoning applies to different problems.

The **general procedure** is shown in the left column.

Two Worked Examples, side by side, make it easy to see how differences are handled.

Three-Column Example

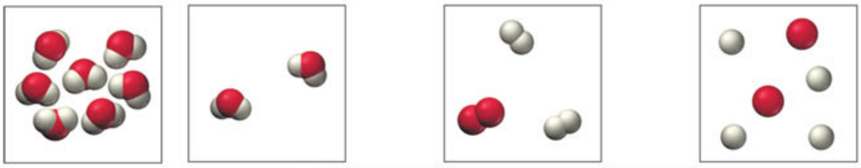
PROCEDURE FOR... Predicting Molecular Geometries	**EXAMPLE 10.2** Predicting Molecular Geometries Predict the geometry and bond angles of PCl_3.	**EXAMPLE 10.3** Predicting Molecular Geometries Predict the geometry and bond angles of ICl_4^-.
1. Draw the Lewis structure for the molecule.	PCl_3 has 26 valence electrons. 	ICl_4^- has 36 valence electrons. 
2. Determine the total number of electron groups around the central atom. Lone pairs, single bonds, double bonds, triple bonds, and single electrons each count as one group.	The central atom (P) has four electron groups.	The central atom (I) has six electron groups.
3. Determine the number of bonding groups and the number of lone pairs around the central atom. These should sum to your result from step 2. Bonding groups include single bonds, double bonds, and triple bonds.	 Three of the four electron groups around P are bonding groups and one is a lone pair.	 Four of the six electron groups around I are bonding groups and two are lone pairs.
4. Refer to Table 10.1 to determine the electron geometry and molecular geometry. If no lone pairs are present around the central atom, the bond angles will be that of the ideal geometry. If lone pairs are present, the bond angles may be smaller than the ideal geometry.	The electron geometry is tetrahedral (four electron groups) and the molecular geometry—the shape of the molecule—is *trigonal pyramidal* (three bonding groups and one lone pair). Because of the presence of a lone pair, the bond angles are less than 109.5°.  Trigonal pyramidal	The electron geometry is octahedral (six electron groups) and the molecular geometry—the shape of the molecule—is *square planar* (four bonding groups and two lone pairs). Even though lone pairs are present, the bond angles are 90° because the lone pairs are symmetrically arranged and do not compress the I—Cl bond angles.  Square planar
	FOR PRACTICE 10.2 Predict the molecular geometry and bond angle of ClNO.	**FOR PRACTICE 10.3** Predict the molecular geometry of I_3^-.



Conceptual Connections are strategically placed to reinforce conceptual understanding of the most complex concepts.

Conceptual Connection 1.3 Chemical and Physical Changes

The diagram on the left represents liquid water molecules in a pan. Which of the three diagrams (a, b or c) best represents the water molecules after they have been vaporized by the boiling of liquid water?



(a) (b) (c)

Each chapter includes several Conceptual Connections, in which students are asked to think about concepts and solve problems without doing any math.

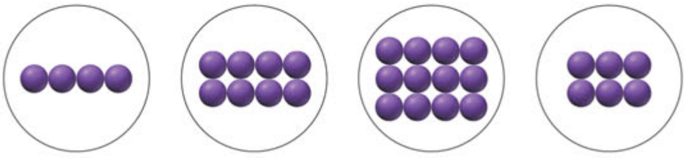
Conceptual Connection 4.1 Stoichiometry

Under certain conditions sodium can react with oxygen to form sodium oxide according to the reaction:

$$4\ Na(s) + O_2(g) \rightarrow 2\ Na_2O(s)$$

A flask contains the amount of oxygen represented by the diagram at left.

Which image below best represents the amount of sodium required to completely react with all of the oxygen in the flask according to the equation?



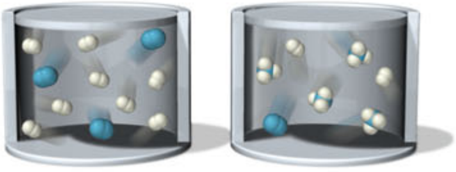
(a) (b) (c) (d)

Conceptual Connection 5.5 Pressure and Number of Moles

Nitrogen and hydrogen react to form ammonia according to the following equation:

$$N_2(g) + 3\ H_2(g) \rightleftharpoons 2\ NH_3(g)$$

Consider the following representations of the initial mixture of reactants and the resulting mixture after the reaction has been allowed to react for some time:



If the volume is kept constant, and nothing is added to the reaction mixture, what happens to the total pressure during the course of the reaction?

(a) the pressure increases
(b) the pressure decreases
(c) the pressure does not change

NEW! Approximately 50 Conceptual Connections have been added, including many that involve visualization and drawing.

Visualizing and Understanding Chemistry

With *Chemistry: A Molecular Approach,* Tro introduced his revolutionary **multipart images that include** macroscopic, molecular, and symbolic perspectives with the goal of connecting you to what you see and experience (the macroscopic world) with the molecules responsible for that world (molecular) and with the way chemists represent those molecules (symbolic). This is, after all, what chemistry is all about.

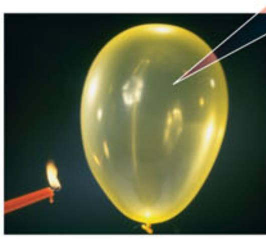
Annotated Molecular Art

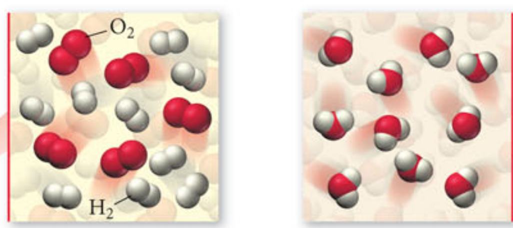
Oxidation–Reduction Reaction

▶ FIGURE 4.22 Oxidation–Reduction Reaction The hydrogen in the balloon reacts with oxygen upon ignition to form gaseous water (which is dispersed in the flame).

$$2\,H_2(g) + O_2(g) \longrightarrow 2\,H_2O(g)$$

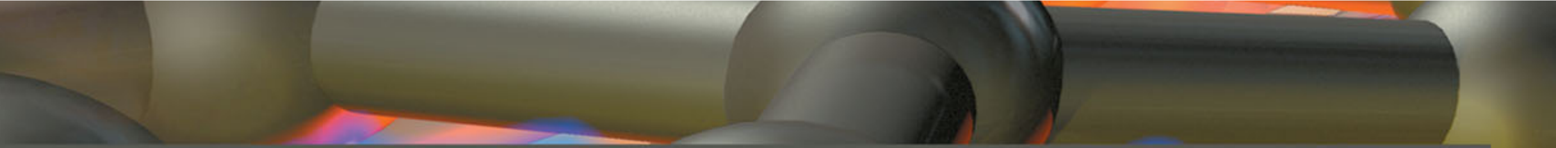
Hydrogen and oxygen react to form gaseous water.





$$2\,H_2(g) \quad + \quad O_2(g) \longrightarrow 2\,H_2O(g)$$

Many illustrations have three parts: what you can see with your eyes (macroscopic) what the molecules are doing (molecular) and how chemists represent the process with equations (symbolic).



Enhanced End-of-Chapter Material

The **end-of-chapter review section** helps you study the chapter's concepts and skills in a systematic way that is ideal for test preparation.

NEW! **Chapter Self Assessment Quiz** at the end of each chapter consists of 10–15 multiple-choice questions that are similar to those on other standardized exams and will also be assignable in MasteringChemistry.

CHAPTER IN REVIEW

Self Assessment Quiz

Q1. Which compound do you expect to be soluble in octane (C_8H_{18})?
a) CH_3OH b) CBr_4 c) H_2O d) NH_3

Q2. An aqueous solution is saturated in both potassium chlorate and carbon dioxide gas at room temperature. What happens when the solution is warmed to 85 °C?
a) Potassium chlorate precipitates out of solution.
b) Carbon dioxide bubbles out of solution.
c) Potassium chlorate precipitates out of solution and carbon dioxide bubbles out of solution.
d) Nothing happens; all of the potassium chloride and the carbon dioxide remain dissolved in solution.

