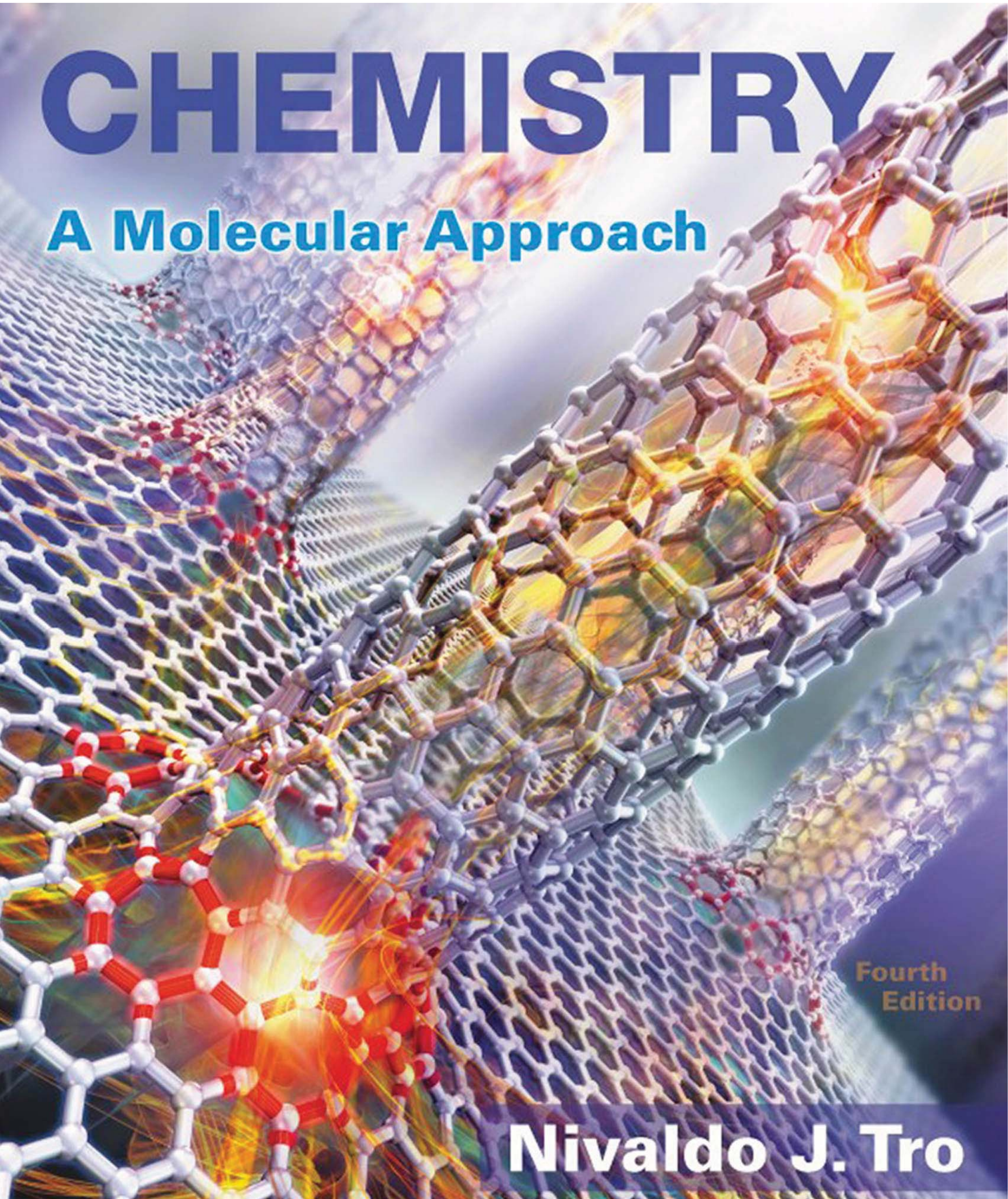
CHEMISTRY
A Molecular Approach
Fourth Edition
Nivaldo J. Tro

CHEMISTRY

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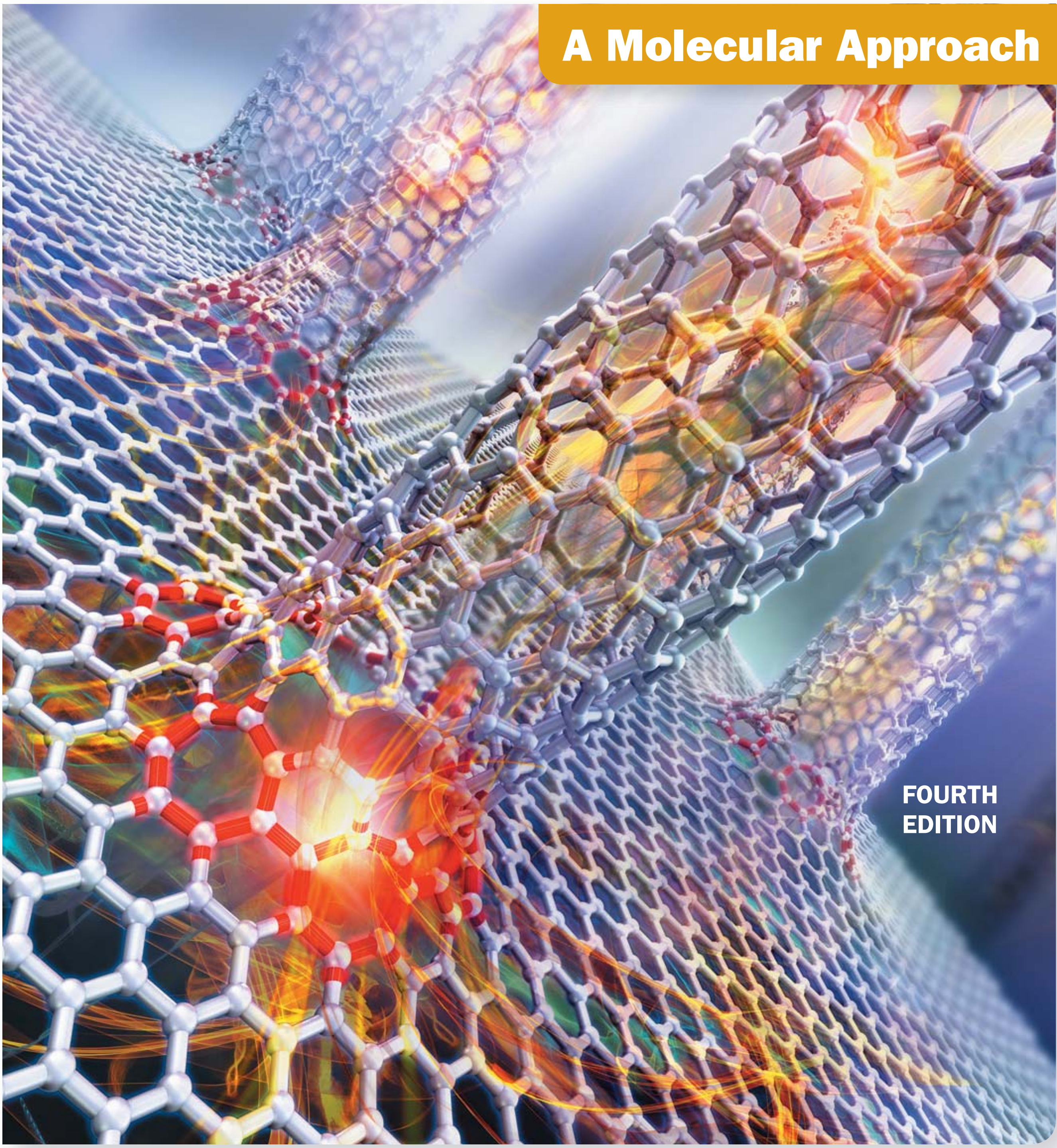
CHEMISTRY

A Molecular Approach



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Nivaldo J. Tro
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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.

TO MICHAEL, ALI, KYLE, AND KADEN

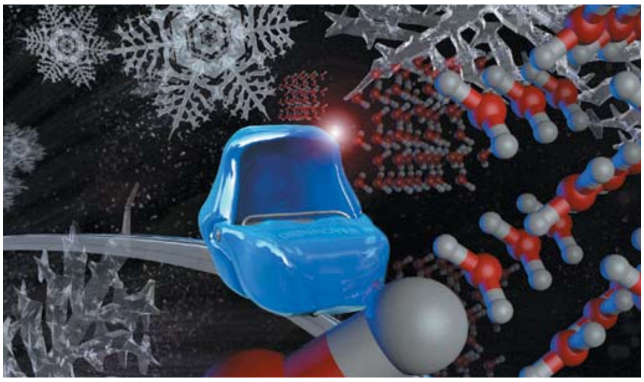
BRIEF CONTENTS

INTERACTIVE MEDIA CONTENTS

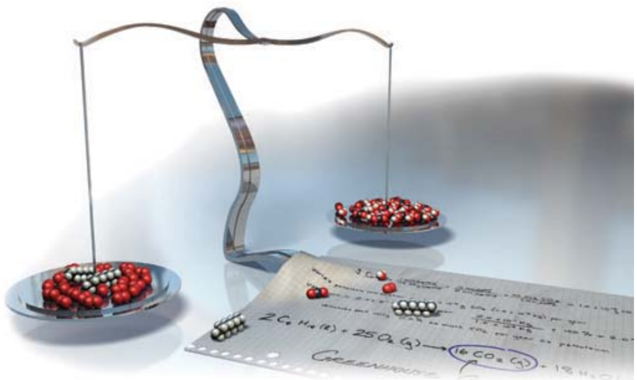
Interactive Worked Examples (IWEs) https://media.pearsoncmg.com/ph/esm/esm_tro_chemistry_4/media/index.html

Key Concept Videos (KCVs) https://media.pearsoncmg.com/ph/esm/esm_tro_chemistry_4/media/index.html

