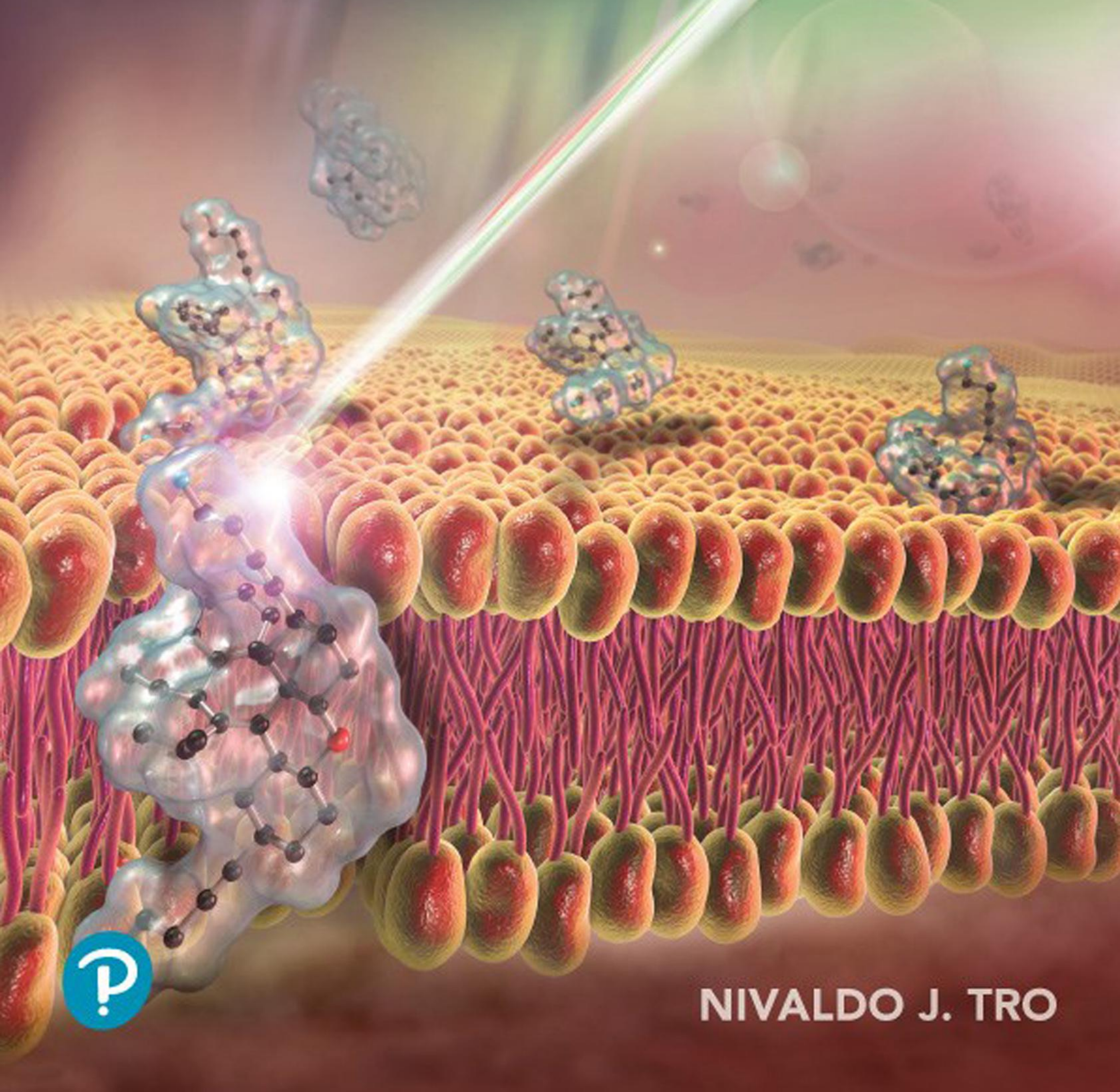
PRINCIPLES OF CHEMISTRY

A MOLECULAR APPROACH

FOURTH EDITION



NIVALDO J. TRO

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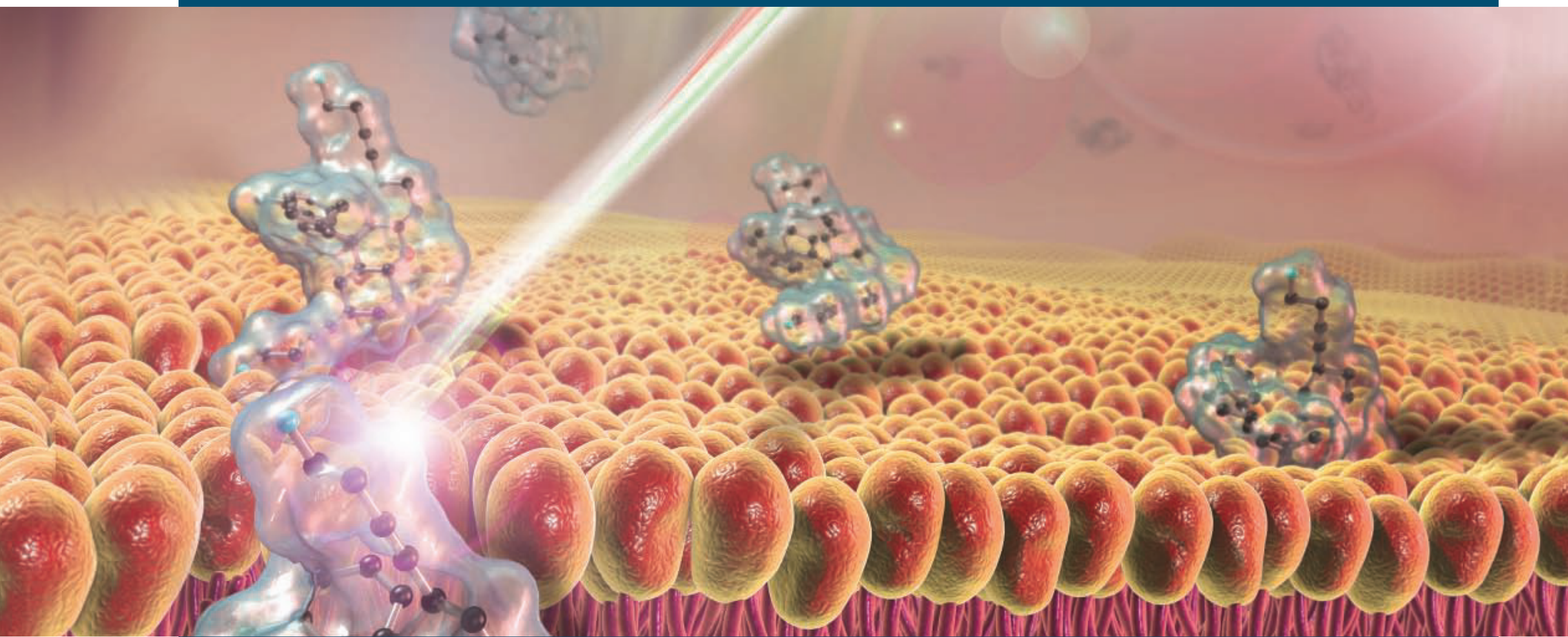

Nivaldo J. Tro

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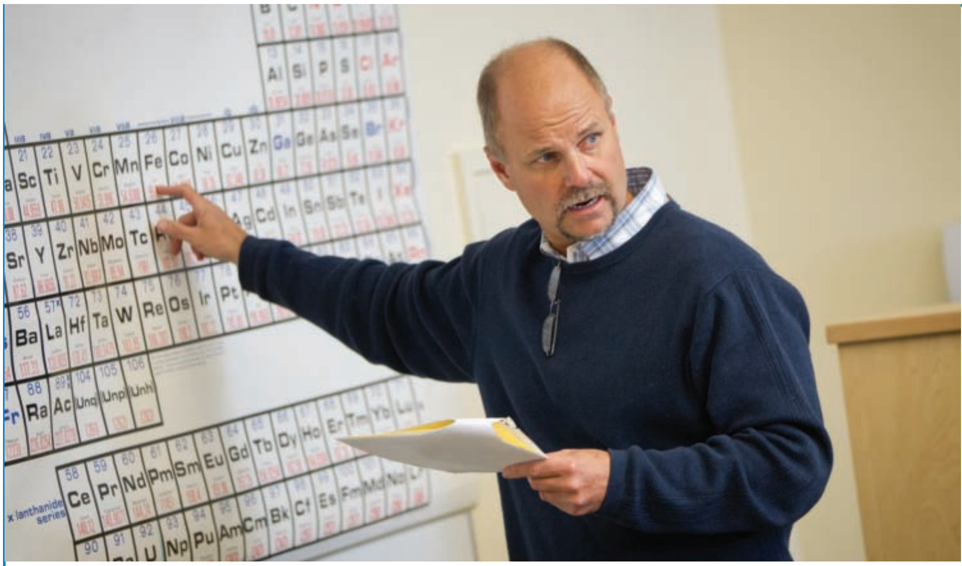
About the Author