Q3. A 500.0 ml sample of pure water is allowed to come to equilibrium with pure oxygen gas at a pressure of 755 mmHg. What mass of oxygen gas dissolves in the water? (The Henry's law constant for oxygen gas is 1.3×10^{-3} M/atm.)
a) 15.7 g b) 6.5×10^{-3} g c) 0.041 g d) 0.021 g

Q4. A potassium bromide solution is 7.55 % potassium bromide by mass and its density is 1.03 g/mL. What mass of potassium bromide is contained in 35.8 mL of the solution?
a) 2.78 g b) 2.70 g c) 4.88 g d) 2.62 g

Q5. A solution contains 22.4 g glucose ($C_6H_{12}O_6$) dissolved in 0.500 L of water. What is the molality of the solution? (Assume a density of 1.00 g/mL for water.)
a) 0.238 *m* b) 44.8 *m* c) 0.249 *m* d) 4.03 *m*

Q6. A sodium nitrate solution is 12.5% $NaNO_3$ by mass and has a density of 1.02 g/mL. Calculate the molarity of the solution.
a) 1.44 M b) 12.8 M c) 6.67 M d) 1.50 M

Q7. Determine the vapor pressure of an aqueous ethylene glycol ($C_2H_6O_2$) solution that is 14.8 % $C_2H_6O_2$ by mass. The vapor pressure of pure water at 25 °C is 23.8 torr.
a) 3.52 torr b) 22.7 torr c) 1.14 torr d) 20.3 torr

Q8. A solution contains a mixture of substance A and substance B, both of which are volatile. The mole fraction of substance A is 0.35. At 32 °C the vapor pressure of pure A is 87 mmHg and the vapor pressure of pure B is 122 mmHg. What is the total vapor pressure of the solution at this temperature?
a) 110 mmHg b) 209 mmHg
c) 99.3 mmHg d) 73.2 mmHg

Q9. What mass of glucose ($C_6H_{12}O_6$) should be dissolved in 10.0 kg of water to obtain a solution with a freezing point of −4.2 °C?
a) 0.023 kg b) 4.1 kg c) 0.41 kg d) 14.1 kg

Q10. Which of these aqueous solutions has the highest boiling point?
a) 1.25 M $C_6H_{12}O_6$
b) 1.25 M KNO_3
c) 1.25 M $Ca(NO_3)_2$
d) None of the above (they all have the same boiling point)

Q11. The osmotic pressure of a solution containing 22.7 mg of an unknown protein in 50.0 mL of solution is 2.88 mmHg at 25 °C. Determine the molar mass of the protein.
a) 246 g/mol b) 3.85 g/mol
c) 2.93×10^3 g/mol d) 147 g/mol

Q12. The enthalpy of solution for NaOH is −44.46 kJ/mol. What can you conclude about the relative magnitudes of the absolute values of ΔH_{solute} and $\Delta H_{hydration}$, where ΔH_{solute} is the heat associated with separating the solute particles and $\Delta H_{hydration}$ is the heat associated with dissolving the solute particles in water?
a) $|\Delta H_{solute}| > |\Delta H_{hydration}|$
b) $|\Delta H_{solute}| < |\Delta H_{hydration}|$
c) $|\Delta H_{solute}| = |\Delta H_{hydration}|$
d) None of the above (nothing can be concluded about the relative magnitudes)

Q13. A 2.4 *m* aqueous solution of an ionic compound with the formula MX_2 has a boiling point of 103.4 °C. Calculate the van't Hoff factor (*i*) for MX_2 at this concentration.
a) 2.8 b) 83 c) 0.73 d) 1.0

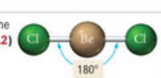
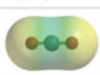
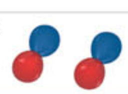
Q14. A solution is an equimolar mixture of two volatile components A and B. Pure A has a vapor pressure of 50 torr and pure B has a vapor pressure of 100 torr. The vapor pressure of the mixture is 85 torr. What can you conclude about the relative strengths of the intermolecular forces between particles of A and B (relative to those between particles of A and those between particles of B)?
a) The intermolecular forces between particles A and B are *weaker* than those between particles of A and those between particles of B.
b) The intermolecular forces between particles A and B are *stronger* than those between particles of A and those between particles of B.
c) The intermolecular forces between particles A and B are *the same as* those between particles of A and those between particles of B.
d) Nothing can be concluded about the relative strengths of intermolecular forces from this observation.

Q15. An aqueous solution is in equilibrium with a gaseous mixture containing an equal number of moles of oxygen, nitrogen, and helium. Rank the relative concentrations of each gas in the aqueous solution from highest to lowest.
a) $[O_2] > [N_2] > [He]$
b) $[He] > [N_2] > [O_2]$
c) $[N_2] > [He] > [O_2]$
d) $[N_2] > [O_2] > [He]$

Answers: 1. (b) 2. (b) 3. (d) 4. (a) 5. (c) 6. (d) 7. (b) 8. (a) 9. (b) 10. (c) 11. (c) 12. (b) 13. (a) 14. (a) 15. (a)

NEW! **Learning Outcomes have been added at the chapter level** and are also emphasized graphically. These goals correlate with the end-of-chapter problems in the text and in MasteringChemistry.®

Key Learning Outcomes

Chapter Objectives	Assessment
Using VSEPR Theory to Predict the Basic Shapes of Molecules (10.2) 	Example 10.1 For Practice 10.1 Exercises 31–32
Predicting Molecular Geometries Using VSEPR Theory and the Effects of Lone Pairs (10.4)	Examples 10.2–10.3 For Practice 10.2–10.3 Exercises 35–36
Predicting the Shapes of Larger Molecules (10.4)	Example 10.4 For Practice 10.4 Exercises 41–42, 45–46
Using Molecular Shape to Determine Polarity of a Molecule (10.5) 	Example 10.5 For Practice 10.5 Exercises 49–52
Writing Hybridization and Bonding Schemes Using Valence Bond Theory (10.7)	Examples 10.6–10.8 For Practice 10.6–10.8 For More Practice 10.8 Exercises 61–66
Drawing Molecular Orbital Diagrams to Predict Bond Order and Magnetism of a Diatomic Molecule (10.8) 	Examples 10.9–10.11 For Practice 10.9–10.11 For More Practice 10.10 Exercises 71–72, 75–78, 81–82

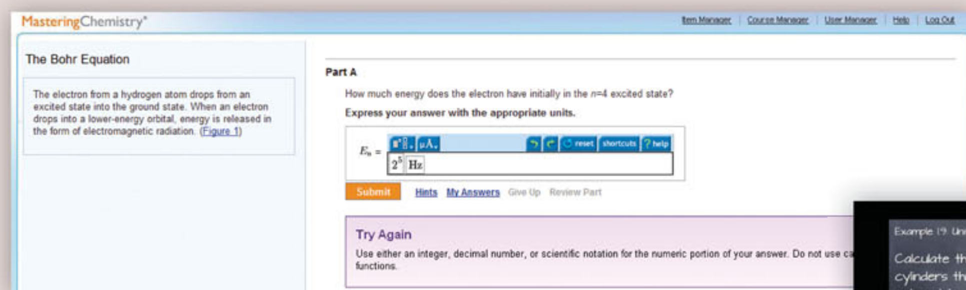
End-of-Chapter Review

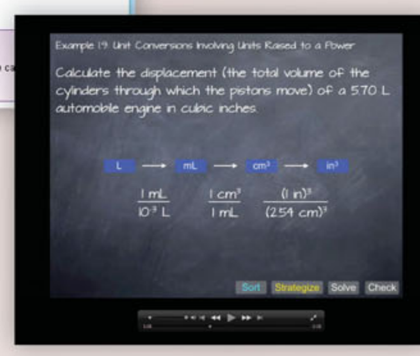
- **Key Terms** list all of the chapter's boldfaced terms, organized by section in order of appearance, with page references. Definitions are found in the Glossary.
- **The Key Concepts** section summarizes the chapter's most important ideas.
- **The Key Equations and Relationships** section lists each of the key equations and important quantitative relationships from the chapter.
- NEW! **Key Learning Objectives** list the concepts that you should know after reading the chapter and are linked to in-chapter and end-of-chapter examples that show mastery of those skills.

MasteringChemistry® for Students

www.masteringchemistry.com

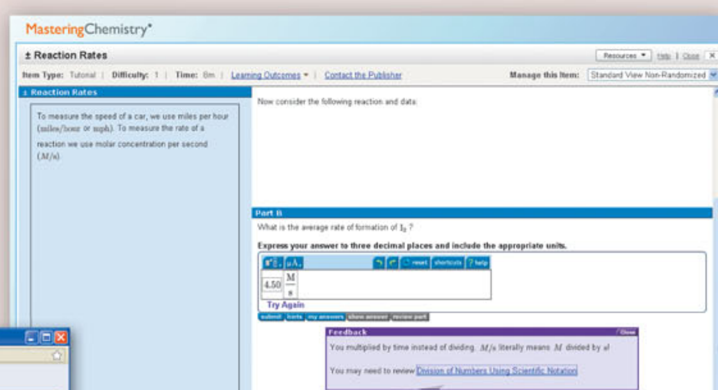
MasteringChemistry tutorials guide students through the most challenging topics while helping them make connections between related chemical concepts. Immediate feedback and tutorial assistance help students understand and master concepts and skills in chemistry—allowing them to retain more knowledge and perform better in this course and beyond.