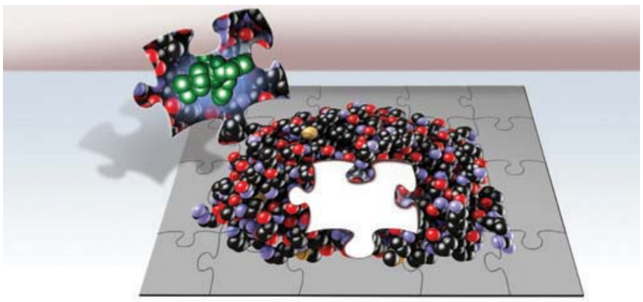
CONTENTS

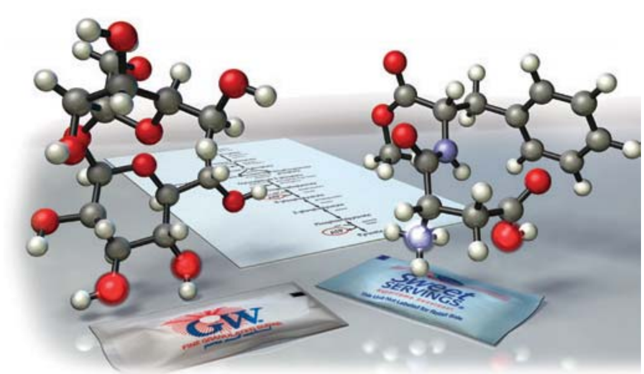


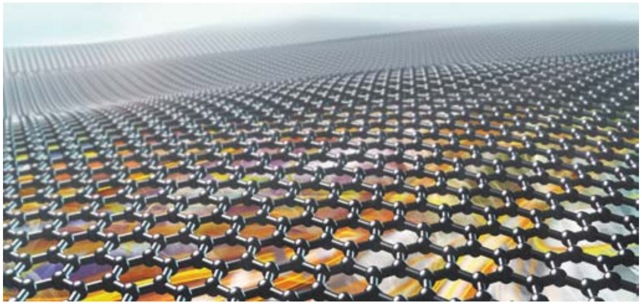
2 Atoms and Elements 44




4 Fe(s) + 3 O2(g) → 2 Fe2O3(s)



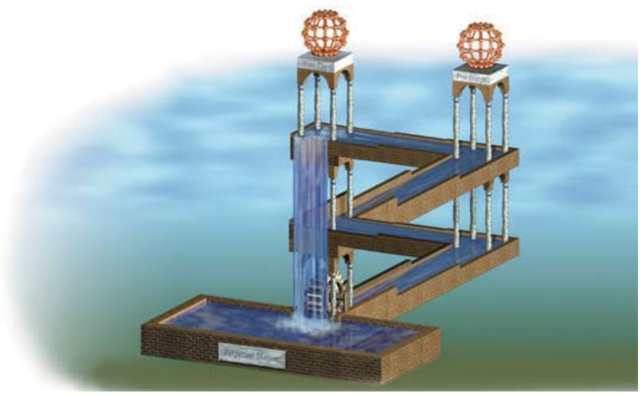




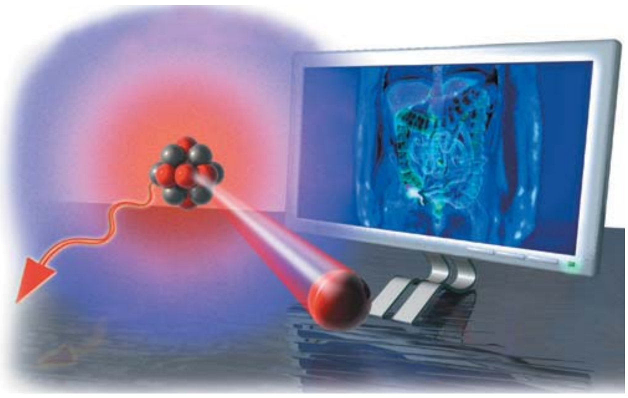

Life of Pi


Rate k=Ae$^{-Ea/RT}$


ANTIFREEZE




Fuel Cell

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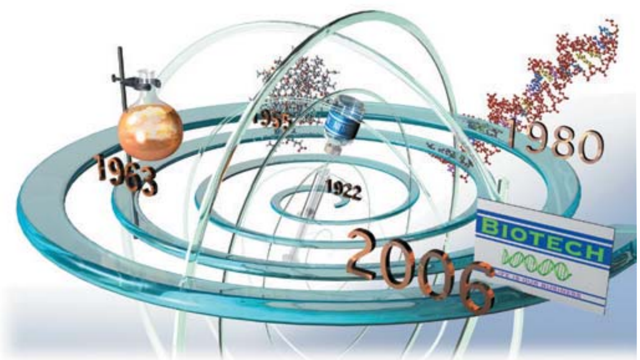
1963
1922
1980
2006
BIOTECH


V
Vanadium

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. Although 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 create 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 previous 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 reviewed content or have contacted me directly, you will likely see your suggestions reflected in the changes I have made. Thank you.

Some of the most exciting changes in this edition are in the media associated with the book. I have added approximately 57 new Key Concept Videos and 61 new Interactive Worked examples to the media package. You can see a more detailed description of these videos in the following section entitled *What's New in This Edition*. This means that you now have a library of over 150 interactive videos to enhance your course. In my courses, I use these videos to implement a *before, during, after* strategy for my students. My goal is simple: *Engage students in active learning before class, during class, and after class.* To that end, I assign a key concept video *before* each class session.

The video introduces students to a key concept for that day and gets them thinking about it before they come to class. *During* class, I expand on the concept and use *Leaning Catalytics* to question my students. Instead of passively listening to a lecture, they are interacting with the concepts through questions that I pose. Some of these questions are answered individually; other times I have them pair up with a partner. This approach has changed my classroom. Students engage in the material in new ways. They have to think and process and interact. It is deeply satisfying for me to see my students so engaged. Finally, *after* class, I give them another assignment, often an interactive worked example with a follow-up question. At this point, they have to apply what they have learned to solve a problem.

The results have been fantastic. My students are enjoying the process because they are engaged before, during, and after class rather than only looking at material the night before a problem set is due. I have seen evidence of their improved learning through increases in their scores on the American Chemical Society Standard General Chemistry Exam, which I always administer as the final exam for my course.

Although we have added exciting new media elements and made other changes to the book, the book's goal 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 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.

Second, *Chemistry: A Molecular Approach* is 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.*

Third, *Chemistry: A Molecular Approach* is a *visual book.* Wherever possible, I use images to deepen the student's insight into chemistry. In developing chemical principles, multipart images help 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.

Fourth, *Chemistry: A Molecular Approach* is 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. This philosophy is also integral to the *Key Concept Videos*, which concisely reinforce student appreciation of the core concepts in each chapter.

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 have to meet them where they are, challenge them to the highest level of achievement, and 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. The most significant changes to the book and its supplements are listed below:

- NEW! Chapter 12: *Solids and Modern Materials*. This chapter contains new topics and consolidates content on materials that was found in other parts of the book in previous editions into one new chapter. All chapters beyond Chapter 12 have been renumbered.
- With the help of my colleagues, Thomas Greenbowe (University of Oregon), Kristin Ziebert (Oregon State University), and Michael Everest (Westmont College), I have added two new categories of end-of-chapter questions designed to help students build what we call "twenty-first-century skills." The first new category of questions is *Data Interpretation and Analysis*. These questions present real data in real-life situations and ask students to analyze that data. These in-depth exercises give students much needed practice in reading graphs, digesting tables, and making data-driven decisions. The second new category of questions is *Questions for Group Work*. Our group work questions give students the opportunity to work with their peers in small groups. The questions can be used in or out of the classroom, but the idea is to foster collaborative learning and to encourage students to work together as a team to solve problems.
- I have added approximately 57 new Key Concept Videos and 61 new Interactive Worked Examples to the media package that accompanies the book. (Since the previous edition had 40 Interactive worked examples, there is now a total of 158 interactive videos.) These tools are designed to help professors engage their students in active learning. Recent research has conclusively demonstrated that students learn better when they are active in the learning process, as opposed to passively listening and simply taking in content. The Key Concept Videos are brief (two to five minutes), and each introduces a key concept from a chapter. The student does not just passively listen to the video; the video stops in the middle and poses a question to the student. The student must answer the question before the video continues. Each video also includes a follow-up question that is assignable in MasteringChemistry^{TM}. The Interactive Worked Examples are similar in concept, but instead of explaining a key concept, they walk the student through one of the in-chapter worked examples from the book. Like the Key Concept Videos, Interactive Worked Examples stop in the middle and force the student to interact by completing a step in the example. The examples also have a follow-up question that is assignable in MasteringChemistry^{TM}. The power of interactivity to make connections in problem solving is immense. I did not quite realize this power until we started creating the Interactive Worked Examples and I saw how I could use the animations to make connections that are just not possible on the static page.
- There are approximately 21 new Conceptual Connection questions throughout the book.
- All the data throughout the book have been updated 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;* the unnumbered figure in Section 6.10 of *U.S. Energy Consumption; Figure 6.12 Energy Consumption by Source; Table 6.6 Changes in National Average Pollutant Levels, 1980–2013; Table 14.4 Change in Pollutant Levels*; *Figure 14.19 Ozone Depletion in the Antarctic Spring; Figure 16.15 Sources of U.S. Energy; Figure 16.16 Acid Rain;* and *Figure 16.18 U.S. Sulfur Dioxide Pollutant Levels*.
- Example 4.13 *Writing Equations for Acid–Base Reactions Involving a Strong Acid* and Example 14.2 *Determining the Order and Rate Constant of a Reaction* have been expanded.
- New worked examples have been added, including Example 4.14 *Writing Equations for Acid–Base Reactions Involving a Weak Acid*; Example 18.2 *Calculating ΔS for a Change of State;* Example 12.2 *Calculating the Packing Efficiency of a Unit Cell*; and Example 12.3 *Relating Unit Cell Volume, Edge Length, and Atomic Radius*.
- Several chapter-opening sections and (or) the corresponding art, including Sections 1.1, 2.1, 5.1, 16.1, and 17.1, have been replaced or modified.
- New information about *Thermoluminescent Dosimeters*, including new Figure 20.7, has been added.
- A definition and explanation for the heat (or enthalpy) of sublimation have been added to Section 11.6.
- A new section (Section 18.4) on the *Entropy Changes Associated with State Changes* has been added. This section also includes expanded coverage on reversible and irreversible processes.
- Several sections in Chapter 20: *Radioactivity and Nuclear Chemistry* have been modified, including Sections 20.3 and 20.5 and Tables 20.1 and 20.4.
- Approximately 40 end-of-chapter problems (in addition to over 40 new problems that have been added to new Chapter 12) have been added or modified.

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 this book. Most importantly, I thank my editor, 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 also grateful to Jennifer Hart, who has now worked with me on multiple editions of several books and in several different roles, including her role overseeing development. Jennifer, your guidance, organizational skills, and wisdom are central to the success of my projects, and I am eternally grateful. I also thank my development editor Erin

Mulligan, who has worked with me on many projects over several editions. Erin is an outstanding thinker and wordsmith who also has a great eye for detail and helps me tremendously on all aspects of my projects. Thank you, Erin. Thanks also to my media editor, Jackie Jakob. Jackie has been instrumental in helping me craft and develop the Key Concept Videos and Interactive Worked Examples that accompany this text. Her expertise, vision, and attention to detail are second to none. The quality and success of these videos are largely attributable to Jackie. Thanks, Jackie.

New to this edition is Sarah Shefveland. Although we have only worked together a short while, I am already indebted to her helpfulness. I am also grateful to Lindsey Pruett, who helped with organizing reviews, as well as numerous other tasks associated with keeping the team running smoothly. I am also grateful to Jeanne Zalesky, Editor-in-Chief for Physical Sciences. She has supported me and my projects and allowed me to succeed. I am also grateful to my team of marketing managers, Chris Barker and Elizabeth Ellsworth. Chris and I go way back, and I am excited to work with him in this new role. Elizabeth and I have only worked together for a short while, but I am already impressed by her energy and ideas for 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 Derek Bacchus and Elise Landson for their creativity and hard work in crafting the design of this text. Finally, I would like to thank Beth Sweeten and the rest of the Pearson production team. They are a first-class operation—this text has benefited immeasurably from their talents and hard work. I also thank Francesca Monaco and her coworkers at CodeMantra. I am a picky author and Francesca is endlessly patient and a true professional. I am also greatly indebted to my copy editor, Betty Pessagno, for her dedication and professionalism, and to Eric Schrader for his exemplary photo research. And of course, I am continually grateful for Paul Corey, with whom I have now worked for over 15 years and 12 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.

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 and Mark Sargent, the president and provost (respectively) of Westmont College, who have allowed me the time and space to work on my books. Thank you, Gayle and Mark, 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; and my nephews and nieces, Germain, Danny, Lisette, Sara, and Kenny. These are the people with whom I celebrate life.

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 like to thank all of the general chemistry students who have been in my classes throughout my 25 years as a professor at Westmont College. You have taught me much about teaching that is now in this book.

Lastly, I am indebted to the many reviewers, listed on the following pages, whose ideas are embedded 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 Thomas Greenbowe, Michael Everest, Kristin Ziebart, Michael Burand, Jeff Bryan,and Ali Sezer who played particularly important roles in many of the new features of this edition. I am also grateful to the accuracy reviewers (Michael Burand, Brian Gute, Tracy Knowles, Tom McGrath, Gary Mines, and Allison Soult) who tirelessly checked page proofs for correctness.