Nivaldo Tro has been teaching college Chemistry since 1990 and is currently teaching at Santa Barbara City College. 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. Professor Tro has been awarded grants from the American Chemical Society Petroleum Research Fund, the Research Corporation, and the National Science Foundation to study the dynamics of various processes occurring in thin adlayer films adsorbed on dielectric surfaces. 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, and being outdoors with his family.

To Michael, Ali, Kyle, and Kaden

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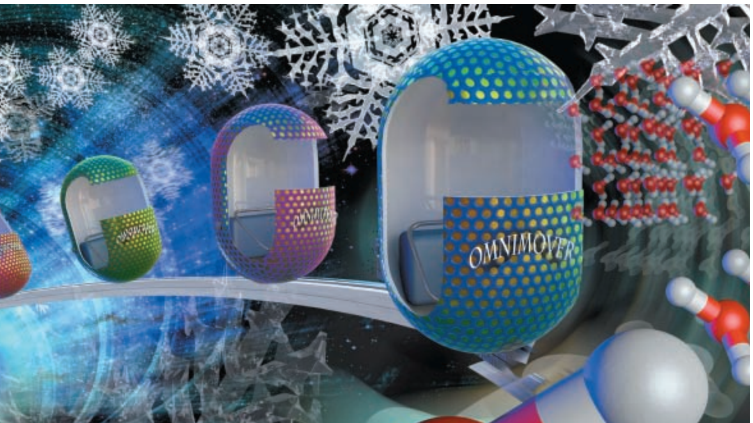

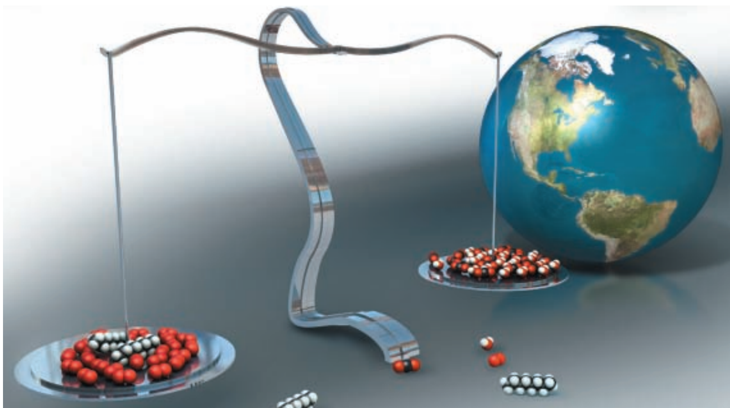

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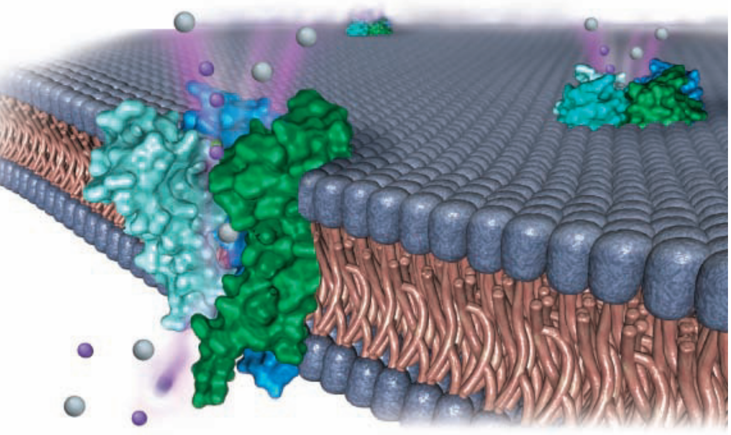
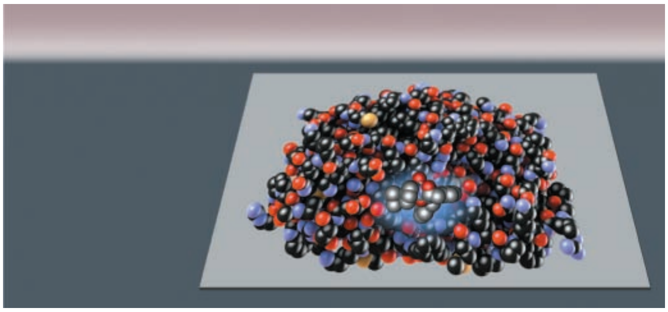
$4 Fe(s) + 3 O_2(g) \rightarrow 2 Fe_2O_3(s)$


Schrödinger's Cat





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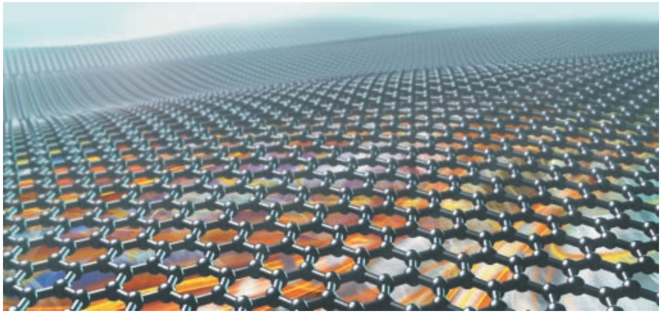

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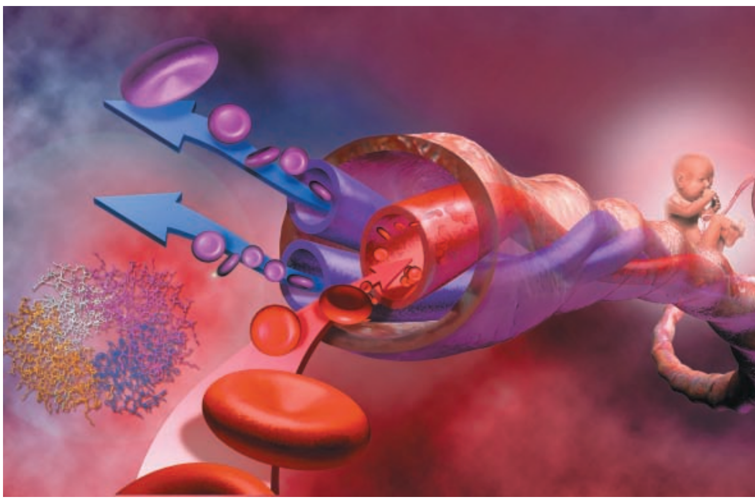

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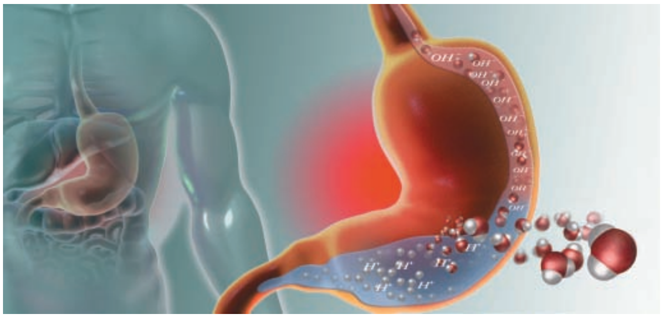

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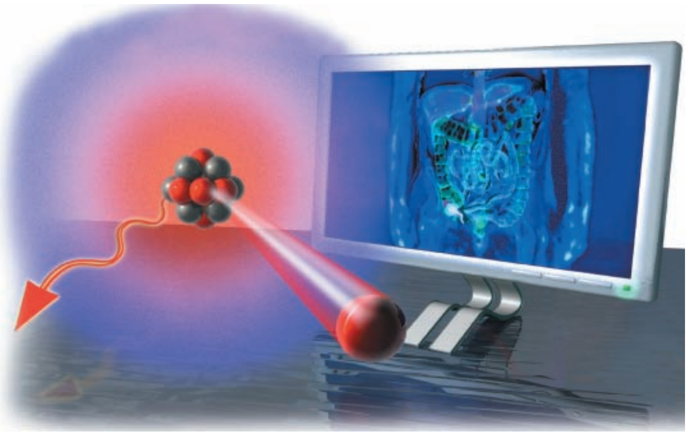

Preface

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. 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 dependence of the world we *can* see on 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 hair spray 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 hair spray depleting the ozone layer and thereby leading to global warming, the chlorofluorocarbons that deplete ozone have been banned from hair spray 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 understanding 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.