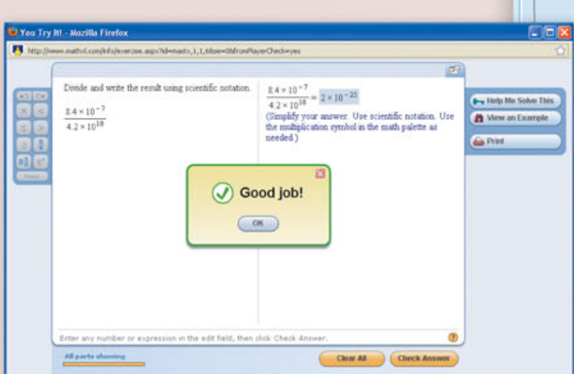


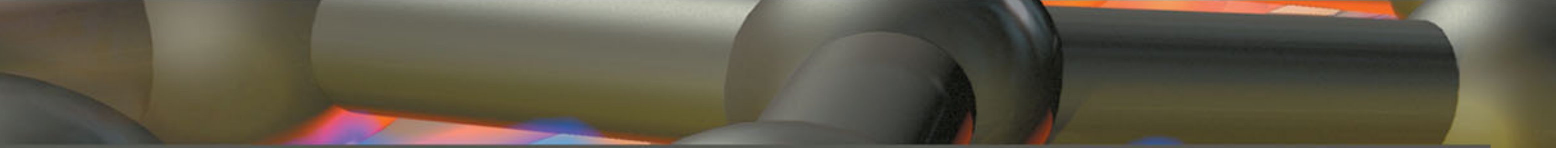


MasteringChemistry is the only system to provide **instantaneous feedback** specific to the most common wrong answers. Students can submit an answer and receive immediate, error-specific feedback. Simpler sub-problems—hints—are provided upon request.

Math Remediation links found in selected tutorials launch algorithmically generated math exercises that give students unlimited opportunity for practice and mastery of math skills. Math Remediation exercises provide additional practice and free up class and office-hour time to focus on the chemistry. Exercises include guided solutions, sample problems, and learning aids for extra help, and offer helpful feedback when students enter incorrect answers.

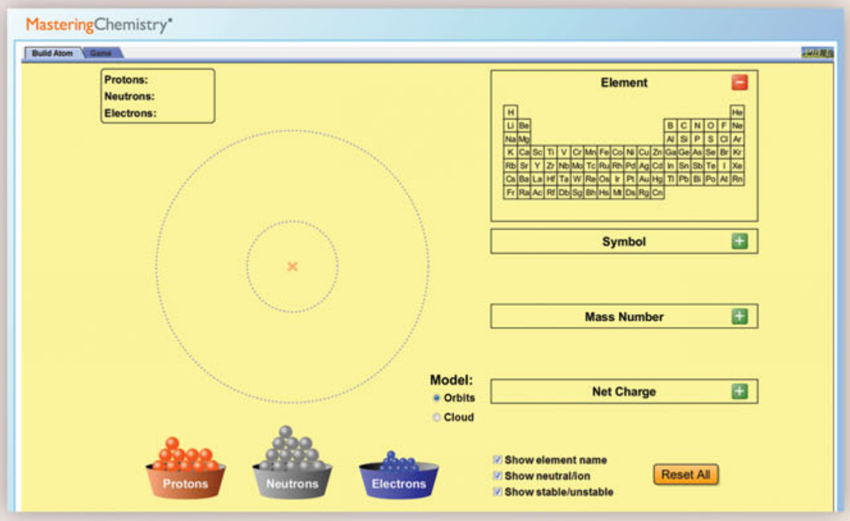






MasteringChemistry brings chemistry to life by illustrating key topics in general chemistry.

NEW! **15 Pause and Predict Video Quizzes** ask students to predict the outcome of experiments and demonstrations as they watch the videos; a set of multiple-choice questions challenges students to apply the concepts from the video to related scenarios. These videos are also available in web and mobile-friendly formats through the Study Area of MasteringChemistry and in the Pearson eText.

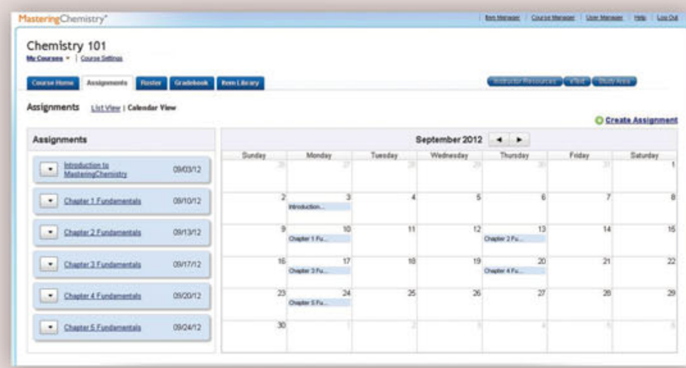


NEW! **15 Simulations,** assignable in MasteringChemistry, include those developed by the PhET Chemistry Group, and the leading authors in the simulation development covering some of the most difficult chemistry concepts.

MasteringChemistry® for Instructors

www.masteringchemistry.com

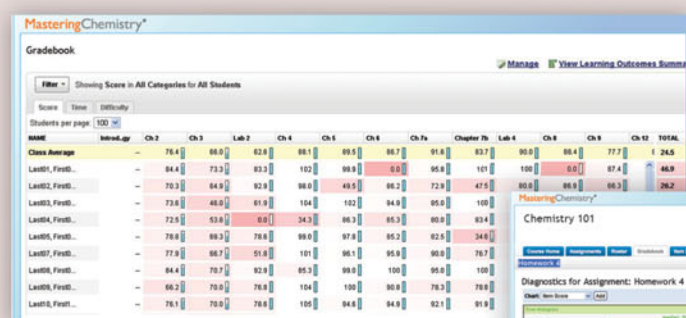
The Mastering platform was developed **by scientists** for science students and instructors. Mastering has been refined from data-driven insights derived from over a decade of real-world use by faculty and students.



NEW! Calendar Features

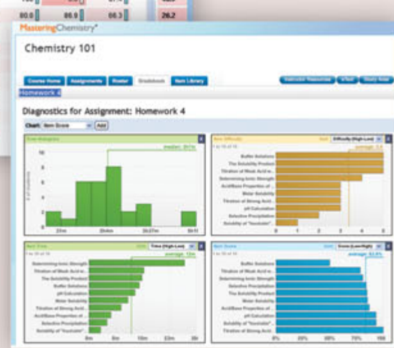
The Course Home default page now features a **Calendar View** displaying upcoming assignments and due dates.

- Instructors can schedule assignments by dragging and dropping the assignment onto a date in the calendar. If the due date of an assignment needs to change, instructors can drag the assignment to the new due date and change the "available from and to dates" accordingly.
- The calendar view gives students a syllabus-style overview of due dates, making it easy to see all assignments due in a given month.



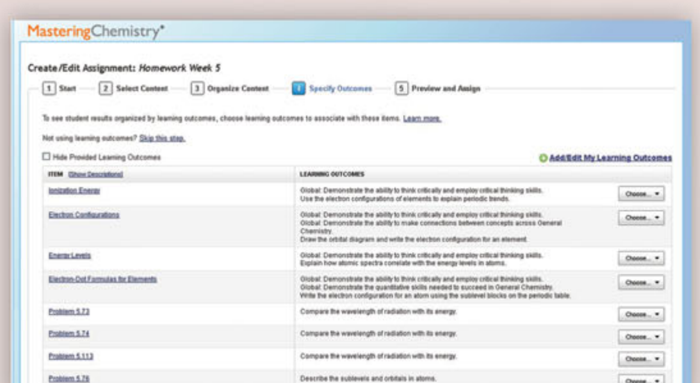
Gradebook

Every assignment is automatically graded. Shades of red highlight struggling students and challenging assignments.



Gradebook Diagnostics

This screen provides you with your favorite diagnostics. With a single click, charts summarize the most difficult problems, vulnerable students, grade distribution, and even score improvement over the course.



NEW! Learning Outcomes

Let Mastering do the work in tracking student performance against your learning outcomes:

- Add your own or use the publisher provided learning outcomes.
- View class performance against the specified learning outcomes.
- Export results to a spreadsheet that you can further customize and share with your chair, dean, administrator, or accreditation board.