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21st Century Skills

Tro's approach to General Chemistry addresses 21st century skills, including the ability to analyze and interpret data and the capacity to work well in groups. Concepts are covered in a thorough and approachable manner, which ensures that every explanation is relevant and helps students see the real-world importance and applications of Chemistry. Students can learn concepts and build skills through numerous resources for use before, during, and after class.

Data Interpretation and Analysis

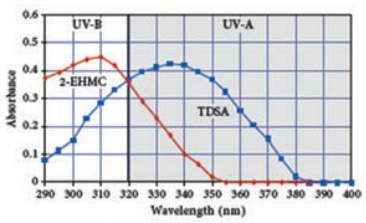
UV Radiation and Sunscreen

114. On average sunlight shines on the surface of Earth with an intensity of 910 Watts/m^2. Some of this energy is in the form of ultraviolet (UV) radiation. The compounds in chemical sunscreens absorb ultraviolet rays and release the energy as lower-energy infrared (IR) rays, thereby preventing the skin-damaging UV rays from reaching the skin. You may have noticed references to UV-A (320–400 nm) and UV-B (280–320 nm) protection in sunscreen packaging and advertisements. Figure a► lists the chemical formula and molar mass of two compounds, 2-ethylhexyl *p*-methoxycinnamate (2-EHMC), a UV-B sunscreen, and terephthalylidenedicamphor sulfonic acid (TDSA), a UV-A sunscreen.

Sunscreen Compound	Chemical Formula	$\mathcal{M}$ (g/mol)
terephthalylidenedicamphor sulfonic acid (TDSA)	$C_{28}H_{34}O_8S_2$	562.70
2-ethylhexyl *p*-methoxycinnamate (2-EHMC)	$C_{18}H_{26}O_3$	290.39

▲ **FIGURE a Chemical Formula and Molar Mass ($\mathcal{M}$) of Chemicals Commonly Found in Sunscreens**

Organic molecules have groups of atoms bonded together that can vibrate and rotate, making more energy states available. As a result, instead of absorbing exact wavelengths of radiation as elements do, organic molecules absorb over a broad range of wavelengths. Figure b▼ plots absorbance versus wavelength for 2-EHMC and TDSA. Greater absorbance indicates that the compound absorbs more light.



▲ **FIGURE b Sunscreen Absorption**
http://mycpss.com/critical-wavelength-broad-spectrum-uv-protection/

Use the information provided in the figures to answer the following questions:

a. Calculate the energy absorbed by TDSA at its maximum absorption for one photon of UV radiation.
b. Calculate the energy absorbed by 2-EHMC at its maximum absorption for one photon of UV radiation.
c. Which absorbs more energy, 2-EHMC or TDSA, at their respective maximum wavelengths?
d. Why are these two compounds commonly included in sunscreen products?
e. A person does not apply sunscreen and has 0.42 m^2 of skin exposed to the sun for 1.00 hour. Calculate the total energy (in Joules) absorbed by the skin. Assume there are 3.066×10^{21} photons/meter^2/sec. Assume an average wavelength of 330 nm in order to calculate the energy of a UV photon. Assume half of the photons that strike the skin are reflected.
f. In order for a sunscreen product with equal amounts of TDSA and 2-EHMC to provide adequate protection from UV-A and UV-B rays for 1.00 hour, how many molecules of TDSA and 2-EHMC must be present on the skin? Assume one molecule of TDSA and one molecule 2-EHMC can each absorb 10,000 photons per hour. Assume the photon rate is the same as in part e.
g. Calculate the mass of TDSA and 2-EHMC in grams that must be present on the exposed skin referenced in parts e and f in order to protect the skin.

◄ **NEW! Data Interpretation and Analysis** questions present real data in real life situations and ask students to analyze that data. These in-depth exercises give students practice reading graphs, digesting tables, and making data-driven decisions.

Data Interpretation and Analysis

Heavy Metals in Recycled Paper Packages

142. Demand for recycled paper has increased as consumers have become more aware of the environmental issues surrounding waste disposal. Paper is a natural raw material made from renewable wood and plants. Recycled paper is made from waste paper and paperboard. Both new paper and recycled paper contain traces of heavy metals. However, some types of recycled paper contain more heavy metals than new paper due, in part, to the inks used for printing or adding color to the original paper. Metals can migrate from the paper packaging and containers used for food to the food itself. This metal migration is controlled and monitored to reduce the exposure of humans to heavy metals.

Food agencies in each country determine the limit of cadmium, zinc, nickel, and copper in packaging materials. Most countries impose a limit of heavy metals in recycled paper not to exceed 100.0 ppm or 100.0 mg/kg. The limit for lead in egg-, fruit-, or vegetable-packaging is lower—not to exceed—20.0 mg/kg. The table in Figure a▼ lists the results of the analysis of samples of recycled paper produced by a manufacturer during a three-month period.

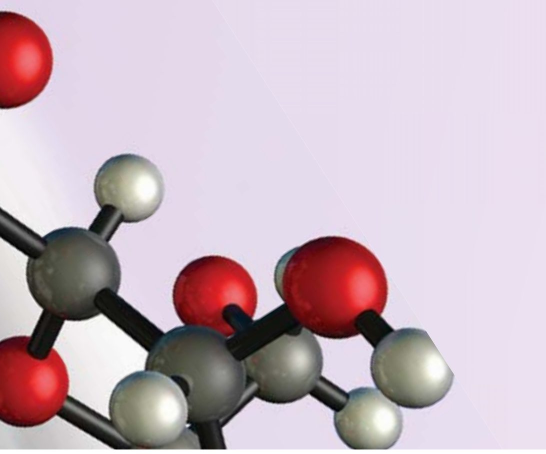
	Zn	Pb	Cd	Ni	Cu
March	2.7	3.5	0.129	1.7	32.3
April	3.2	2.8	0.092	1.6	29.2
May	3.7	2.4	0.096	1.5	19.9

▲ **FIGURE a Heavy Metal Values in Three Samples of Recycled Paper (mg/kg ± 0.1)**

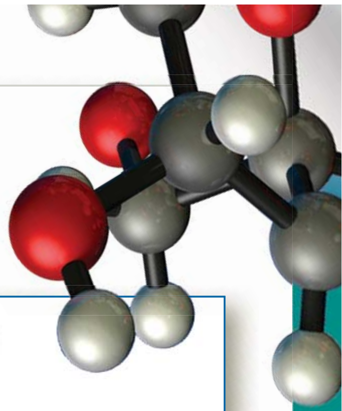
The goal of the manufacturer is to reduce the amount of heavy metals—especially lead—in the recycled paper it produces and sells. From March to May, the manufacturer varied the methods of production each month to determine which method would produce paper with the lowest metal content. Each month, lab technicians cut small samples of recycled paper with an area of 1.000 dm^2 and a thickness of 0.0500 cm. The technicians then prepared the samples for analysis. The average density of the samples is 800.0 ± 0.0245 kg/m^3.

Use the information provided in the figure to answer the following questions:

a. Did the company reduce the amount of lead in its product between March and May?
b. Which metal was not reduced?
c. Each month's sample represents a different manufacturing process. Which process would you recommend the manufacturer choose to continue to use over the next year while additional processes are tested? Why?
d. What is the total amount of the five metals for the April sample (in mg/kg)?
e. What is the total mass (in mg) of the five metals for the April sample found in the 1.000 dm^2 × 0.0500 cm sample?
f. Lead has four stable isotopes: ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb with % abundances of 1.40, 24.10, 22.10, and 52.40, respectively. Determine the mass (in mg) of ^{208}Pb in the April sample.
g. Sketch the mass spectrum for lead.



21st Century Skills



Active Classroom Learning

Questions for Group Work

Discuss these questions with the group and record your consensus answer.

148. Assign one of the three simple gas laws to each member of your group. For the assigned gas law, have each member write two equations, draw a graph, and describe it in a complete sentence. Have each group member present his or her law to the group.

149. Review the ideal gas law. Without referring back to the text, use algebra to write the ideal gas law and solve for each of the individual variables it contains. Have each group member solve for a different variable and present answers to the group.

150. Hydrogen peroxide (H_2O_2) decomposes in the presence of a catalyst to form water and oxygen. The catalyst is added to 5.00 mL of a hydrogen peroxide solution at 25.0 °C, and 49.5 mL of gas is collected over water at a total pressure of 763.8 mmHg.

a. Write and balance the chemical reaction (note: catalysts do not appear in balanced chemical equations).
b. Look up the vapor pressure of water under these conditions.
c. What is the partial pressure of oxygen collected over the water?
d. How many moles of oxygen are collected?
e. How many grams of hydrogen peroxide were in the original sample?
f. What is the concentration (in mol/L) of the hydrogen peroxide solution?
g. Which part of this process is conceptually most difficult for your group?

151. A box contains equal amounts of helium, argon, and krypton (all gases) at 25 °C. Using complete sentences, describe the temperatures, masses, average velocities, and average kinetic energy of the three kinds of gas in the mixture. What do they have in common? What are the differences? How are these properties related?

152. Calculate the pressure exerted by 1 mol of an ideal gas in a box that is 0.500 L and 298 K. Have each group member calculate the pressure of 1 mol of the following gases in the same box at the same temperature: He, Ne, H_2, CH_4, and CO_2. Compare group members' answers as well as all answers with the pressure of an ideal gas. Assuming that the van der Waals equation predictions are accurate, account for why the pressure of each gas is higher or lower than that predicted for an ideal gas.

Active Classroom Learning

Questions for Group Work

Discuss these questions with the group and record your consensus answer.

130. Have each member of your group represent an atom of a metal or an atom of a nonmetal. Each group member holds a coin to represent an electron. Which group members are most reluctant to give up their electrons? Which group members are most willing to give up their electrons? Determine which kind of bond could form between each pair of group members. Tabulate your results.

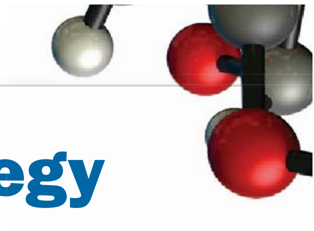
131. Spend a few minutes reviewing the Lewis dot symbols for the atoms H through Ne. Form a circle and have each group member ask the group member on his or her right to draw the Lewis symbol for a specific atom. Keep going around until each group member can write all the Lewis dot symbols for the atoms H through Ne. Determine the formal charge for each symbol. In a complete sentence or two, describe why they are all the same.

132. Draw the Lewis dot symbols for the atoms Al and O. Use the Lewis model to determine the formula for the compound formed from these two atoms.

133. Draft a list of step-by-step instructions for writing the correct Lewis dot structure for any molecule or polyatomic ion.

134. Pass a piece of paper around the group and ask each group member in turn to perform the next step in the process of determining a correct Lewis structure (including formal charges on all atoms and resonance structures, if appropriate) for the following molecules and ions: N_2H_4, CCl_4, CO_3^{2-}, and NH_4^+.

NEW! Questions for Group Work give students the opportunity to work with their peers in small groups. The questions can be used in or out of the classroom, and the goal is to foster collaborative learning and encourage students to work together as a team to solve problems.



Interactive Problem-Solving Strategy

A unique and consistent step-by-step format encourages logical thinking throughout the problem-solving process, driving students to think through problems critically, rather than to simply memorize formulas.