Higher education in science is changing. Foremost among those changes is a shift toward *active learning.* A flood of recent studies has demonstrated that General Chemistry students learn better when they are active in the learning process. However, implementing active learning can be a difficult and time-consuming process. One of my main goals in this revision is to give you, the professor, a range of tools to easily implement active learning in your class. My goal is simple: *I want to make it easy for you to engage your students in active learning before class, during class, and after class.*

- **BEFORE CLASS** Although the term *active learning* has been applied mainly to in-class learning, the main idea—*that we learn better when we are actively engaged*—applies to all of learning. I have developed two main tools to help students prepare for class in an active way. The first tool is a complete library of 3– to 6–minute *Key Concept Videos* (*KCVs*) that, with this edition, span virtually all of the key concepts in a general chemistry course. The videos introduce a key concept and encourage active learning because they stop in the middle and pose a question that must be answered before the video continues playing. Each video also has an associated follow-up question that can be assigned using Mastering Chemistry. You can assign a video before each one of your classes to get your students thinking about the concepts for that day. A second tool for use before class is *active reading*. Each chapter in the book now contains 10–12 *Conceptual Connection* questions. These questions are live in the ebook, assignable in Mastering Chemistry, and contain wrong answer feedback. Instead of passively reading the assigned material with no accountability, you can now encourage your students to engage in *active reading*, in which they read a bit and then answer a question that probes their comprehension and gives them immediate feedback.
- **DURING CLASS** By delivering some content through key concept videos and active reading before class, you can make room in your lecture to pose questions to your students that make the class experience active as well. This book features two main tools for in-class use. The first tool is *Learning Catalytics*, which allows you to pose many different types of questions to your students during class. Instead of passively listening to your lecture, students interact with the concepts you present through questions you pose. Your students can answer the questions individually, or you can pair them with a partner or small group. A second tool for in-class use is the *Questions for Group Work*. These questions appear in the end-of-chapter material and are specifically designed to be answered in small groups.
- **AFTER CLASS** Active learning can continue after class with two additional tools. The first is another library of 3– to 6–minute videos called *Interactive Worked Examples (IWEs).* Each IWE video walks a student through the solution to a chemistry problem. Like the KCVs, the IWE video stops in the middle and poses a question that must be answered before the video continues playing. Each video also has an associated follow-up problem that can be assigned using Mastering Chemistry. The second tool for after (or outside of) class active learning is *Active Exam Preparation*. Research studies suggest that students who take a pretest before an exam do better on the exam, especially if the pretest contains immediate feedback. Each chapter in this book contains a *Self-Assessment Quiz* that you can use to easily make a pretest for any of your exams. The *Self-Assessment Quizzes* are live in the ebook, assignable in Mastering Chemistry, and contain wrong answer feedback. Simply choose the questions that you want from each of the quizzes that span the chapters on your exam, and you can create an assignable pretest that students can use to actively prepare for your exams.

Although we have added many active learning tools to this edition and made other changes as well, 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. My own 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 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 and yet can be used and understood by any student willing to put in the necessary effort.

Principles of 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. *Principles of 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, *Principles of 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, *Principles of 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. In this edition, the art program has been thoroughly revised in two major ways. First, navigation of the more complex figures has been reoriented to track from left to right whenever possible. Second, figure captions have been migrated into the image itself as an "author voice" that explains the image and guides the reader through it. The resulting images are rich with information but also clear and quickly understood.

Fourth, *Principles of 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.

Lastly, *Principles of Chemistry: A Molecular Approach* is 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 contact me with any questions or comments about the book.

Nivaldo J. Tro
nivatro@gmail.com

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 INTERACTIVE VIDEOS** I have added 16 new *Key Concept Videos (KCVs)* and 24 new *Interactive Worked Examples (IWEs)* to the media package that accompanies the book. *The video library now contains nearly 200 interactive videos.* These tools are designed to help professors engage their students in active learning.
- **NEW IN-CHAPTER QUESTIONS WITH FEEDBACK** I have added approximately 67 new *Conceptual Connection* questions throughout the book and have changed the format to multiple choice (with wrong answer feedback in the ebook or through Mastering Chemistry). Each chapter now has 10–12 of these embedded assignable questions. These questions transform the reading process from passive to active and hold students accountable for reading assignments.
- **NEW *MISSED THIS?* FEATURE** I have added a new feature called *MISSED THIS?* to the *Self-Assessment Quizzes* and to the *Problems by Topic* section of the end-of-chapter problems. This feature lists the resources that students can use to learn how to answer the question or solve the problem. The resources include chapter sections to read, *Key Concept Videos (KCVs)* to watch, and *Interactive Worked Examples (IWEs)* to view. Students often try to solve an assigned question or problem before doing any reading or reviewing; they seek resources only *after* they have missed the question or problem. The *MISSED THIS?* feature guides them to reliable resources that provide just-in-time instruction.
- **NEW FOR PRACTICE FEEDBACK** I have enhanced 64 of the in-chapter *For Practice* problems (which immediately follow an in-chapter worked example) with feedback that can be accessed in the ebook or through Mastering Chemistry.
- **REVISED ART PROGRAM** The art program has been extensively revised. Navigation of the more complex figures has been reoriented to track from left to right, and many figure captions have been broken up and have been moved into the image itself as an "author voice" that explains the image and guides the reader through it.
- **REVISED DATA INTERPRETATION AND ANALYSIS QUESTIONS** The *Data Interpretation and Analysis* questions that accompany each chapter have been extensively revised to make them clearer and more accessible to students.
- **NEW SECTION ON DATA INTERPRETATION AND ANALYSIS** I have added a new section to Chapter 1 (Section 1.9) on the general topic of analyzing and interpreting data. This section introduces the skills required to address many of the revised data interpretation and analysis questions.
- **NEW HOW TO . . . FEATURE** All guidance for essential skills such as problem-solving techniques, drawing Lewis structures, and naming compounds is now presented in a consistent, step-by-step numbered list called *How To...*
- **REVISED CHAPTER 4** Chapter 4 in the previous edition covered both stoichiometry and chemical reactions in solution. In this edition, this content has been

expanded slightly and has been divided into two more focused chapters, so that Chapter 4 is now focused on stoichiometry and Chapter 5 on chemical reactions in solution. This new organization lessens the cognitive load for students and allows each chapter to be more direct and focused. All subsequent chapters have been renumbered accordingly.