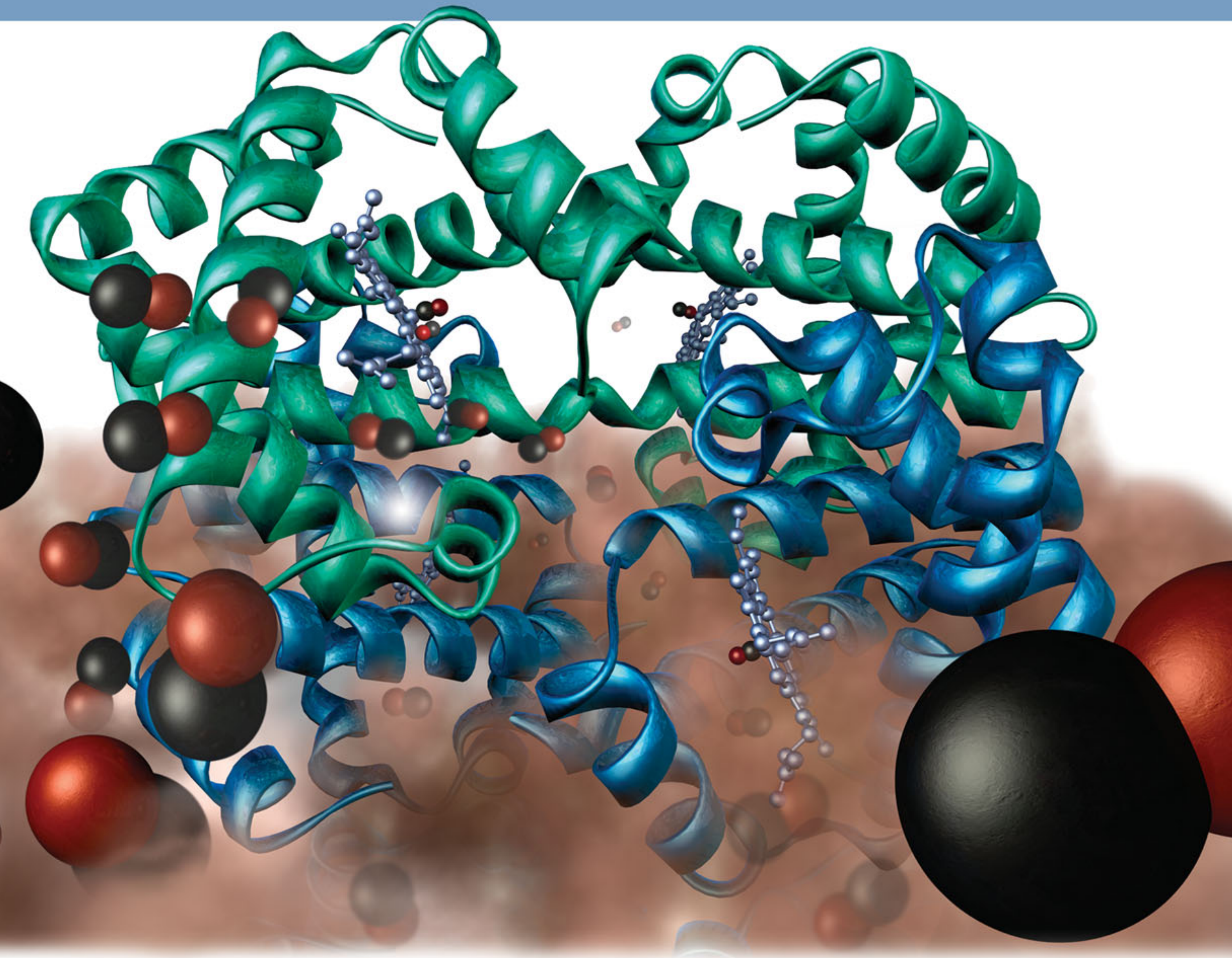
CHEMISTRY

1 Matter, Measurement, and Problem Solving

The most incomprehensible thing about the universe is that it is comprehensible.

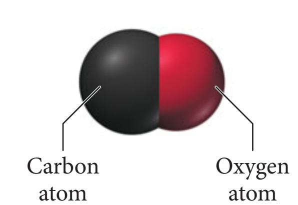
—Albert Einstein (1879–1955)

WHAT DO YOU THINK is the most important idea in all of human knowledge? There are, of course, many possible answers to this question—some practical, some philosophical, and some scientific. If we limit ourselves only to scientific answers, mine would be this: **the properties of matter are determined by the properties of atoms and molecules**. Atoms and molecules determine how matter behaves—if they were different, matter would be different. The properties of water molecules determine how water behaves, the properties of sugar molecules determine how sugar behaves, and the properties of the molecules that compose our bodies determine how our bodies behave. The understanding of matter at the molecular level gives us unprecedented control over that matter. For example, our understanding of the details of the molecules that compose living organisms has revolutionized biology over the last 50 years.



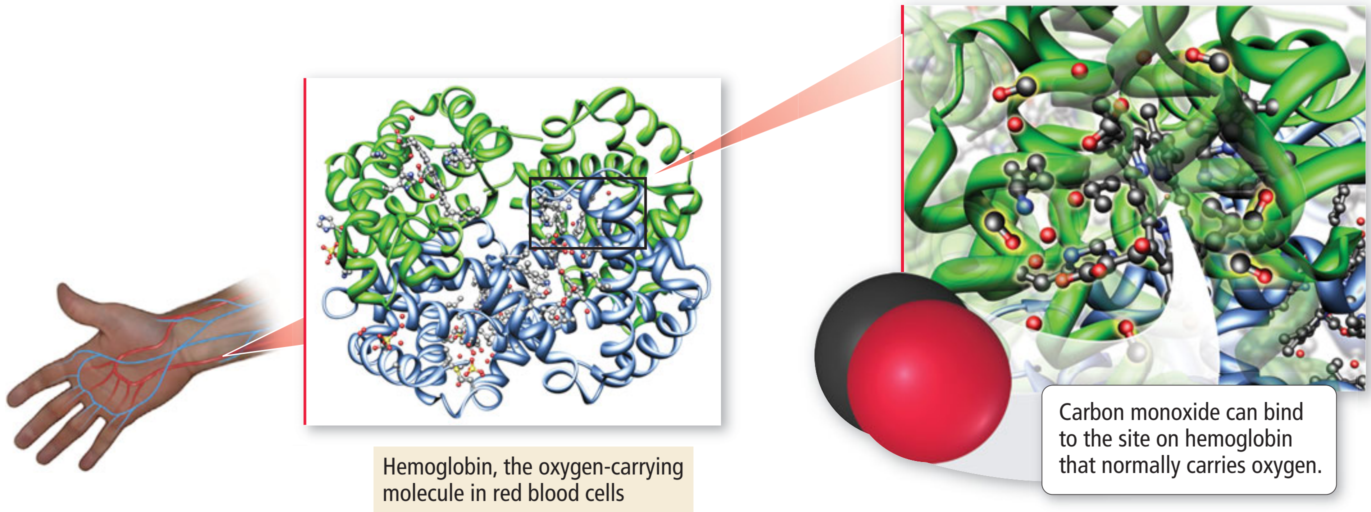
Hemoglobin (depicted in blue and green) is the oxygen-carrying protein in blood. Hemoglobin normally binds oxygen, but it can also bind carbon monoxide molecules (the linked red and black spheres).

1.1 Atoms and Molecules



The air over most U.S. cities, including my own, contains at least some pollution. A significant component of that pollution is carbon monoxide, a colorless gas emitted in the exhaust of cars and trucks. Carbon monoxide gas is composed of carbon monoxide molecules, each of which contains a carbon *atom* and an oxygen *atom* held together by a chemical bond. **Atoms** are the submicroscopic particles that constitute the fundamental building blocks of ordinary matter. Free atoms are rare in nature; instead they bind together in specific geometrical arrangements to form **molecules**.

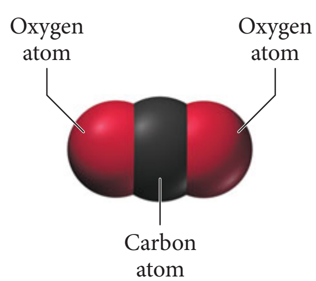
The properties of the substances around us depend on the atoms and molecules that compose the substances, so the properties of carbon monoxide *gas* depend on the properties of carbon monoxide *molecules*. Carbon monoxide molecules happen to be just the right size and shape, and happen to have just the right chemical properties, to fit neatly into cavities within hemoglobin molecules in blood that normally carry oxygen molecules (Figure 1.1 ▸). Consequently, carbon monoxide diminishes the oxygen-carrying capacity of blood. Breathing air containing too much carbon monoxide (greater than 0.04% by volume) can lead to unconsciousness and even death because not enough



▲ **FIGURE 1.1 Binding of Oxygen and Carbon Monoxide to Hemoglobin** Hemoglobin, a large protein molecule, is the oxygen carrier in red blood cells. Each subunit of the hemoglobin molecule contains an iron atom to which oxygen binds. Carbon monoxide molecules can take the place of oxygen, thus reducing the amount of oxygen reaching the body's tissues.

oxygen reaches the brain. Carbon monoxide deaths can occur as a result of running an automobile in a closed garage or using a propane burner in an enclosed space for too long. In smaller amounts, carbon monoxide causes the heart and lungs to work harder and can result in headaches, dizziness, weakness, and confusion.

Carbon dioxide molecule

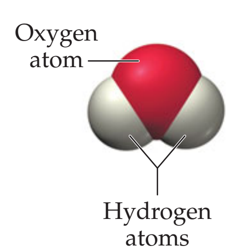


Cars and trucks emit another closely related molecule, called carbon dioxide, in far greater quantities than carbon monoxide. The only difference between carbon dioxide and carbon monoxide is that carbon dioxide molecules contain two oxygen atoms instead of just one. However, this extra oxygen atom dramatically affects the properties of the gas. We breathe much more carbon dioxide—which composes 0.04% of air, and is a product of our own respiration as well—than carbon monoxide, yet it does not kill us. Why? Because the presence of the second oxygen atom prevents carbon dioxide from binding to the oxygen-carrying site in hemoglobin, making it far less toxic. Although high levels of carbon dioxide (greater than 10% of air) can be hazardous for other reasons, lower levels can enter the bloodstream with no adverse effects. Such is the molecular world. Any differences between molecules—such as the extra oxygen atom in carbon monoxide—results in differences between the substances that the molecules compose.