Example 17.6 **Strong Acid–Strong Base Titration pH Curve**

A 50.0-mL sample of 0.200 M sodium hydroxide is titrated with 0.200 M nitric acid. Calculate pH:
(a) after adding 30.00 mL of HNO_3 **(b)** at the equivalence point

SOLUTION

(a) Begin by calculating the initial amount of NaOH (in moles) from the volume and molarity of the NaOH solution. Because NaOH is a strong base, it dissociates completely, so the amount of OH^- is equal to the amount of NaOH.

$$\text{moles NaOH} = 0.0500\ \text{L} \times \frac{0.200\ \text{mol}}{1\ \text{L}} = 0.0100\ \text{mol}$$
$$\text{moles } OH^- = 0.0100\ \text{mol}$$

Calculate the amount of HNO_3 (in moles) added at 30.0 mL from the molarity of the HNO_3 solution.

$$\text{mol } HNO_3 \text{ added} = 0.0300\ \text{L} \times \frac{0.200\ \text{mol}}{1\ \text{L}} = 0.00600\ \text{mol } HNO_3$$

As HNO_3 is added to the solution, it neutralizes some of the OH^-. Calculate the number of moles of OH^- remaining by setting up a table based on the neutralization reaction that shows the amount of OH^- before the addition, the amount of H_3O^+ added, and the amounts left after the addition.

	$OH^-(aq)$ +	$H_3O^+(aq) \longrightarrow 2\ H_2O(l)$
Before addition	0.0100 mol	≈0.00 mol
Addition	—	0.00600 mol
After addition	0.0040 mol	0.00 mol

Calculate the OH^- concentration by dividing the amount of OH^- remaining by the *total volume* (initial volume plus added volume).

$$[OH^-] = \frac{0.0040\ \text{mol}}{0.0500\ \text{L} + 0.0300\ \text{L}} = 0.0500\ \text{M}$$

Calculate the pOH from $[OH^-]$.

$$\text{pOH} = -\log(0.0500) = 1.30$$

Calculate the pH from the pOH using the equation pH + pOH = 14.

$$\text{pH} = 14 - \text{pOH} = 14 - 1.30 = 12.70$$

(b) At the equivalence point, the strong base has completely neutralized the strong acid. The $[H_3O^+]$ at 25 °C from the ionization of water is 1.00×10^{-7} M and the pH is therefore 7.00.

pH = 7.00

FOR PRACTICE 17.6 Calculate the pH in the titration in Example 17.6 after the addition of 60.0 mL of 0.200 M H

Icons appear next to examples indicating an **Interactive Worked Example** digital version is available in the eText and on mobile devices via a QR code located here, and on the back cover of your textbook.

NEW! 61 Interactive Worked Examples make Tro's unique problem-solving strategies interactive, bringing his award-winning teaching directly to all students using his text. In these digital, mobile versions, students are shown how to break down problems using Tro's proven "Sort, Strategize, Solve, and Check" technique, helping to learn how to consistently solve chemical problems. These examples can be utilized as an after class activity.

Strong Acid-Strong Base Titration pH Curve

A 50.0-mL sample of 0.200 M sodium hydroxide is titrated with 0.200 M nitric acid.
Calculate: (a) the pH after adding 30.00 mL of HNO_3

$$\text{moles NaOH} = 0.0500\ \text{L} \times \frac{0.200\ \text{mol}}{1\ \text{L}} = 0.0100\ \text{mol}$$
$$\text{moles } OH^- = 0.0100\ \text{mol}$$
$$\text{moles } HNO_3 \text{ added} = 0.0300\ \text{L} \times \frac{0.200\ \text{mol}}{1\ \text{L}} = 0.00600\ \text{mol } HNO_3$$
$$[OH^-] = \frac{0.0040\ \text{mol}}{0.0500\ \text{L} + 0.0300\ \text{L}} = 0.0500\ \text{M}$$

	$OH^-(aq)$ +	$H_3O^+(aq) \rightarrow 2\ H_2O(l)$
Before addition	0.0100 mol	≈0.00 mol
Addition	-	0.00600 mol
After addition	0.0040 mol	≈0.00 mol

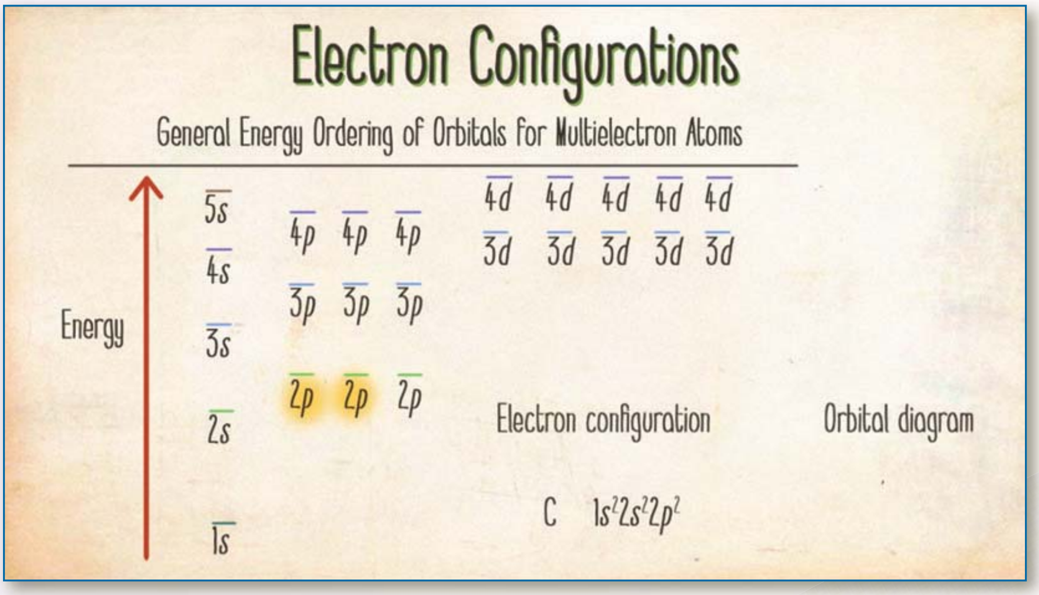
What is the pH of the solution at this point?

a) 0.0500
b) 1.30
c) 12.70

A Focus on Conceptual Understanding

NEW! 57 Key Concept Videos combine artwork from the textbook with both 2D and 3D animations to create a dynamic on-screen viewing and learning experience. These short videos include narration and brief live-action clips of author Niva Tro explaining the key concepts of each chapter. These videos can be utilized as a before class activity.

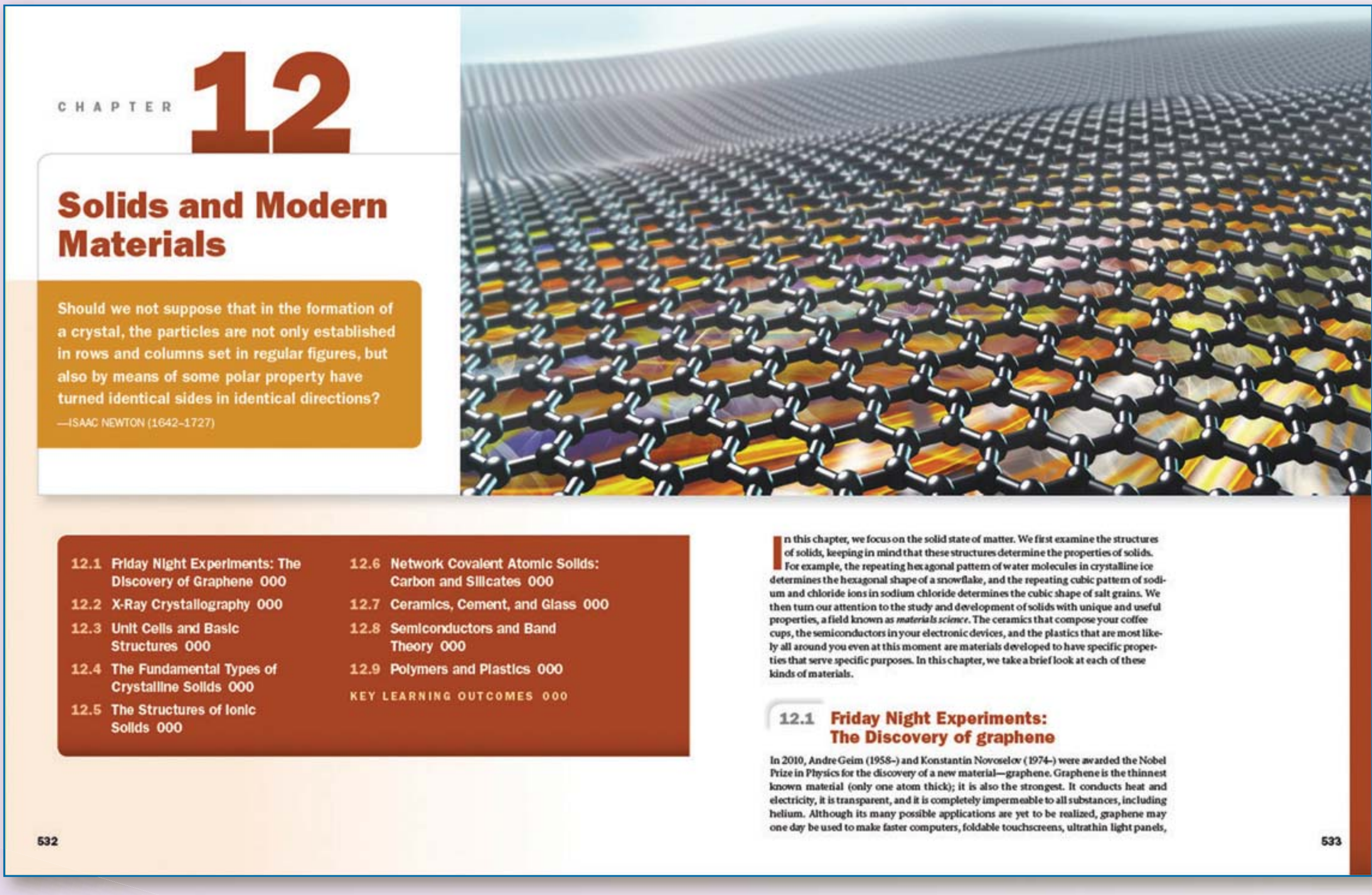
KCV **Electron Configurations**



NEW!

Chapter 12—Solids and Modern Materials

This chapter contains new topics and consolidates content on materials that was found in other parts of the book in previous editions into one new chapter. New and consolidated topics include unit cells, carbon and silicates, ceramics, cement, glass, polymorphs, polyethylene, and the band gap in Group 4A elements.



CHAPTER 12

Solids and Modern Materials

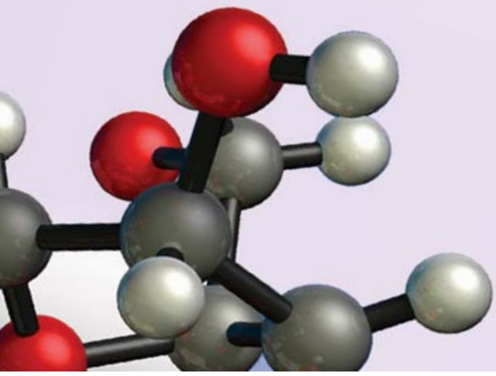
Should we not suppose that in the formation of a crystal, the particles are not only established in rows and columns set in regular figures, but also by means of some polar property have turned identical sides in identical directions?
—ISAAC NEWTON (1642–1727)

In this chapter, we focus on the solid state of matter. We first examine the structures of solids, keeping in mind that these structures determine the properties of solids. For example, the repeating hexagonal pattern of water molecules in crystalline ice determines the hexagonal shape of a snowflake, and the repeating cubic pattern of sodium and chloride ions in sodium chloride determines the cubic shape of salt grains. We then turn our attention to the study and development of solids with unique and useful properties, a field known as *materials science*. The ceramics that compose your coffee cups, the semiconductors in your electronic devices, and the plastics that are most likely all around you even at this moment are materials developed to have specific properties that serve specific purposes. In this chapter, we take a brief look at each of these kinds of materials.