- **NEW ACTIVITY SERIES CONTENT** I added a new subsection to Section 5.9 entitled *The Activity Series: Predicting Whether a Redox Reaction Is Spontaneous.* The new section includes new figures, tables, and a new worked example.
- **NEW READY-TO-GO LEARNING MODULES** These online modules offer students easy access to the best Tro content in Mastering Chemistry without needing to have it assigned.
- **NEW TWO-TIER OBJECTIVES** A system of two-tier objectives is being applied to the text and to the Mastering Chemistry assets. The two tiers are Learning Objectives, or LOs, and Enabling Objectives, or EOs. The LOs are broad, high-level objectives that summarize the overall learning goal, while the EOs are the building block skills that enable students to achieve the LO. The learning objectives are given in the Learning Outcomes table at the end of the chapter.
- **REVISED DATA** 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*; the unnumbered figure in Section 7.10 of *U.S. Energy Consumption*; Figure 7.12: *Energy Consumption by Source*; Table 7.6: *Changes in National Average Pollutant Levels, 1990–2016*; Figure 15.19: *Ozone Depletion in the Antarctic Spring*; Figure 17.15: *Sources of U.S. Energy*; Figure 17.16: *Acid Rain*; and Figure 17.18: *U.S. Sulfur Dioxide Pollutant Levels*.
- **REVISED CHAPTER OPENERS** Many chapter-opening sections and (or) the corresponding art—including Chapters 1, 3, 4, 5, 6, 7, 10, 11, 18, 19, and 20—have been replaced 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. Thanks also to Matt Walker, my new developmental editor on this project. Matt is creative, organized, and extremely competent. He has made significant contributions to this revision and has helped me with the many tasks that must be simultaneously addressed and developed during a revision as significant as this one. Matt, I hope this is only the beginning of a long and fruitful collaboration. I also owe a special debt of gratitude to Barbara Yien and Laura Southworth. Barbara was involved in many parts of content development, and Laura played a critical role in the revision of the art program. Many thanks to the both of you!

Thanks also to my media editor, Paula Iborra. Paula has been instrumental in helping me craft and develop the Key Concept Videos, Interactive Worked Examples, and other media content that accompany this text. Gracias, Paula.

I am also grateful to Harry Misthos, 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. Thanks also to Adam Jaworski, who oversees science courseware at Pearson. I am grateful to have his wise and steady, yet innovative, hand at the wheel, especially during the many changes that are happening within educational publishing. I am also grateful to my marketing managers, Chris Barker and Elizabeth Bell. Chris and I go way back and have worked together in many different ways. Chris, thanks for all you do to promote my books. Elizabeth is a marketing manager extraordinaire. She has endless energy and ideas for marketing this book. I have enjoyed working with her over the last several years and wish to congratulate her on the recent birth of her first child. Congratulations, Elizabeth! 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 Paul, who makes my ideas come alive with his art, has been with us from the beginning, and I owe a special debt of gratitude to him. I am also grateful to Maria Guglielmo Walsh and Elise Lansdon 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 over many projects, 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 18 years and 16 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 am also grateful to those who have supported me personally while working on this book. 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, 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 appendices. Michael, you are amazing—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 29 years as a professor. 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 Corey Beck who has played an important role in developing the objectives for this edition. I am also grateful to the accuracy of reviewers who tirelessly checked page proofs for correctness.

Reviewers of the Fourth Edition

Vanessa Castleberry, *Baylor University*
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Richard Spinney, *Ohio State University*
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Vinodhkumar Subramaniam, *East Carolina University*
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Jacquelyn Thomas, *Southwestern College*
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Focus Group Participants

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Focus Group 13

Kim Cortes, *Kennesaw State University*
Patrick Daubenmire, *Loyola University - Chicago*
Michael Dianovsky, *South Dakota State University*
Deborah Exton, *University of Oregon*
Joel Goldberg, *University of Vermont*
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Focus Groups 1–12

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Amy Irwin, *Monroe Community College*
Maria Korolev, *University of Florida*
Jennifer Schwartz Poehlmann, *Stanford University*
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Mohammed Daoudi, *University of Central Florida*
Kate Deline, *College of San Mateo*
Stephanie Dillon, *Florida State University*
Ralph C. Dougherty, *Florida State University*
William Eck, *University of Wisconsin, Marshfield/Wood County*
Robert J. Eierman, *University of Wisconsin, Eau Claire*
Amina K. El-Ashmawy, *Collin County Community College*
William A. Faber, *Grand Rapids Community College*
Richard W. Frazee, *Rowan University*
Barbara A. Gage, *Prince George's Community College*
Simon Garrett, *California State University, Northridge*
Raymond F. Glienna, *Glendale Community College*
Eric S. Goll, *Brookdale Community College*
Pierre Y. Goueth, *Santa Monica College*

W. Tandy Grubbs, *Stetson University*
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Jason A. Halfen, *University of Wisconsin, Eau Claire*
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Paul I. Higgs, *Barry University*
Norris W. Hoffman, *University of South Alabama*
Tony Holland, *Wallace Community College*
Todd A. Hopkins, *Butler University*
Moheb Ishak, *St. Petersburg College, St. Petersburg*
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Steven W. Keller, *University of Missouri, Columbia*
Ellen Kime-Hunt, *Riverside Community College, Riverside Campus*
Peter J. Krieger, *Palm Beach Community College, Lake Worth*
Roy A. Lacey, State *University of New York, Stony Brook*
David P. Licata, *Coastline Community College*
Michael E. Lipschutz, *Purdue University*
Patrick M. Lloyd, CUNY, *Kingsborough Community College*
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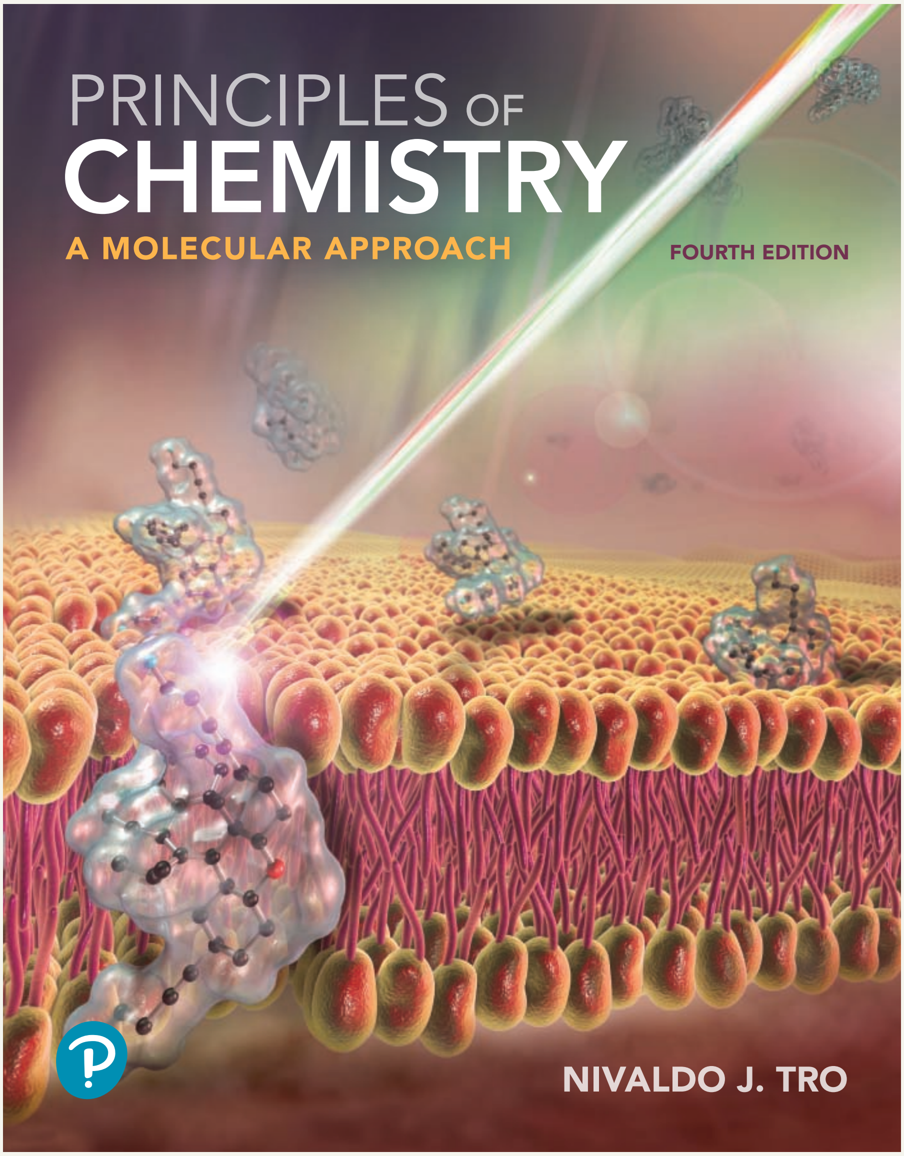
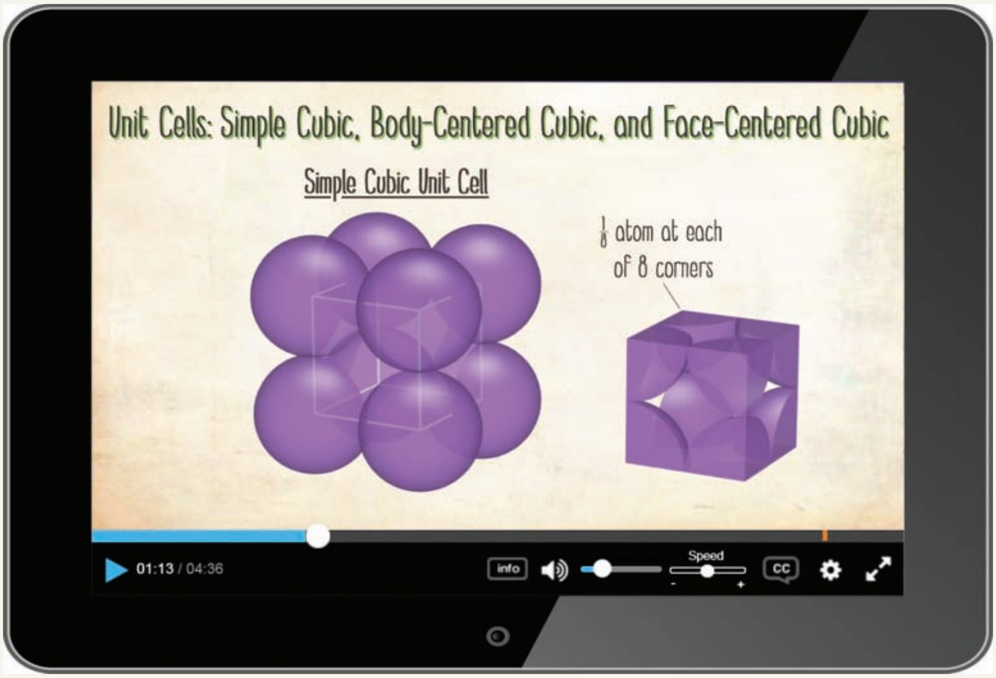
Actively Engage Students to Become Expert Problem Solvers and Critical Thinkers