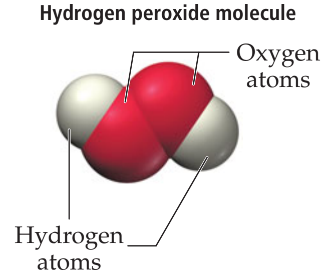
As another example, consider two other closely related molecules, water and hydrogen peroxide:

In the study of chemistry, atoms are often portrayed as colored spheres, with each color representing a different kind of atom. For example, a black sphere represents a carbon atom, a red sphere represents an oxygen atom, and a white sphere represents a hydrogen atom. For a complete color code of atoms, see Appendix IIA.

Water molecule



Hydrogen peroxide molecule



A water molecule is composed of *one* oxygen atom and two hydrogen atoms. A hydrogen peroxide molecule is composed of *two* oxygen atoms and two hydrogen atoms. This seemingly small molecular difference results in a huge difference in the properties of water and hydrogen peroxide. Water is the familiar and stable liquid we all drink and bathe in. Hydrogen peroxide, in contrast, is an unstable liquid that, in its pure form, burns the skin on contact and is used in rocket fuel. When you pour water onto your hair, your hair simply becomes wet. However, if you put diluted hydrogen peroxide on your hair—which you may have done if you have ever bleached your hair—a chemical reaction occurs that strips your hair of its color.

The hydrogen peroxide we use as an antiseptic or bleaching agent is considerably diluted.

The details of how specific atoms bond to form a molecule—in a straight line, at a particular angle, in a ring, or in some other pattern—as well as the type of atoms in the molecule, determine everything about the substance that the molecule composes. If we want to understand the substances around us, we must understand the atoms and molecules that compose them—this is the central goal of chemistry. A good simple definition of **chemistry** is

Chemistry—the science that seeks to understand the behavior of matter by studying the behavior of atoms and molecules.

The term *atoms* in this definition can be interpreted loosely to include atoms that have lost or gained electrons.

1.2 The Scientific Approach to Knowledge

Throughout history, humans have approached knowledge about the physical world in different ways. For example, the Greek philosopher Plato (427–347 B.C.) thought that the best way to learn about reality was not through the senses, but through reason. He believed that the physical world was an imperfect representation of a perfect and transcendent world (a world beyond space and time). For him, true knowledge came not through observing the real physical world, but through reasoning and thinking about the ideal one.

Although some Greek philosophers, such as Aristotle, did use observation to attain knowledge, they did not emphasize experiment and measurement to the extent that modern science does.

The *scientific* approach to knowledge, however, is exactly the opposite of Plato's. Scientific knowledge is empirical—it is based on *observation* and *experiment*. Scientists observe and perform experiments on the physical world to learn about it. Some observations and experiments are qualitative (noting or describing how a process happens), but many are quantitative (measuring or quantifying something about the process). For example, Antoine Lavoisier (1743–1794), a French chemist who studied combustion (or burning), made careful measurements of the mass of objects before and after burning them in closed containers. He noticed that there was no change in the total mass of material within the container during combustion. In doing so, Lavoisier made an important *observation* about the physical world.

▲ A painting of the French chemist Antoine Lavoisier with his wife, Marie, who helped him in his work by illustrating his experiments and translating scientific articles from English. Lavoisier, who also made significant contributions to agriculture, industry, education, and government administration, was executed during the French Revolution. (The Metropolitan Museum of Art)

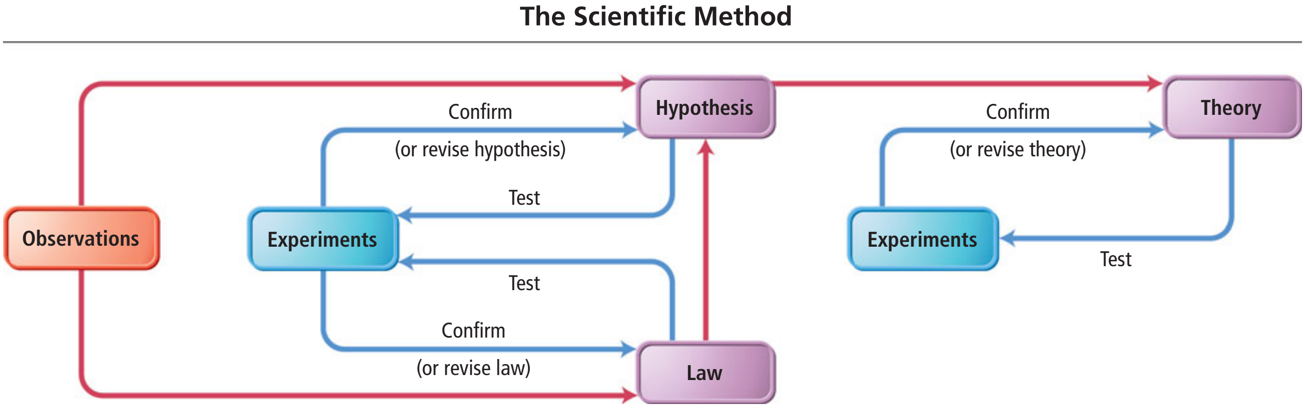
Observations often lead scientists to formulate a **hypothesis**, a tentative interpretation or explanation of the observations. For example, Lavoisier explained his observations on combustion by hypothesizing that when a substance burns, it combines with a component of air. A good hypothesis is *falsifiable*, which means that it makes predictions that can be confirmed or refuted by further observations. Scientists test hypotheses by **experiments**, highly controlled procedures designed to generate observations that may confirm or refute a hypothesis. The results of an experiment may support a hypothesis or prove it wrong—in which case the scientist must modify or discard the hypothesis.

In some cases, a series of similar observations leads to the development of a **scientific law**, a brief statement that summarizes past observations and predicts future ones. Lavoisier summarized his observations on combustion with the **law of conservation of mass**, which states, "In a chemical reaction, matter is neither created nor destroyed." This statement summarized his observations on chemical reactions and predicted the outcome of future observations on reactions. Laws, like hypotheses, are also subject to experiments, which can support them or prove them wrong.

Scientific laws are not *laws* in the same sense as civil or governmental laws. Nature does not follow laws in the way that we obey the laws against speeding or running a stop sign. Rather, scientific laws *describe* how nature behaves—they are generalizations about what nature does. For that reason, some people find it more appropriate to refer to them as *principles* rather than *laws*.

One or more well-established hypotheses may form the basis for a scientific **theory**. A scientific theory is a model for the way nature is and tries to explain not merely what nature does but why. As such, well-established theories are the pinnacle of scientific knowledge, often predicting behavior far beyond the observations or laws from which they were developed. A good example of a theory is the **atomic theory** proposed by English chemist John Dalton (1766–1844). Dalton explained the law of conservation of mass, as well as other laws and observations of the time, by proposing that matter is composed of small, indestructible particles called atoms. Since these particles are merely rearranged in chemical changes (and not created or destroyed), the total amount of mass remains the same. Dalton's theory is a model for the physical world—it gives us insight into how nature works and, therefore, *explains* our laws and observations.

In Dalton's time, people thought atoms were indestructible. Today, because of nuclear reactions, we know that atoms can be broken apart into their smaller components.



▲ **FIGURE 1.2** The Scientific Approach to Knowledge

Finally, the scientific approach returns to observation to test theories. For example, scientists can test the atomic theory by trying to isolate single atoms or by trying to image them (both of which, by the way, have already been accomplished). Theories are validated by experiments; however, theories can never be conclusively proven because some new observation or experiment always has the potential to reveal a flaw. Notice that the scientific approach to knowledge begins with observation and ends with observation. An experiment is in essence a highly controlled procedure for generating critical observations designed to test a theory or hypothesis. Each new set of observations has the potential to refine the original model. Figure 1.2▲ summarizes one way to map the scientific approach to knowledge. Scientific laws, hypotheses, and theories are all subject to continued experimentation. If a law, hypothesis, or theory is proved wrong by an experiment, it must be revised and tested with new experiments. Over time, the scientific community eliminates or corrects poor theories and laws, and valid theories and laws—those consistent with experimental results—remain.

Established theories with strong experimental support are the most powerful pieces of scientific knowledge. You may have heard the phrase "That is just a theory," as if theories are easily dismissible. Such a statement reveals a deep misunderstanding of the nature of a scientific theory. Well-established theories are as close to truth as we get in science. The idea that all matter is made of atoms is "just a theory," but it has over 200 years of experimental evidence to support it. It is a powerful piece of scientific knowledge on which many other scientific ideas have been built.