12.1 Friday Night Experiments: The Discovery of graphene

In 2010, Andre Geim (1958–) and Konstantin Novoselov (1974–) were awarded the Nobel Prize in Physics for the discovery of a new material—graphene. Graphene is the thinnest known material (only one atom thick); it is also the strongest. It conducts heat and electricity, it is transparent, and it is completely impermeable to all substances, including helium. Although its many possible applications are yet to be realized, graphene may one day be used to make faster computers, foldable touchscreens, ultrathin light panels,

532 533



Active and Adaptive

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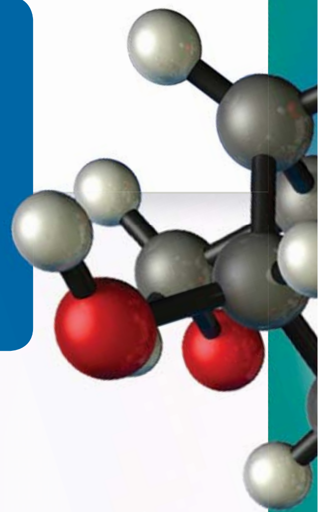
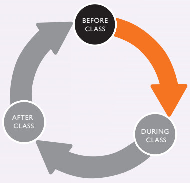


NEW! Ready-to-Go Teaching Modules in the Instructor Resources section help instructors efficiently make use of the available teaching tools for each chapter. Pre-built before class assignments, in-class activities, and after-class assignments are provided for ease of use. Instructors can incorporate active learning into their course with the suggested activity ideas, Learning Catalytics questions, and clicker questions.



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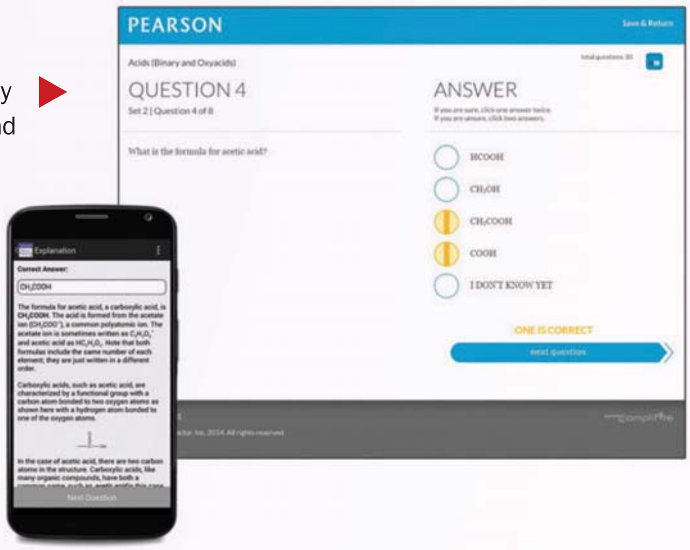
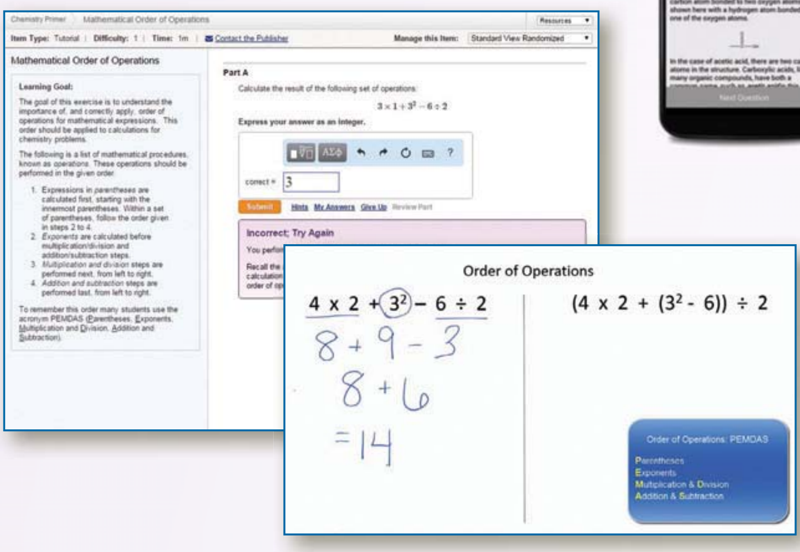
Dynamic Study Modules help students study effectively on their own by continuously assessing their activity and performance in real time. In this edition, 66 topics include key math skills, general chemistry skills such as nuclear chemistry, phases of matter, redox reactions, acids and bases, and organic and biochemistry skills.





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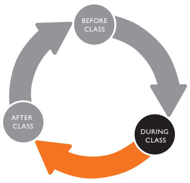

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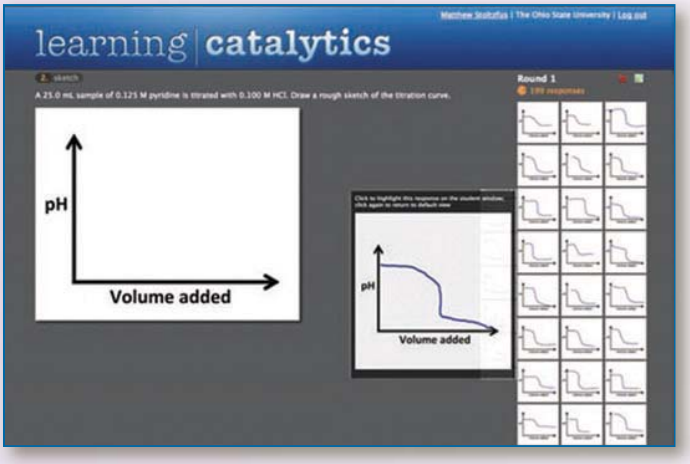
Learning Catalytics™ generates class discussion, guides lecture, and promotes peer-to-peer learning with real-time analytics. MasteringChemistry with eText now provides Learning Catalytics—an interactive student response tool that uses students' smartphones, tablets, or laptops to engage them in more sophisticated tasks and thinking. Instructors can:

- Pose a variety of open-ended questions that help students develop critical thinking skills
- Monitor responses to find out where students are struggling
- Use real-time data to adjust instructional strategy and try other ways of engaging students during class
- Manage student interactions by automatically grouping students for discussion, teamwork, and peer-to-peer learning



Questions for Group Work

Tools for active learning have been enhanced throughout the book, allowing students to dive into material in an engaging and effective way.

Active Classroom Learning

Questions for Group Work

Discuss these questions with the group and record your consensus answer.

140. Have each group member write a problem involving the transfer of heat from one material in Table 6.4 to another material in the table. Working as a group, solve each problem. The group member who wrote each problem may act as the group facilitator when the group is working on his or her problem. What do all of your problems have in common? How do they differ?

141. Classify each process as endothermic or exothermic. What is the sign of ΔH for each process? Explain your answers.

a. gasoline burning in an engine
b. steam condensing on a mirror
c. water boiling in a pot

Provide at least two additional examples of exothermic processes and two additional examples of endothermic processes. Have each member of your group provide an example.

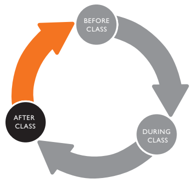
142. A propane tank on a home barbeque contains 10.4×10^3 g of propane.

a. Write the balanced chemical reaction for the combustion of gaseous propane (C_3H_8) to form water vapor and gaseous carbon dioxide.
b. Use the value for ΔH_{rxn} provided in the text to calculate the total amount of heat produced when the entire contents of the tank of propane is burned.
c. What mass of water could be warmed from 25 °C to 100 °C with this much heat?

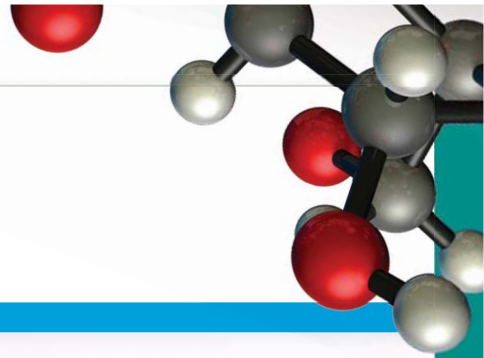
Solid carbon, C(*s*, graphite), gaseous hydrogen, $H_2(g)$, and the sugar glucose, $C_6H_{12}O_6(s)$ are all burned with oxygen in a calorimeter, and the amount of heat given off is determined for each process. How can these data be used to determine the heat of formation of glucose? Your answer should include both chemical reactions and complete sentences.

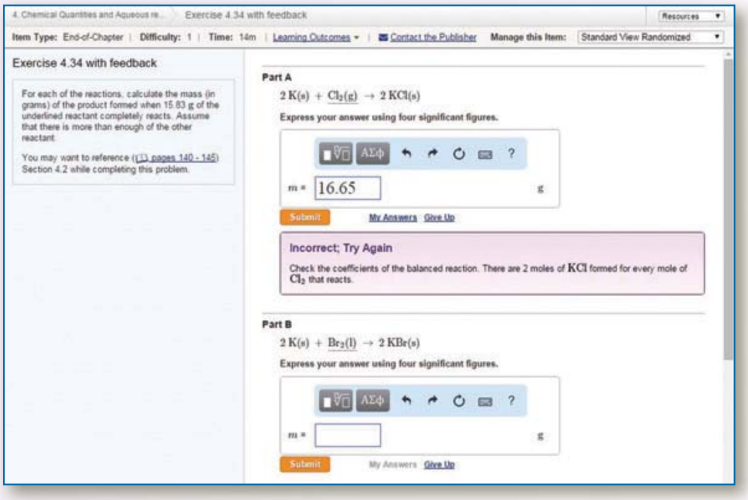
143. Consider the decomposition of liquid hydrogen peroxide (H_2O_2) to form water and oxygen.

a. What is the heat of formation for hydrogen peroxide?
b. What is the heat of formation for liquid water?
c. What is the heat of formation for gaseous oxygen? Why?
d. Write the balanced chemical equations that correspond to the ΔH values you looked up for parts a, b, and c.
e. Write the balanced chemical equation for the decomposition of hydrogen peroxide to form water and oxygen. (Write the equation such that the coefficient on oxygen is 1.)
f. What is the heat of reaction for the process in part e?
g. Draw a scale diagram of this reaction (1 cm = 100 kJ) that shows the relative energies of reactants (on the left), products (on the right), and the elements in their most stable states (in the middle). Label all the energies you know.