Nivaldo Tro's *Principles of Chemistry: A Molecular Approach* presents chemistry visually through multi-level images—macroscopic, molecular, and symbolic representations—to help students see the connections between the world they see around them, the atoms and molecules that compose the world, and the formulas they write down on paper. The **4th Edition** pairs digital, pedagogical innovation with insights from learning design and educational research to create an active, integrated, and easy-to-use framework. The new edition introduces a fully integrated book and media package that streamlines course setup, actively engages students in becoming expert problem solvers, and makes it possible for professors to teach the general chemistry course easily and effectively.



Learn core concepts...

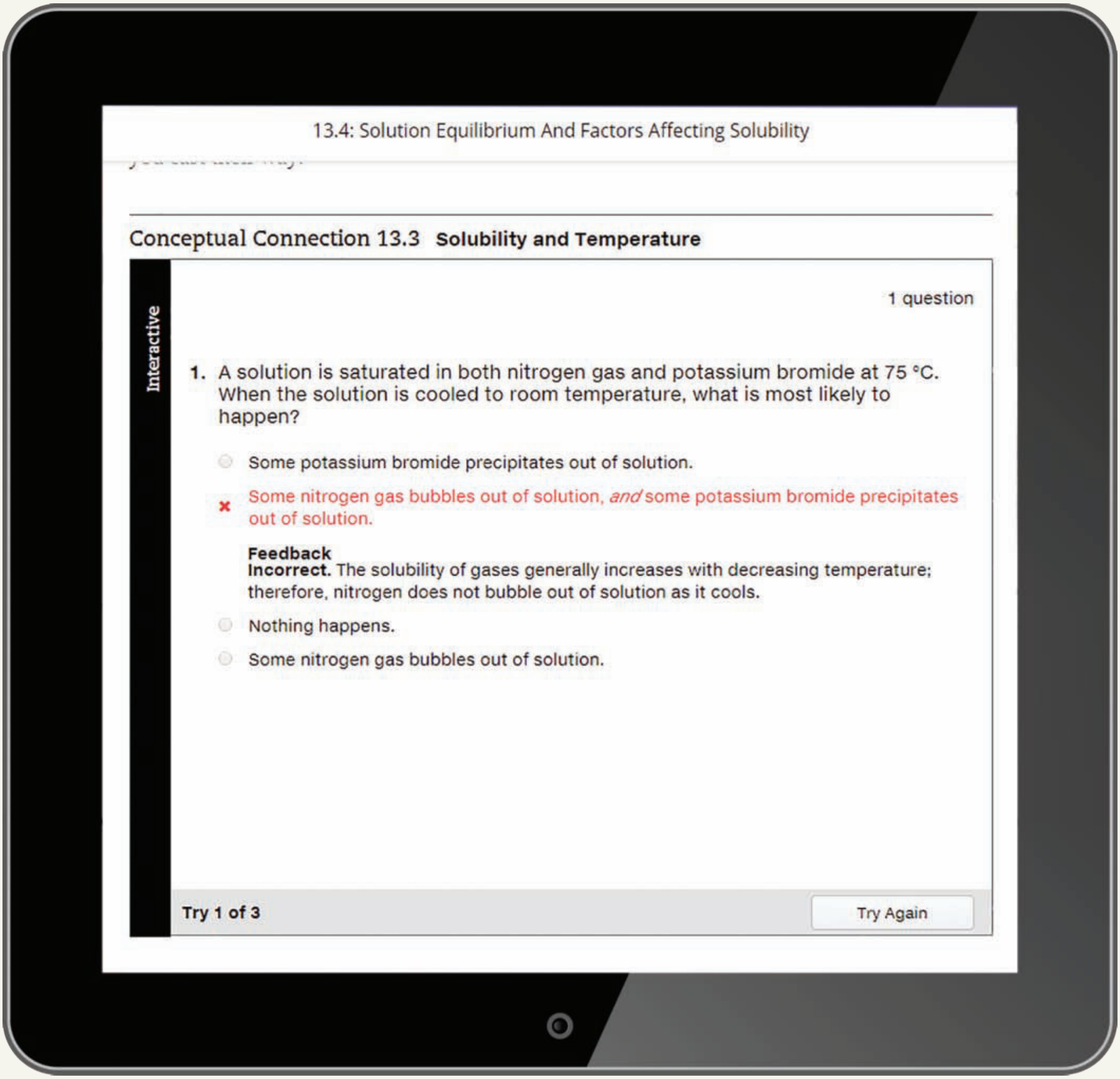


Key Concept Videos combine artwork from the textbook with 2D and 3D animations to create a dynamic on-screen viewing and learning experience. The 4th edition includes **16 new** videos, for a total of **74**.

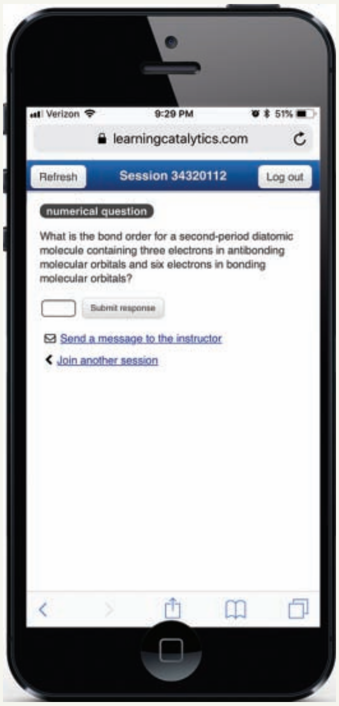
These short videos include **narration and brief live-action clips of author Nivaldo Tro** explaining every key concept in general chemistry. All Key Concept Videos are available on mobile devices, embedded in Pearson eText, and are assignable in Mastering Chemistry.