One last word about the scientific approach to knowledge: some people wrongly imagine science to be a strict set of rules and procedures that automatically lead to inarguable, objective facts. This is not the case. Even our diagram of the scientific approach to knowledge is only an idealization of real science, useful to help us see the key distinctions of science. Real science requires hard work, care, creativity, and even a bit of luck. Scientific theories do not just arise out of data—men and women of great genius and creativity craft theories. A great theory is not unlike a master painting, and many see a similar kind of beauty in both. (For more on this aspect of science, see the box entitled *Thomas S. Kuhn and Scientific Revolutions.*)

Conceptual Connection 1.1 Laws and Theories

Which statement best explains the difference between a law and a theory?

(a) A law is truth; a theory is mere speculation.

(b) A law summarizes a series of related observations; a theory gives the underlying reasons for them.

(c) A theory describes *what* nature does; a law describes *why* nature does it.

The Nature of Science

Thomas S. Kuhn and Scientific Revolutions

When scientists talk about science, they often talk in ways that imply that their theories are "true." Further, they talk as if they arrive at theories in logical and unbiased ways. For example, a theory central to chemistry that we have discussed in this chapter is John Dalton's atomic theory—the idea that all matter is composed of atoms. Is this theory "true"? Was it reached in logical, unbiased ways? Will this theory still be around in 200 years?

The answers to these questions depend on how we view science and its development. One way to view science—let's call it the *traditional view*—is as the continual accumulation of knowledge and the building of increasingly precise theories. In this view, a scientific theory is a model of the world that reflects what is *actually in* nature. New observations and experiments result in gradual adjustments to theories. Over time, theories get better, giving us a more accurate picture of the physical world.

In the twentieth century, a different view of scientific knowledge began to develop. A book by Thomas Kuhn, published in 1964 and entitled *The Structure of Scientific Revolutions*, challenged the traditional view. Kuhn's ideas came from his study of the history of science, which, he argued, does not support the idea that science progresses in a smooth cumulative way. According to Kuhn, science goes through fairly quiet periods that he called *normal science*. In these periods, scientists make their data fit the reigning theory, or paradigm. Small inconsistencies are swept aside during periods of normal science. However, when too many inconsistencies and anomalies develop, a crisis emerges. The crisis brings about a *revolution* and a new reigning theory. According to Kuhn, the new theory is usually quite different from the old one; it not only helps us to make sense of new or anomalous information, but also enables us to see accumulated data from the past in a dramatically new way.

Kuhn further contended that theories are held for reasons that are not always logical or unbiased, and that theories are not *true* models—in the sense of a one-to-one mapping—of the physical world. Because new theories are often so different from the ones they replace, he argued, and because old theories always make good sense to those holding them, they must not be "True" with a capital *T*; otherwise "truth" would be constantly changing.

Kuhn's ideas created a controversy among scientists and science historians that continues to this day. Some, especially postmodern philosophers of science, have taken Kuhn's ideas one step further. They argue that scientific knowledge is *completely* biased and lacks any objectivity. Most scientists, including Kuhn, would disagree. Although Kuhn pointed out that scientific knowledge has *arbitrary elements*, he also said, "*Observation … can and must drastically restrict the range of admissible scientific belief, else there would be no science.*" In other words, saying that science contains arbitrary elements is quite different from saying that science itself is arbitrary.

Question

In his book, Kuhn stated, "*A new theory … is seldom or never just an increment to what is already known.*" Can you think of any examples that support Kuhn's statement from your knowledge of the history of science? Do you know of any instances in which a new theory or model was drastically different from the one it replaced?

1.3 The Classification of Matter

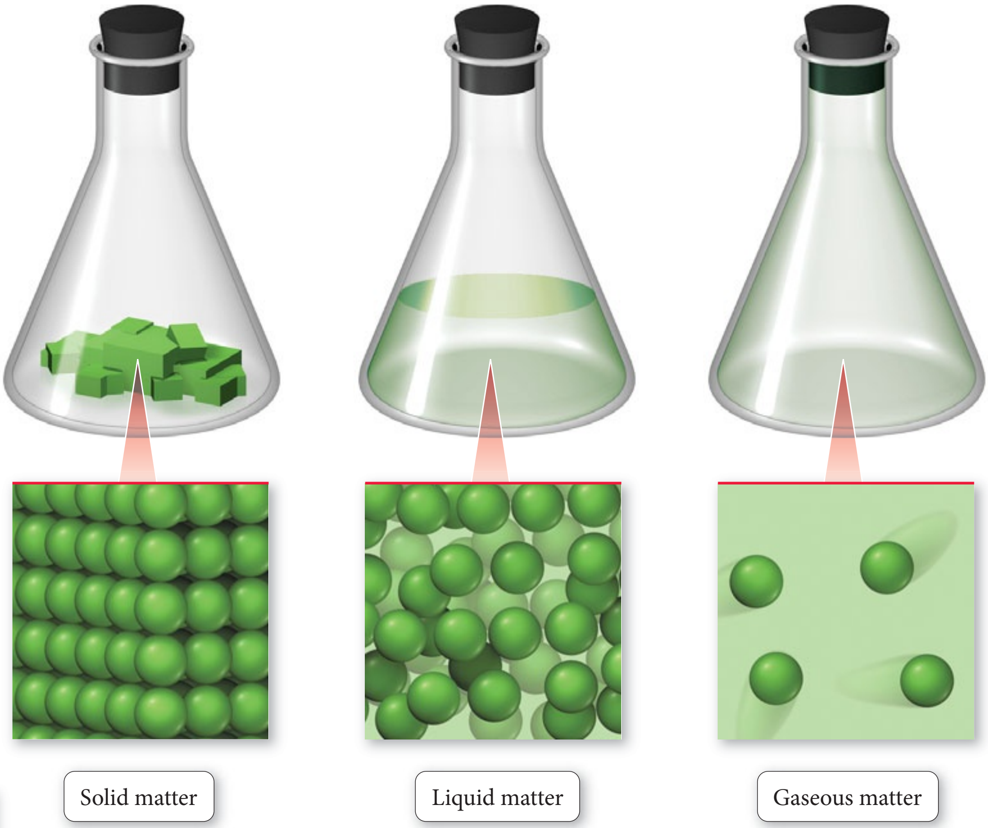
Matter is anything that occupies space and has mass. This book, your desk, your chair, and even your body are all composed of matter. Less obviously, the air around you is also matter—it too occupies space and has mass. We call a specific instance of matter—such as air, water, or sand—a **substance**. We can classify matter according to its **state** (its physical form) and its **composition** (the basic components that make it up).

The States of Matter: Solid, Liquid, and Gas

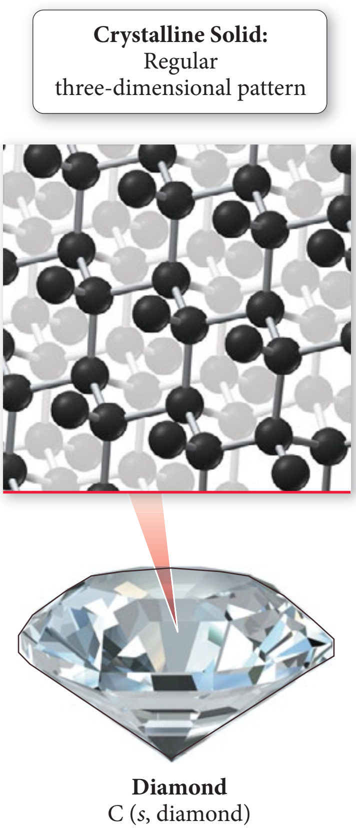
Matter can exist in three different states: **solid**, **liquid**, and **gas**. In *solid matter*, atoms or molecules pack close to each other in fixed locations. Although the atoms and molecules in a solid vibrate, they do not move around or past each other. Consequently, a solid has a fixed volume and rigid shape. Ice, aluminum, and diamond are good examples of solids. Solid matter may be **crystalline**, in which case its atoms or molecules are in patterns with long-range, repeating order (Figure 1.3 ▶), or it may be **amorphous**, in which case its atoms or molecules do not have any long-range order. Table salt and diamond are examples of *crystalline* solids; the well-ordered geometric shapes of salt and diamond crystals reflect the well-ordered geometric arrangement of their atoms (although this is not the case for *all* crystalline solids). Examples of *amorphous* solids include glass and plastic. In *liquid matter*, atoms or molecules pack about as closely as they do in solid

The state of matter changes from solid to liquid to gas with increasing temperature.

Glass and other amorphous solids can be thought of, from one point of view, as intermediate between solids and liquids. Their atoms are fixed in position at room temperature, but they have no long-range structure and do not have distinct melting points.