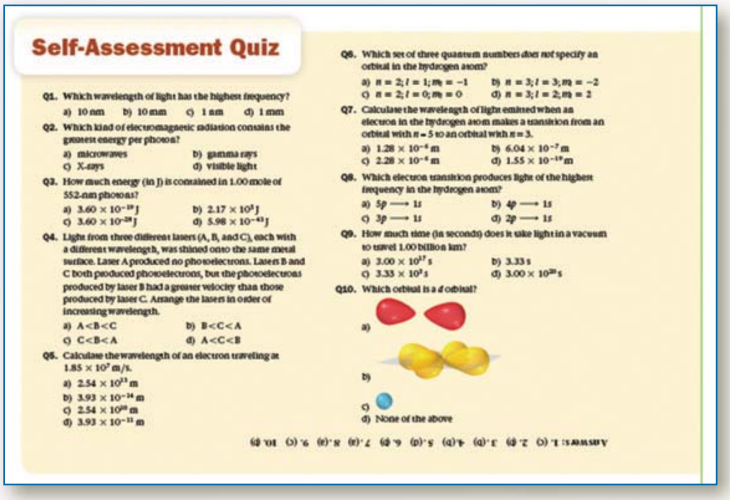
AFTER CLASS

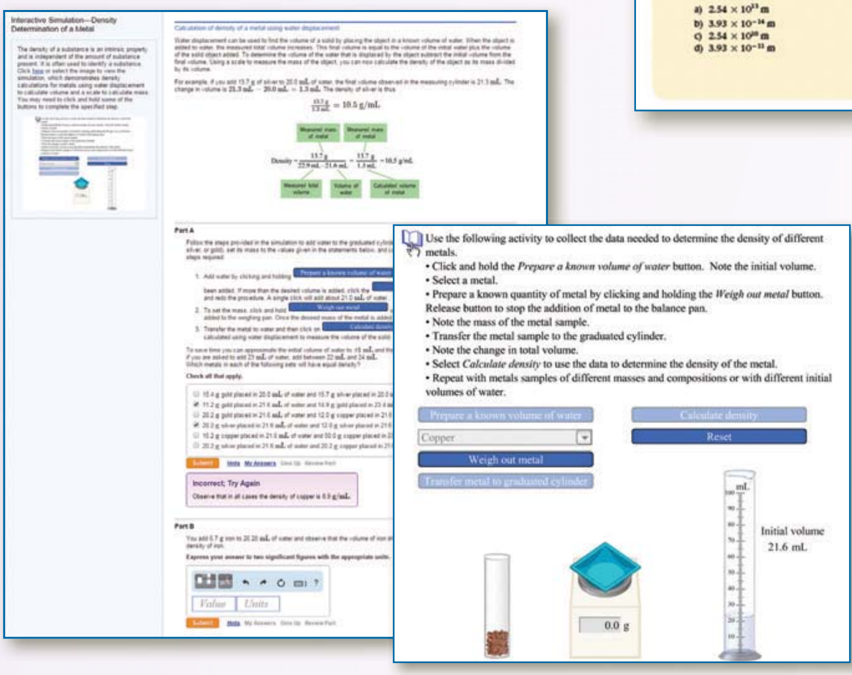




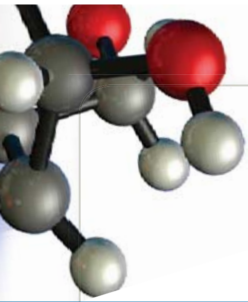
NEW! **In this edition,** 200 more end of chapter problems now contain wrong answer specific feedback with links to the eText.

Self-Assessment Quizzes now contain wrong-answer feedback links to the eText, and an additional 10–15 multiple-choice questions authored in the ACS-exams and MCAT style in each chapter. These improvements help students optimize the use of quizzing to improve their understanding and class performance.





Multimedia-rich Tutorials feature specific wrong-answer feedback, hints, and a wide variety of educationally effective content to guide your students through the toughest topics in chemistry. The hallmark Hints and Feedback offer instruction similar to what students would experience in an office hours visit, allowing them to learn from their mistakes without being given the answer.



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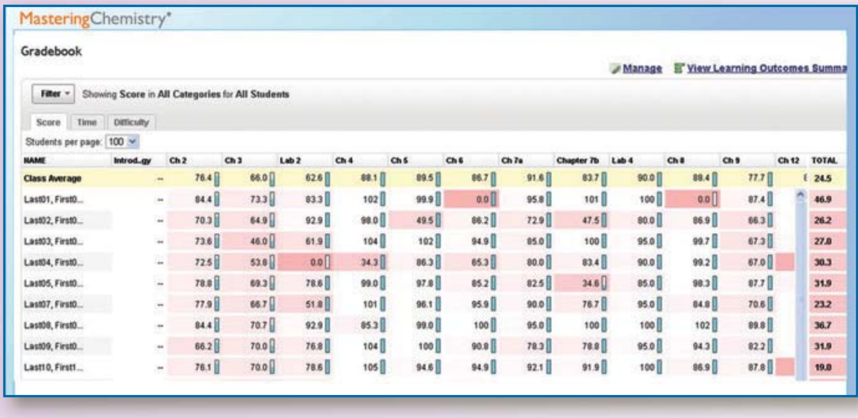

Gradebook
Every assignment is automatically graded. Shades of red highlight struggling students and challenging assignments.

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.

Adaptive Follow-Ups are personalized assignments pairing MasteringChemistry's powerful content with Knewton's adaptive learning engine to provide personalized help to students before misconceptions take hold. These assignments address topics students struggle with on assigned homework, including core prerequisite topics.

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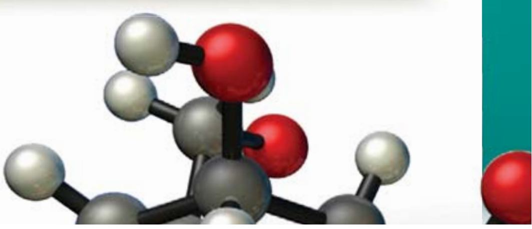
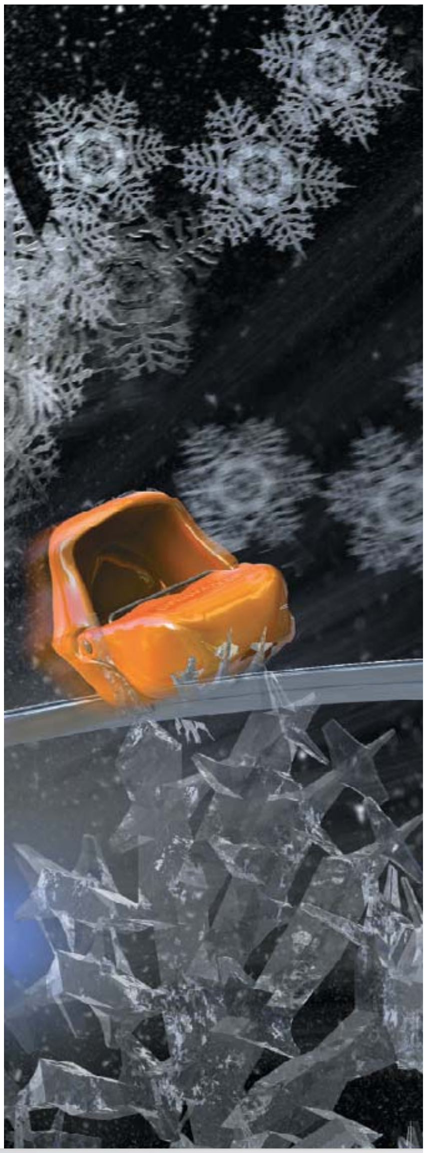
Resource	Available in Print	Available Online	Instructor or Student Resource	Description
Selected Solutions Manual 0134066286/ 9780134066288	✔		Student	Prepared by Kathy Shaginaw, the selected solutions manual for students contains complete, step-by-step solutions to selected odd-numbered, end-of-chapter problems.
Laboratory Manual 013406626X / 9780134066264	✔		Student	Prepared by John B. Vincent and Erica Livingston, this manual contains experiments with a focus on real-world applications. Each experiment covers one or more topics discussed within a chapter of the textbook.
Study Guide 0134066278 / 9780134066271	✔		Student	This Study Guide, prepared by Jennifer Shanoski, presents the major concepts, theories, and applications discussed in the text in a comprehensive and accessible manner.
Instructor's Resource Materials 0134074998 / 9780134074993		✔	Instructor	This resource contains the following: • All illustrations, tables, and photos from the text in JPEG format. • Three pre-built PowerPoint Presentations (lecture, worked examples, and images)
Instructor's Resource Manual 0134125770 / 9780134125770		✔	Instructor	Organized by chapter, this useful guide includes objectives, lecture outlines, references to figures and solved problems, as well as teaching tips. Prepared by Michael Ferguson.
Test Bank 0134126327 / 9780134126326		✔	Instructor	The Test Bank, prepared by Christine Hermann, contains more than 3,000 multiple choice, matching, and short-answer questions.
Solutions Manual 0134066251 / 9780134066257	✔		Instructor	Prepared by Kathy Shaginaw, this manual contains step-by-step solutions to all end-of-chapter exercises. With instructor permission, this manual may be made available to students.
Instructor's Manual for Laboratory Manual 0134143485 / 9780134143484		✔	Instructor	This manual provides solutions to the questions asked before each experiment in the accompanying Laboratory Manual, and provides background and suggestions for the instructor directing the lab.



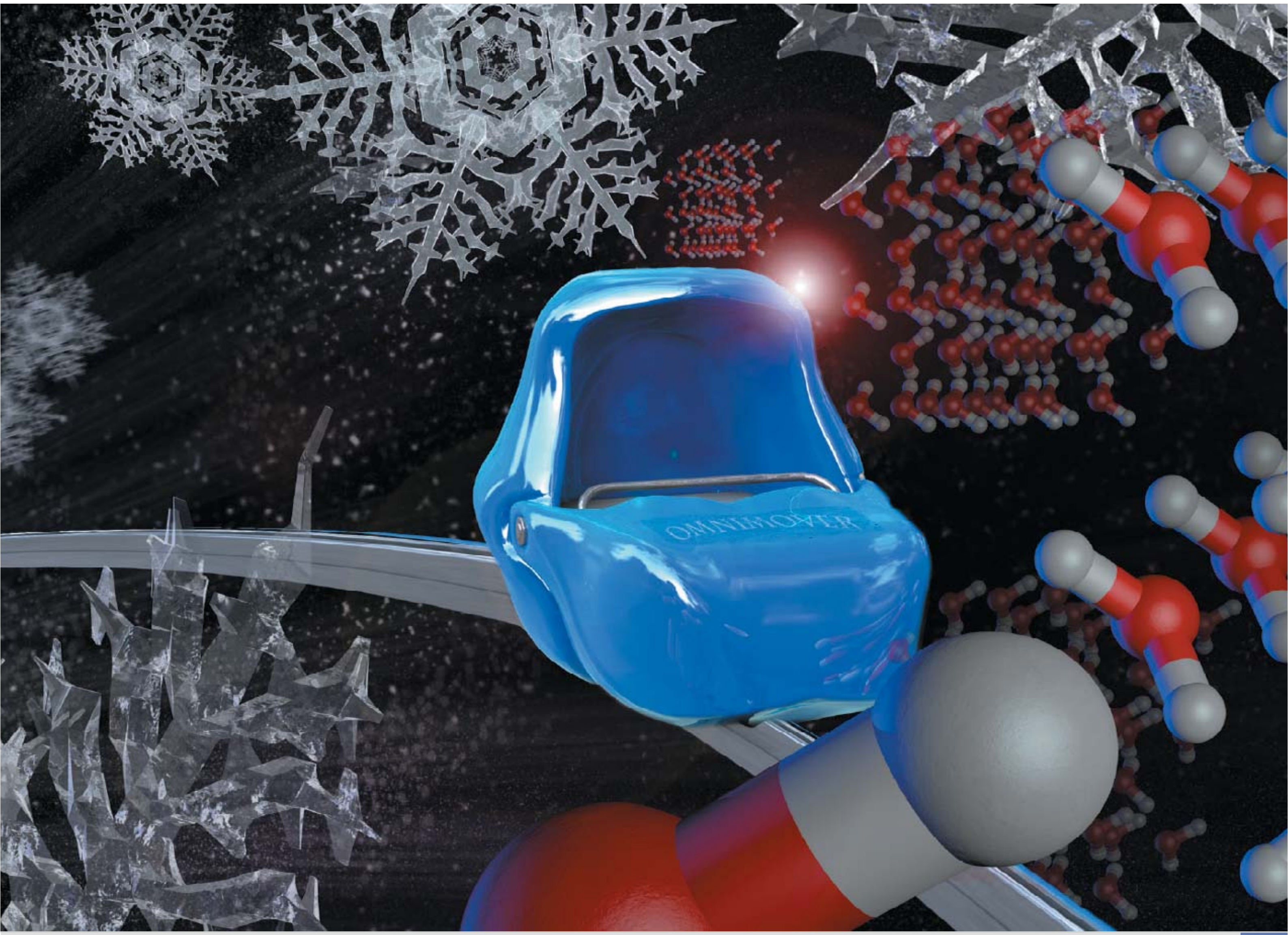
CHAPTER 1

Matter, Measurement, and Problem Solving



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

—ALBERT EINSTEIN (1879–1955)



▲ *This image portrays the Disneyland ride, Adventure Thru Inner Space. The premise of the ride is that you enter a microscope and get shrunk down to the size of an atom. The red and white spheres shown here depict oxygen and hydrogen atoms bound together to form water molecules.*

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.