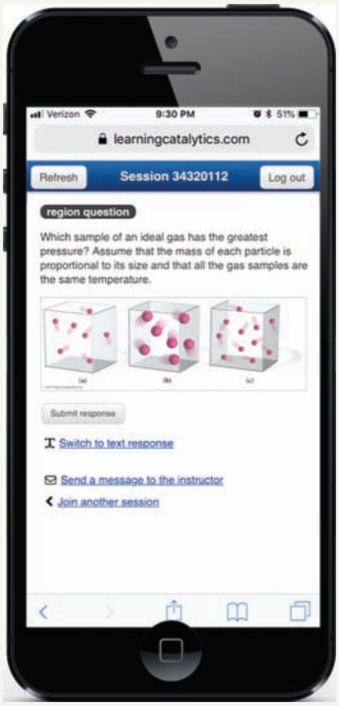
before students even come to class

Newly Interactive Conceptual Connections allow students to interact with all conceptual connections within the Pearson eText, so that they can study on their own and test their understanding in real time. **Complete with answer-specific feedback written by the author himself**, these interactives help students extinguish misconceptions and deepen their understanding of important topics, making reading an active experience.

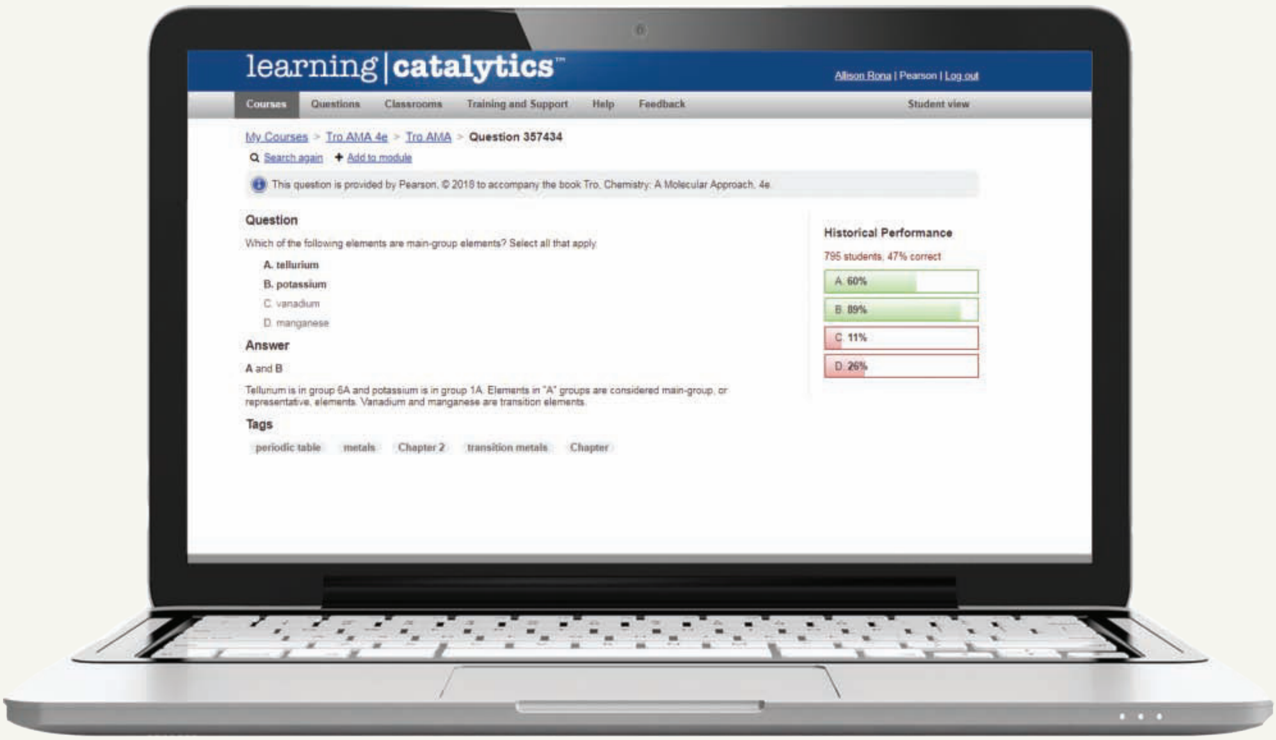


Actively engage students...





With Learning Catalytics, you'll hear from every student when it matters most. You pose a variety of questions that help students recall ideas, apply concepts, and develop critical-thinking skills. Your students respond using their own smartphones, tablets, or laptops.



You can monitor responses with real-time analytics and find out what your students do — and don't — understand. Then, you can adjust your teaching accordingly, and even facilitate peer-to-peer learning, helping students stay motivated and engaged. **Learning Catalytics includes prebuilt questions for every key topic in General Chemistry.**

with in-class activities

QUESTIONS FOR GROUP WORK

Active Classroom Learning

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

139. Explain why 1-propanol ($CH_3CH_2CH_2OH$) is miscible in both water (H_2O) and hexane (C_6H_6) when hexane and water are barely soluble in each other.

140. Have each group member make a flashcard with one of the following on the front: ΔH_{soln}, $\Delta H_{lattice}$, $\Delta H_{solvent}$, ΔH_{mix}, and $\Delta H_{hydration}$. On the back of the card, each group member should describe (in words) the ΔH process his or her card lists and how that ΔH relates to other ΔH values mathematically. Each member presents his or her ΔH to the group. After everyone has presented, members should trade cards and quiz each other.

141. Complete the following table by adding *increases*, *decreases*, or *no effect*:

	Increasing Temperature	Increasing Pressure
solubility of gas in water		
solubility of a solid in water		

142. When 13.62 g (about one tablespoon) of table sugar (sucrose, $C_{12}H_{22}O_{11}$) is dissolved in 241.5 mL of water (density 0.997 g/mL), the final volume is 250.0 mL (about one cup). Have each group member calculate one of the following for the solution and present his or her answer to the group:

a. mass percent
b. molarity
c. molality

143. Calculate the expected boiling and freezing point for the solution in the previous problem. If you had to bring this syrup to the boiling point for a recipe, would you expect it to take much more time than it takes to boil the same amount of pure water? Why or why not? Would the syrup freeze in a typical freezer (−18 °C)? Why or why not?

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Questions for Group Work allow students to collaborate and apply problem-solving skills on questions covering multiple concepts. 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. All questions for group work are pre-loaded into Learning Catalytics for ease of assignment.

Numerous ideas for in-class activities can be found in the Ready-to-Go Teaching Modules in the Instructor Resources in Mastering Chemistry. There, instructors will find the most effective activities, problems, and questions from the text, Mastering, and Learning Catalytics, to use in class.

Kinesthetic Activity: Polarity

5 – 10 minutes
Average time for activity

In groups, students model molecules using rope (representing bond dipoles) to show which molecular shapes are polar or nonpolar. This activity can be done at the front of the classroom or in small groups. Example: For trigonal planar, have one student stand in the middle holding the ends of three ropes. Have three other students stand in a trigonal planar arrangement around the middle student and pull equally on the ropes. Since all the ropes (dipole moments) cancel out, the middle student does not get pulled in any direction; this illustrates that the trigonal planar shape is nonpolar. Other shapes that can be shown include: linear, bent, trigonal planar, square planar, T-shaped.

Master problem-solving...