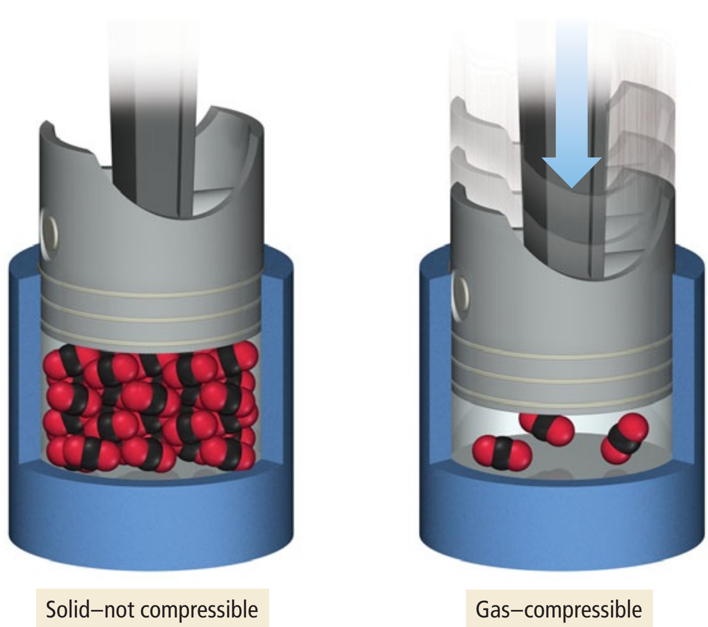
▶ In a solid, the atoms or molecules are fixed in place and can only vibrate. In a liquid, although the atoms or molecules are closely packed, they can move past one another, allowing the liquid to flow and assume the shape of its container. In a gas, the atoms or molecules are widely spaced, making gases compressible as well as fluid (able to flow).



▲ **FIGURE 1.3 Crystalline Solid** Diamond is a crystalline solid composed of carbon atoms arranged in a regular, repeating pattern.

matter, but they are free to move relative to each other, giving liquids a fixed volume but not a fixed shape. Liquids assume the shape of their container. Water, alcohol, and gasoline are all substances that are liquids at room temperature.

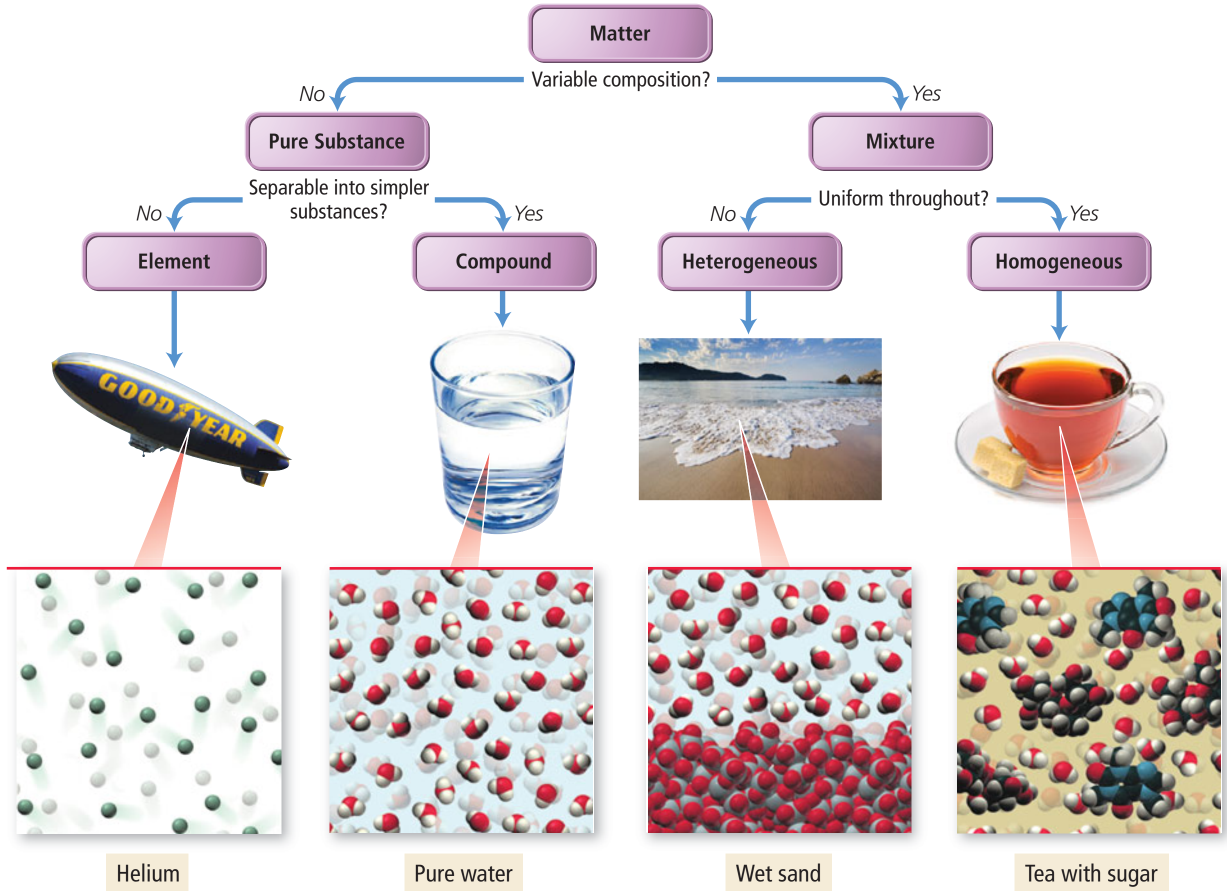
In *gaseous matter*, atoms or molecules have a lot of space between them and are free to move relative to one another, making gases *compressible* (Figure 1.4▼). When you squeeze a balloon or sit down on an air mattress, you force the atoms and molecules into a smaller space so that they are closer together. Gases always assume the shape *and* volume of their container. Substances that are gases at room temperature include helium, nitrogen (the main component of air), and carbon dioxide.



▶ **FIGURE 1.4 The Compressibility of Gases** Gases can be compressed—squeezed into a smaller volume—because there is so much empty space between atoms or molecules in the gaseous state.

Classifying Matter according to Its Composition: Elements, Compounds, and Mixtures

In addition to classifying matter according to its state, we can classify it according to its composition, as shown in the following chart:



The first division in the classification of matter is between a *pure substance* and a *mixture*. A **pure substance** is made up of only one component and its composition is invariant (it does not vary from one sample to another). The *components* of a pure substance can be individual atoms or groups of atoms joined together. For example, helium, water, and table salt (sodium chloride) are all pure substances. Each of these substances is made up of only one component: helium is made up of helium atoms, water is made up of water molecules, and sodium chloride is made up of sodium chloride units. The composition of a pure sample of any one of these is always exactly the same (because you can't vary the composition of a substance made up of only one component).

A **mixture**, by contrast, is composed of two or more components in proportions that can vary from one sample to another. For example, sweetened tea, composed primarily of water molecules and sugar molecules (with a few other substances mixed in), is a mixture. We can make tea slightly sweet (a small proportion of sugar to water) or very sweet (a large proportion of sugar to water) or any level of sweetness in between.

We can categorize pure substances themselves into two types—*elements* and *compounds*—depending on whether or not they can be broken down (or decomposed) into simpler substances. Helium, which we just noted is a pure substance, is also a good example of an **element**, a substance that cannot be chemically broken down into simpler substances. Water, also a pure substance, is a good example of a **compound**, a substance composed of two or more elements (in this case hydrogen and oxygen) in a fixed, definite proportion. On Earth, compounds are more common than pure elements because most elements combine with other elements to form compounds.

We can also categorize mixtures into two types—heterogeneous and homogeneous—depending on how *uniformly* the substances within them mix. Wet sand is a **heterogeneous mixture**, one in which the composition varies from one region of the mixture to another.

Sweetened tea is a **homogeneous mixture**, one with the same composition throughout. Homogeneous mixtures have uniform compositions because the atoms or molecules that compose them mix uniformly. Heterogeneous mixtures are made up of distinct regions because the atoms or molecules that compose them separate. Here again we see that the properties of matter are determined by the atoms or molecules that compose it.

Classifying a substance according to its composition is not always obvious and requires that we either know the true composition of the substance or are able to test it in a laboratory. For now, we will focus on relatively common substances that you are likely to have encountered. Throughout this course, you will gain the knowledge to understand the composition of a larger variety of substances.