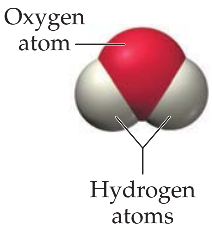
1.1 Atoms and Molecules

KCV **Atoms and Molecules**

As I sat in the "omnimover" and listened to the narrator's voice telling me that I was shrinking down to the size of an atom, I grew apprehensive but curious. Just minutes before, while waiting in line, I witnessed what appeared to be full-sized humans entering a microscope and emerging from the other end many times smaller. I was seven years old, and I was about to ride *Adventure Thru Inner Space*, a Disneyland ride (in Tomorrowland) that simulated the process of shrinking down to the size of an atom. The ride began with darkness and shaking, but then the shaking stopped and giant snowflakes appeared. The narrator explained that you were in the process of shrinking to an ever-smaller size (which explains why the snowflakes grew larger and larger). Soon, you entered the wall of the snowflake itself and began to see water molecules all around you. These also grew larger as you continued your journey into inner space and eventually ended up within the atom itself. Although this Disneyland ride bordered on being corny, and although it has since been shut down, it was my favorite ride as a young child.

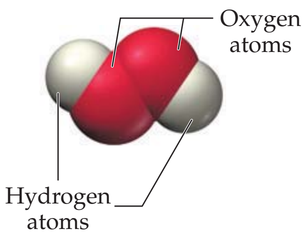
That ride sparked my interest in the world of atoms and molecules, an interest that has continued and grown to this day. I am a chemist because I am obsessed with the connection between the "stuff" around us and the atoms and molecules that compose that stuff. More specifically, I love the idea that we humans have been able to figure out the connection between the *properties of the stuff* around us and the *properties of atoms and molecules*. **Atoms** are sub-microscopic particles that are the fundamental building blocks of ordinary matter. Free atoms are rare in nature; instead they bind together in specific geometrical arrangements to form **molecules**. A good example of a molecule is the water molecule, which I remember so well from the Disneyland ride.

Water molecule



A water molecule is composed of one oxygen atom bound to two hydrogen atoms in the shape shown at left. The exact properties of the water molecule—the atoms that compose it, the distances between those atoms, and the geometry of how the atoms are bound together—determine the properties of water. If the molecule were different, water would be different. For example, if water contained two oxygen atoms instead of just one, it would be a molecule like this:

Hydrogen peroxide molecule



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

This molecule is hydrogen peroxide, which you may have encountered if you have ever bleached your hair. 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, a chemical reaction occurs that strips your hair of its color.

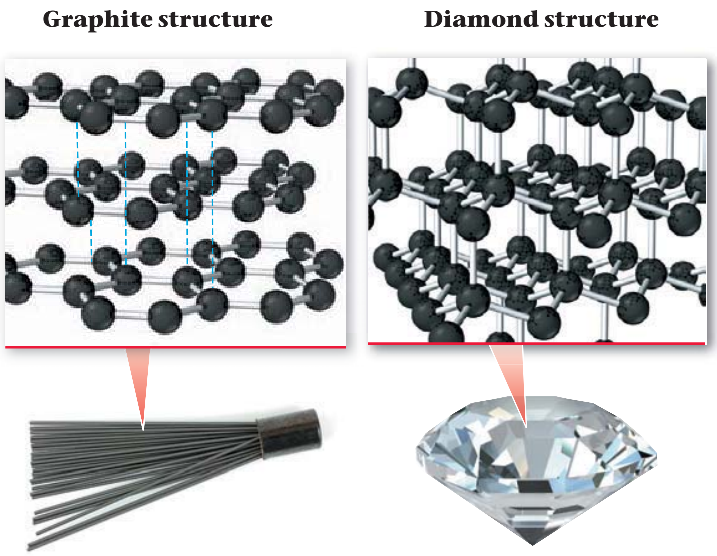
The details of how specific atoms bond to form a molecule—in a straight line, at a particular angle, in a ring, or in some other pattern—as well as the type of atoms in the molecule, determine everything about the substance that the molecule composes. If we want to understand the substances around us,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

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

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

Throughout this book, we explore the connection between atoms and molecules and the matter they compose. We seek to understand how differences on the atomic or molecular level affect the properties on the macroscopic level. Before we move on, let's examine one more example that demonstrates this principle. Consider the structures of graphite and diamond shown on the next page.

Graphite is the slippery black substance (often called pencil lead) that you have probably used in a mechanical pencil. Diamond is the brilliant gemstone found in jewelry. Graphite and diamond are both composed of exactly the same atoms—carbon atoms. The striking differences between the substances are a result of how those atoms are arranged. In graphite, the atoms are arranged in sheets. The atoms within each sheet are tightly bound to each other, but the sheets are *not* tightly bound to other sheets. Therefore the sheets can slide past each other, which is why the graphite in a pencil leaves a trail as you write. In diamond, by contrast, the carbon atoms are all bound together in a three-dimensional structure where layers are strongly bound to other layers, resulting in the strong, nearly unbreakable substance. This example illustrates how even the same atoms can compose vastly different substances when they are bound together in different patterns. Such is the atomic and molecular world—small differences in atoms and molecules can result in large differences in the substances that they compose.



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.E.) 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 (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.

▲ 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 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.

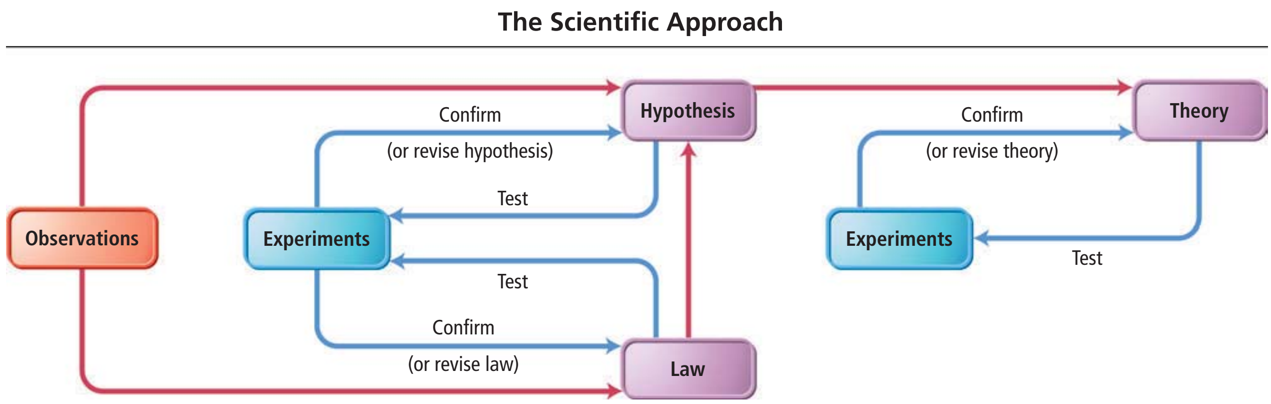
In Dalton's time, people thought atoms were indestructible. Today, because of nuclear reactions, we know that atoms can be broken apart into their smaller components.

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 1.1▼ 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 are based.

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 leads 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

▼ **FIGURE 1.1 The Scientific Approach to Knowledge**



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 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 below 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 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 (1922–1996), published in 1962 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 it 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." *From your knowledge of the history of science, can you think of any examples that support Kuhn's statement? 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

KCV **Classifying Matter**

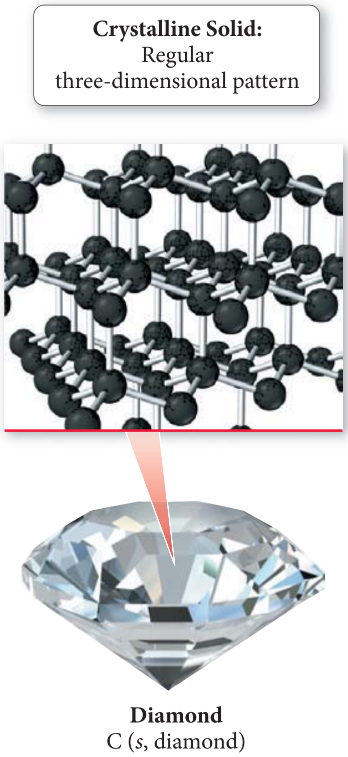
Matter is anything that occupies space and has mass. Your desk, your chair, and even your body are all composed of matter. Less obviously, the air around you is also matter—it too occupies space and has mass. We call a specific instance of matter—such as air, water, or sand—a **substance**. We classify 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

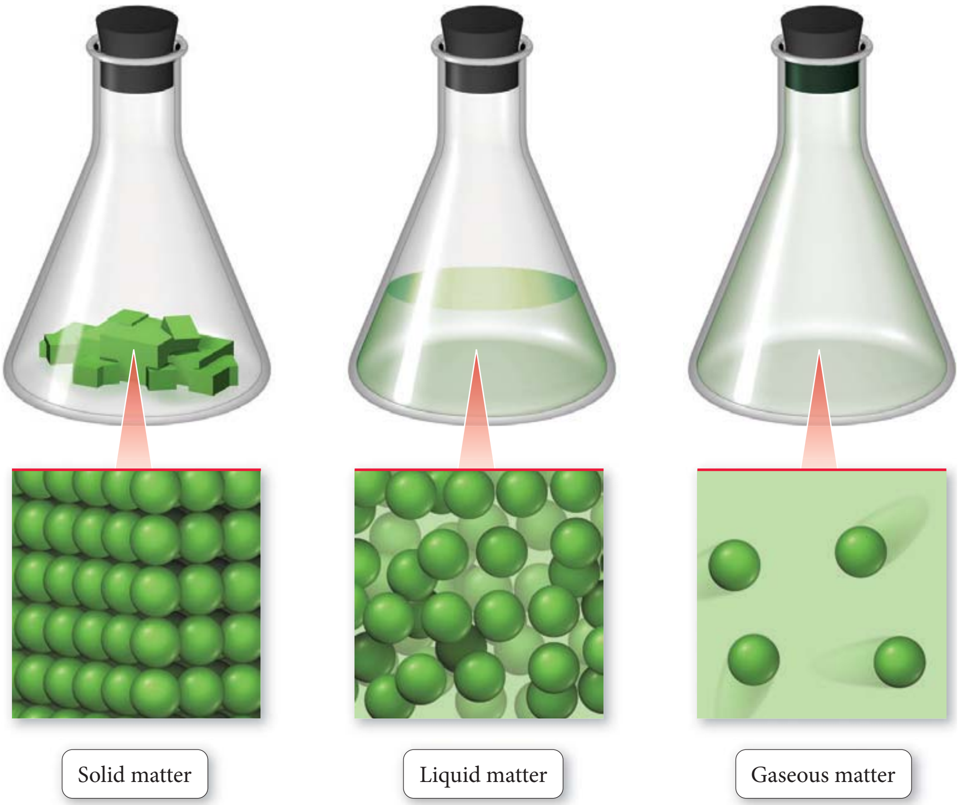
The state of matter changes from solid to liquid to gas with increasing temperature.