PROBLEMS BY TOPIC

Solution Concentration and Solution Stoichiometry

21. Calculate the molarity of each solution.
MISSED THIS? *Read Section 5.2; Watch KCV 5.2, IWE 5.1*
a. 3.25 mol of LiCl in 2.78 L solution
b. 28.33 g $C_6H_{12}O_6$ in 1.28 L of solution
c. 32.4 mg NaCl in 122.4 mL of solution

22. Calculate the molarity of each solution.
a. 0.38 mol of $LiNO_3$ in 6.14 L of solution
b. 72.8 g C_2H_6O in 2.34 L of solution
c. 12.87 mg KI in 112.4 mL of solution

23. What is the molarity of NO_3^- in each solution?
MISSED THIS? *Read Sections 5.2, 5.4; Watch KCV 5.2, IWE 5.1*
a. 0.150 M KNO_3
b. 0.150 M $Ca(NO_3)_2$
c. 0.150 M $Al(NO_3)_3$

24. What is the molarity of Cl^- in each solution?
a. 0.200 M NaCl
b. 0.150 M $SrCl_2$
c. 0.100 M $AlCl_3$

25. How many moles of KCl are contained in each solution?
MISSED THIS? *Read Section 5.2; Watch KCV 5.2, IWE 5.2*
a. 0.556 L of a 2.3 M KCl solution
b. 1.8 L of a 0.85 M KCl solution
c. 114 mL of a 1.85 M KCl solution

26. What volume of 0.200 M ethanol solution contains each amount in moles of ethanol?
a. 0.45 mol ethanol
b. 1.22 mol ethanol
c. 1.2×10^{-2} mol ethanol

27. A laboratory procedure calls for making 400.0 mL of a 1.1 M $NaNO_3$ solution. What mass of $NaNO_3$ (in g) is needed?
MISSED THIS? *Read Section 5.2; Watch KCV 5.2, IWE 5.2*

28. A chemist wants to make 5.5 L of a 0.300 M $CaCl_2$ solution. What mass of $CaCl_2$ (in g) should the chemist use?

29. If 123 mL of a 1.1 M glucose solution is diluted to 500.0 mL, what is the molarity of the diluted solution?
MISSED THIS? *Read Section 5.2; Watch KCV 5.2, IWE 5.3*

30. If 3.5 L of a 4.8 M $SrCl_2$ solution is diluted to 45 L, what is the molarity of the diluted solution?

31. To what volume should you dilute 50.0 mL of a 12 M stock HNO_3 solution to obtain a 0.100 M HNO_3 solution?
MISSED THIS? *Read Section 5.2; Watch KCV 5.2, IWE 5.3*

32. To what volume should you dilute 25 mL of a 10.0 M H_2SO_4 solution to obtain a 0.150 M H_2SO_4 solution?

33. Consider the precipitation reaction:
MISSED THIS? *Read Section 5.3; Watch IWE 5.4*

$$2\,Na_3PO_4(aq) + 3\,CuCl_2(aq) \longrightarrow Cu_3(PO_4)_2(s) + 6\,NaCl(aq)$$

What volume of 0.175 M Na_3PO_4 solution is necessary to completely react with 95.4 mL of 0.102 M $CuCl_2$?

34. Consider the reaction:

$$Li_2S(aq) + Co(NO_3)_2(aq) \longrightarrow 2\,LiNO_3(aq) + CoS(s)$$

What volume of 0.150 M Li_2S solution is required to completely react with 125 mL of 0.150 M $Co(NO_3)_2$?

35. What is the minimum amount of 6.0 M H_2SO_4 necessary to produce 25.0 g of $H_2(g)$ according to the reaction between aluminum and sulfuric acid?
MISSED THIS? *Read Section 5.3; Watch IWE 5.4*

$$2\,Al(s) + 3\,H_2SO_4(aq) \longrightarrow Al_2(SO_4)_3(aq) + 3\,H_2(g)$$

36. What is the molarity of $ZnCl_2$ that forms when 25.0 g of zinc completely reacts with $CuCl_2$ according to the following reaction? Assume a final volume of 275 mL.

$$Zn(s) + CuCl_2(aq) \longrightarrow ZnCl_2(aq) + Cu(s)$$

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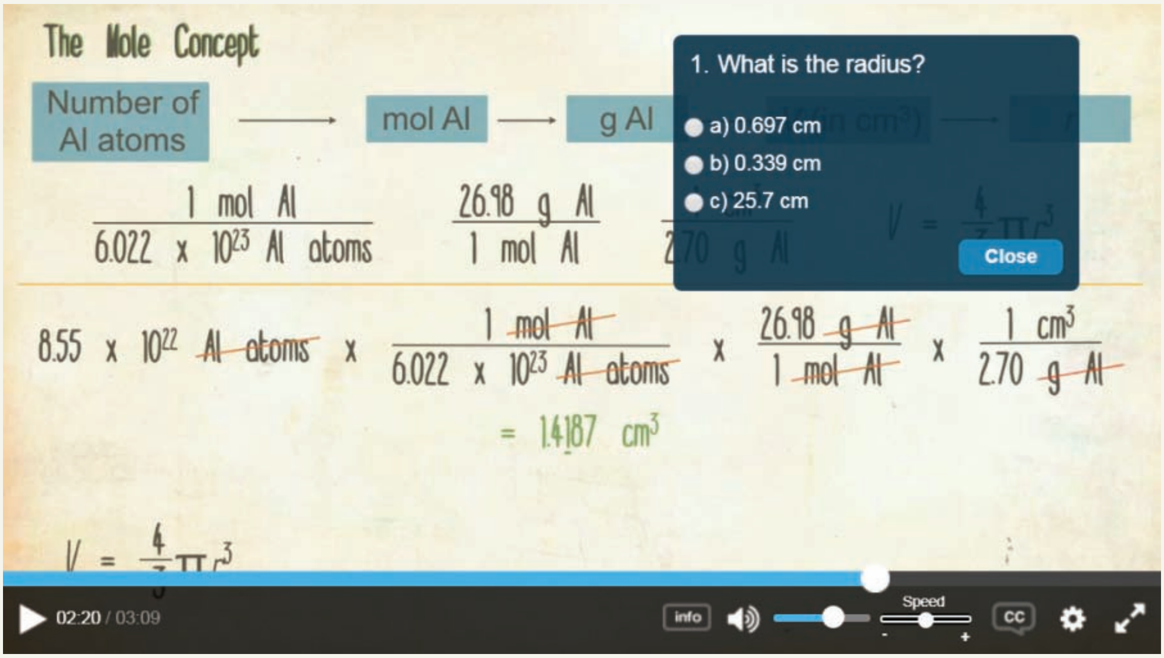
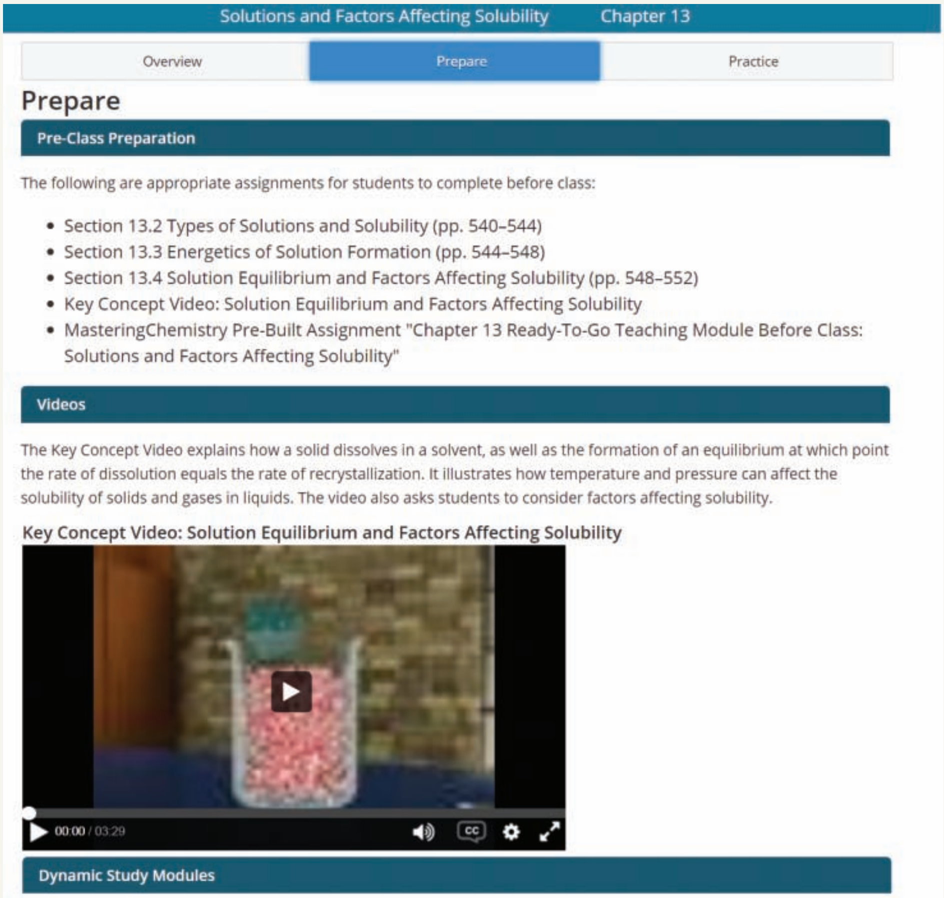
NEW! MISSED THIS? appears in the end-of-chapter Self-Assessment Quizzes and each odd-numbered Problems by Topic exercise. *MISSED THIS?* provides sections to read and videos to watch to help students remediate where necessary.