Conceptual Connection 1.2 Pure Substances and Mixtures

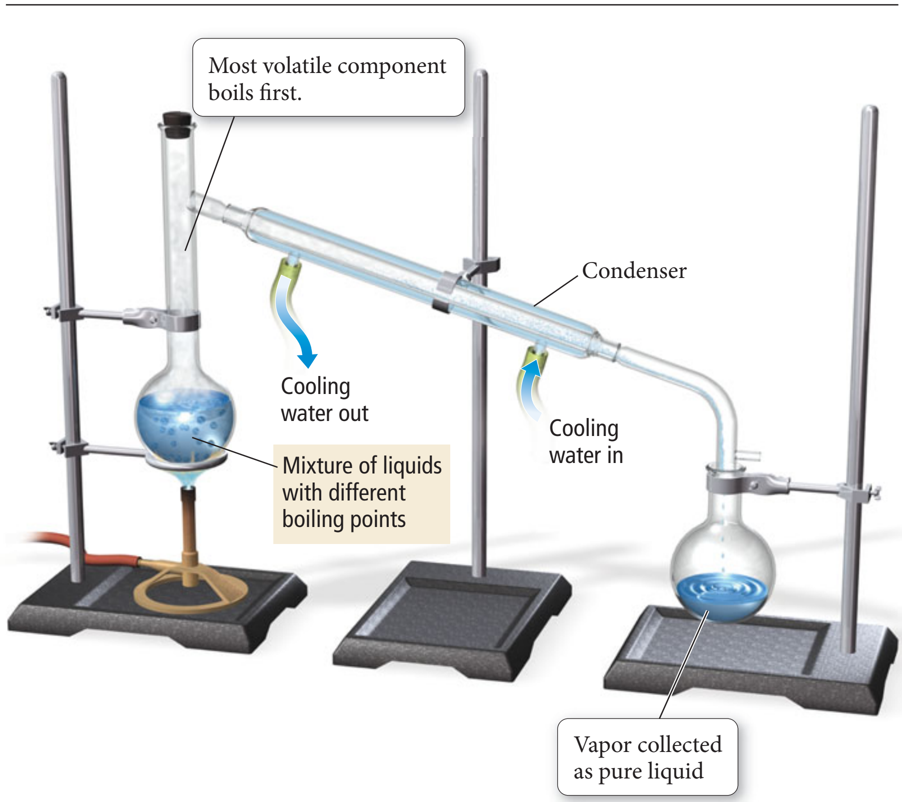
Let a small circle represent an atom of one type of element and a small square represent at atom of a second type of element. Make a drawing of (a) a pure substance (a compound) composed of the two elements (in a one-to-one ratio), (b) a homogenous mixture composed of the two elements, and (c) a heterogeneous mixture composed of the two elements.

Separating Mixtures

Chemists often want to separate a mixture into its components. Such separations can be easy or difficult, depending on the components in the mixture. In general, mixtures are separable because the different components have different physical or chemical properties. We can use various techniques that exploit these differences to achieve separation. For example, we can separate a mixture of sand and water by **decanting**—carefully pouring off—the water into another container. A homogeneous mixture of liquids can usually be separated by **distillation**, a process in which the mixture is heated to boil off the more **volatile** (easily vaporizable) liquid. The volatile liquid is then recondensed in a condenser and collected in a separate flask (Figure 1.5▼). If a mixture is composed of an insoluble solid and a liquid, we can separate the two by **filtration**, in which the mixture is poured through filter paper in a funnel (Figure 1.6▼).

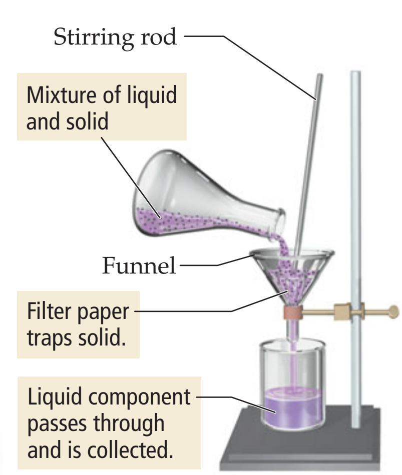
▼ **FIGURE 1.5 Separating Substances by Distillation** When a liquid mixture is heated, the component with the lowest boiling point vaporizes first, leaving behind less volatile liquids or dissolved solids. The vapor is then cooled, condensing it back to a liquid, and collected.

Distillation



▼ **FIGURE 1.6 Separating Substances by Filtration** A solid and liquid mixture can be separated by pouring the mixture through a funnel containing filter paper designed to allow only the liquid to pass.

Filtration



1.4 Physical and Chemical Changes and Physical and Chemical Properties

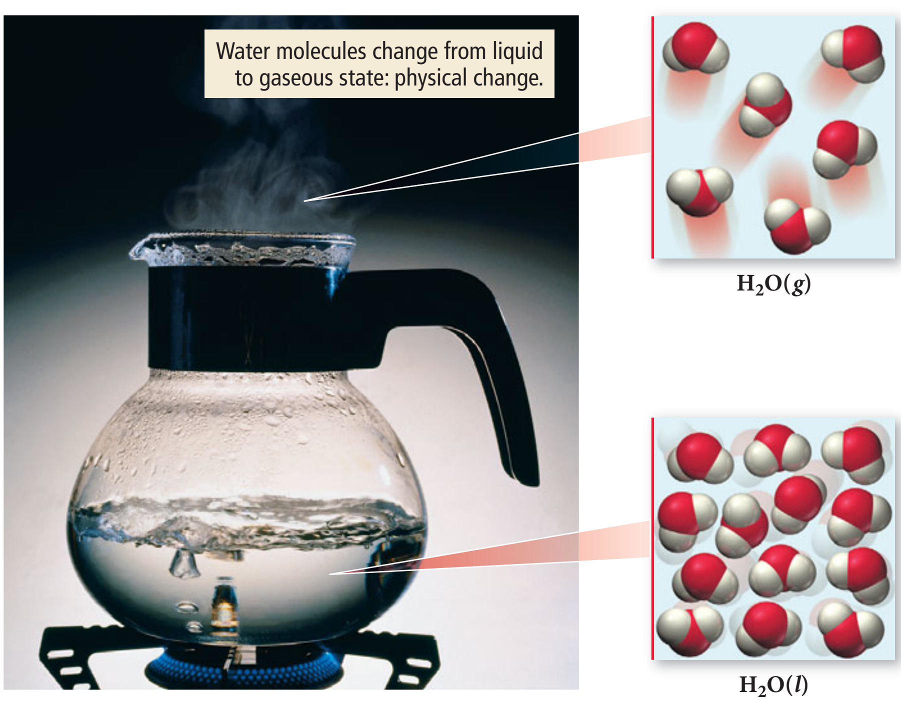
Every day we witness changes in matter: ice melts, iron rusts, gasoline burns, fruit ripens, and water evaporates. What happens to the molecules or atoms that compose these samples of matter during such changes? The answer depends on the type of change. Changes that alter only state or appearance, but not composition, are **physical changes**. The atoms or molecules that compose a substance *do not change* their identity during a physical change. For example, when water boils, it changes its state from a liquid to a gas, but the gas remains composed of water molecules, so this is a physical change (Figure 1.7▼).

In contrast, changes that alter the composition of matter are **chemical changes**. During a chemical change, atoms rearrange, transforming the original substances into different substances. For example, the rusting of iron is a chemical change. The atoms that compose iron (iron atoms) combine with oxygen molecules from air to form iron oxide, the orange substance we call rust (Figure 1.8▼). Some other examples of physical and chemical changes are shown in Figure 1.9▶.

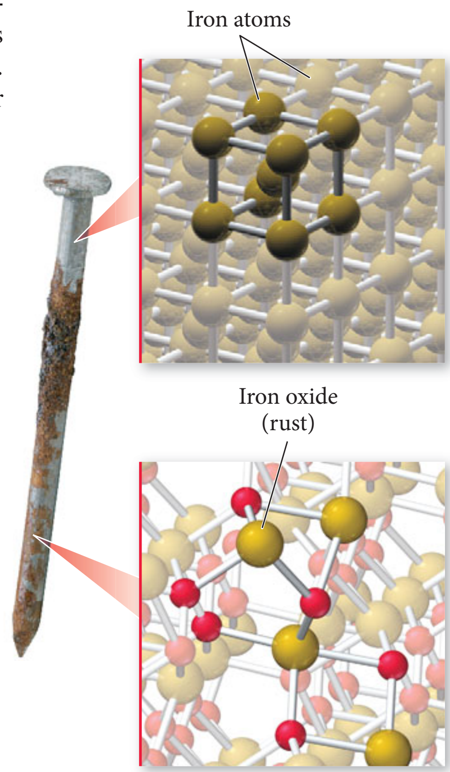
A physical change results in a different form of the same substance, while a chemical change results in a completely different substance.

Physical and chemical changes are manifestations of physical and chemical properties. A **physical property** is a property that a substance displays without changing its composition, whereas a **chemical property** is a property that a substance displays only by changing its composition via a chemical change. The smell of gasoline is a physical property—gasoline does not change its composition when it exhibits its odor. The flammability of gasoline, in contrast, is a chemical property—gasoline does change its composition when it burns, turning into completely new substances (primarily carbon dioxide and water). Physical properties include odor, taste, color, appearance, melting point, boiling point, and density. Chemical properties include corrosiveness, flammability, acidity, toxicity, and other such characteristics.

In Chapter 19 we will also discuss *nuclear changes*, which can involve atoms of one element changing into atoms of a different element.



▲ **FIGURE 1.7 Boiling, a Physical Change** When water boils, it turns into a gas but does not alter its chemical identity—the water molecules are the same in both the liquid and gaseous states. Boiling is thus a physical change, and the boiling point of water is a physical property.



▲ **FIGURE 1.8 Rusting, a Chemical Change** When iron rusts, the iron atoms combine with oxygen atoms to form a different chemical substance, the compound iron oxide. Rusting is therefore a chemical change, and the tendency of iron to rust is a chemical property.