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.

Matter exists in three different states: **solid**, **liquid**, and **gas**. In *solid matter*, atoms or molecules pack closely 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 examples of solids. Solid matter may be **crystalline**, in which case its atoms or molecules are in patterns with long-range, repeating order (Figure 1.2◀), 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 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 containers. Water, alcohol, and gasoline are all substances that are liquids at room temperature.

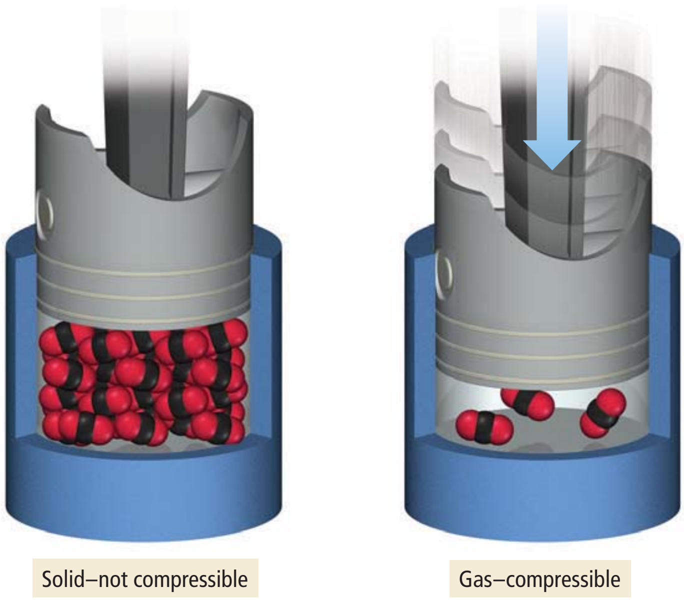


▲ **FIGURE 1.2 Crystalline Solid** Diamond (first discussed in Section 1.1) is a crystalline solid composed of carbon atoms arranged in a regular, repeating pattern.



▲ 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).

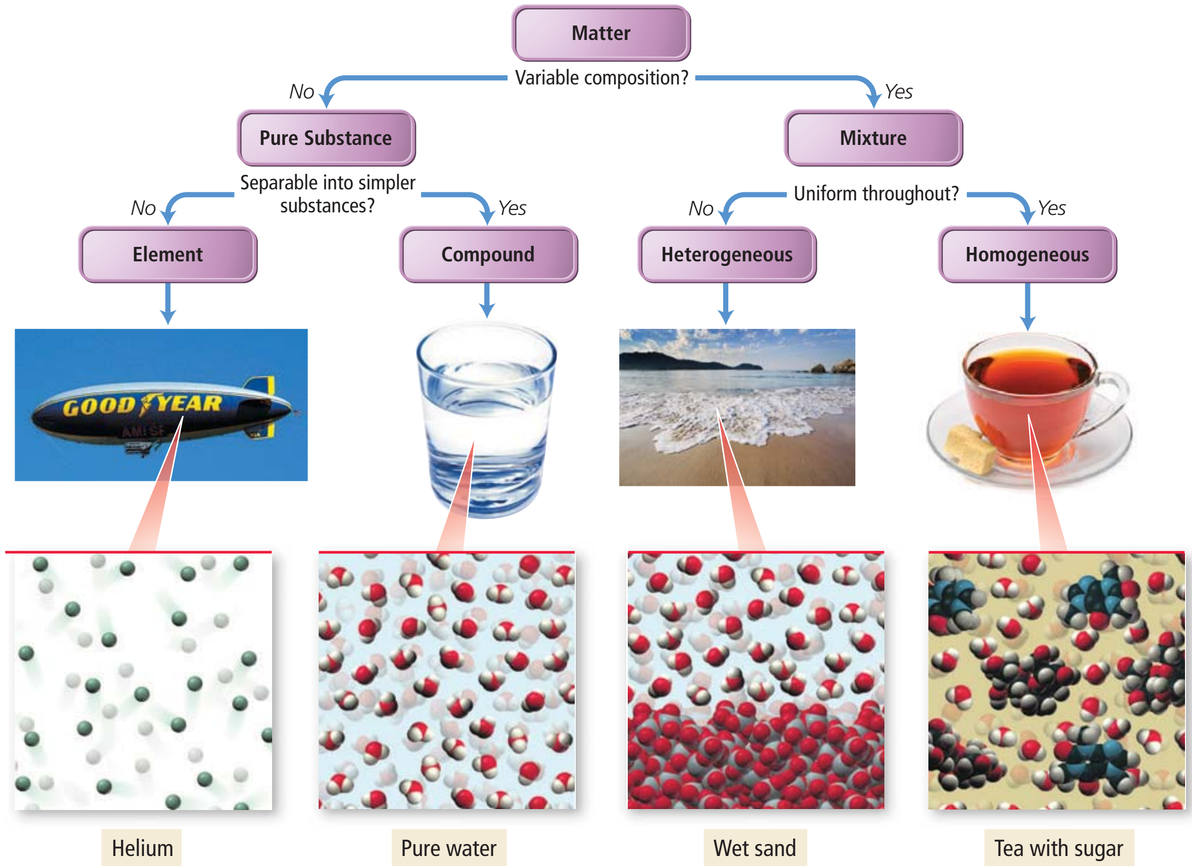
In *gaseous matter*, atoms or molecules have a lot of space between them and are free to move relative to one another, making gases *compressible* (Figure 1.3▶). When you squeeze a balloon or sit down on an air mattress, you force the atoms and molecules into a smaller space so that they are closer together. Gases always assume the shape *and* volume of their containers. Substances that are gases at room temperature include helium, nitrogen (the main component of air), and carbon dioxide.



◀ **FIGURE 1.3 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 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 substances 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 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.

All known elements are listed in the periodic table in the inside front cover of this book.

We 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.

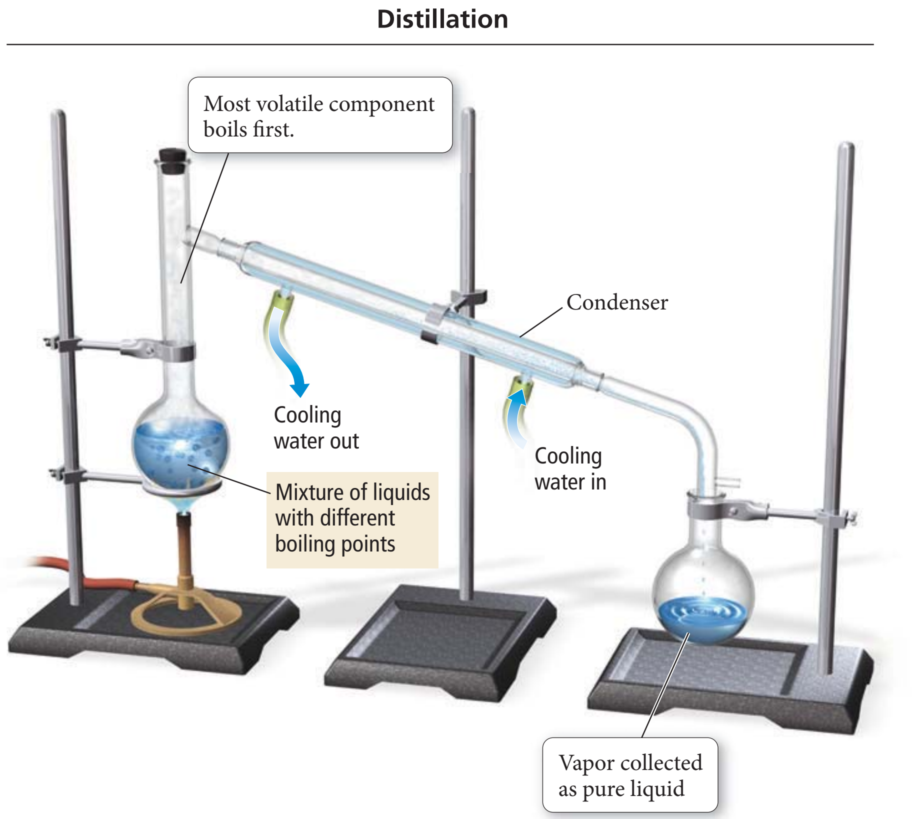
Classifying a substance according to its composition is not always obvious and requires that we either know the true composition of the substance or are able to test it in a laboratory. For now, we focus on relatively common substances that you are likely to have encountered. Throughout this course,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

CONCEPTUAL
CONNECTION 1.2

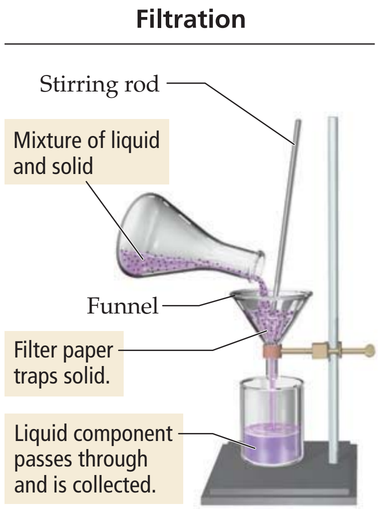
Pure Substances and Mixtures Let a small circle represent an atom of one type of element and a small square represent an atom of a second type of element. Make a drawing of (a) a pure substance (a compound) composed of the two elements (in a one-to-one ratio), (b) a homogeneous mixture composed of the 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 1.4►). 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 1.5►).



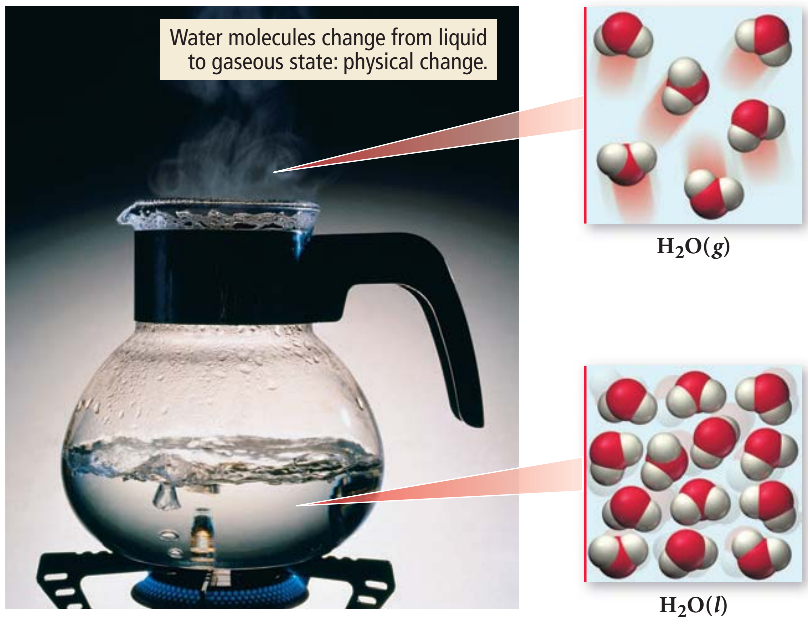
▲ **FIGURE 1.4 Separating Substances by Distillation** When a liquid mixture is heated, the component with the lowest boiling point vaporizes first, leaving behind less volatile liquids or dissolved solids. The vapor is then cooled, condensing it back to a liquid, and collected.



▲ **FIGURE 1.5 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.

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 substances 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 1.6►).



► **FIGURE 1.6 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 a physical change, and the boiling point of water is a physical property.