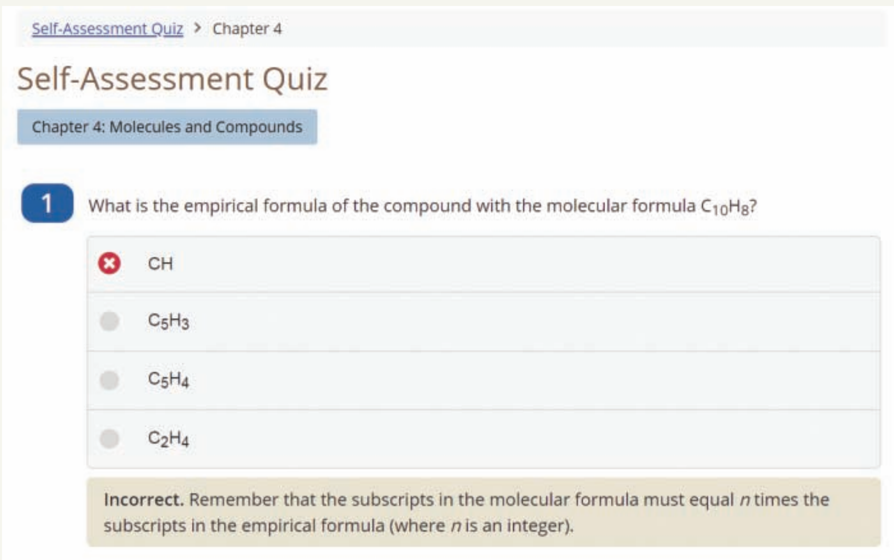
Interactive Worked Examples are digital versions of select worked examples from the text that instruct students how to break down problems using Tro's "Sort, Strategize, Solve, and Check" technique. The Interactive Worked Examples pause in the middle and require the student to interact by completing a step in the example. Each example has a follow-up question that is assignable in Mastering Chemistry. There are 24 new Interactive Worked Examples for a total of 125.

with tools students can use after class



NEW! Ready-to-Go Practice Modules in the Mastering Chemistry Study Area help students master the toughest topics (as identified by professors and fellow students completing homework and practicing for exams). Key Concept Videos, Interactive Worked Examples, and problem sets with answer-specific feedback are all in one easy to navigate place to keep students focused and give them the scaffolded support they need to succeed.

Newly Interactive Self-Assessment Quizzes, complete with answer-specific feedback, allow students to quiz themselves within the Pearson eText, so that they can study on their own and test their understanding in real time. The Self-Assessment Quizzes are also assignable in Mastering Chemistry. Professors can use questions from these quizzes to prepare a pretest on Mastering Chemistry. Research has shown that this kind of active exam preparation improves students' exam scores.

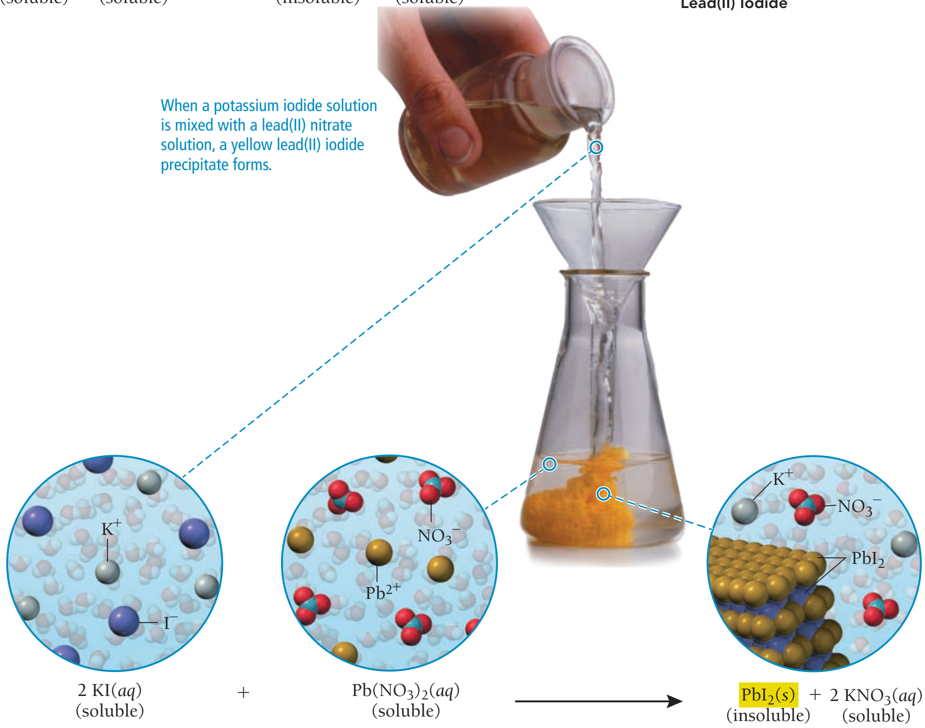


Teach with art based on learning design principles

Extensively updated art program better directs students' attention to key elements in the art and promotes understanding of the processes depicted. Dozens of figures in the 4th Edition were reviewed by learning design specialists to ensure they are clearly navigable for students and now include more helpful annotations and labels to help readers focus on key concepts.

Precipitation Reaction

$$\underset{\text{(soluble)}}{2\ KI(aq)} + \underset{\text{(soluble)}}{Pb(NO_3)_2(aq)} \longrightarrow \underset{\text{(insoluble)}}{PbI_2(s)} + \underset{\text{(soluble)}}{2\ KNO_3(aq)}$$



◀ **FIGURE 5.13 Precipitation of Lead(II) Iodide**

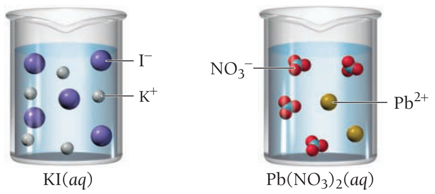
Precipitation reactions do not always occur when two aqueous solutions are mixed. For example, if we combine solutions of KI(*aq*) and NaCl(*aq*), nothing happens (Figure 5.14▶):

$$KI(aq) + NaCl(aq) \not\longrightarrow \text{NO REACTION}$$

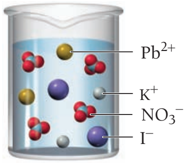
The key to predicting precipitation reactions is to understand that *only insoluble compounds form precipitates*. In a precipitation reaction, two solutions containing soluble compounds combine and an insoluble compound precipitates. Consider the precipitation reaction described previously:

$$\underset{\text{soluble}}{2\ KI(aq)} + \underset{\text{soluble}}{Pb(NO_3)_2(aq)} \longrightarrow \underset{\text{insoluble}}{PbI_2(s)} + \underset{\text{soluble}}{2\ KNO_3(aq)}$$

KI and $Pb(NO_3)_2$ are both soluble, but the precipitate, PbI_2, is insoluble. Before mixing, KI(*aq*) and $Pb(NO_3)_2(aq)$ are both dissociated in their respective solutions:



The instant that the solutions come into contact, all four ions are present:



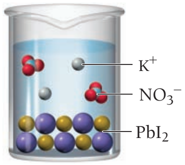
KI(*aq*) and $Pb(NO_3)_2$(*aq*)

Now, new compounds—one or both of which might be insoluble—are possible. Specifically, the cation from either compound can pair with the anion from the other to form possibly insoluble products:

Original compounds			Possible products
K	I	$\longrightarrow$	KNO_3
Pb	$(NO_3)_2$		PbI_2

If the possible products are both soluble, no reaction occurs and no precipitate forms. If one or both of the possible products are insoluble, a precipitation reaction occurs. In this case, KNO_3 is soluble, but PbI_2 is insoluble. Consequently, PbI_2 precipitates.

To predict whether a precipitation reaction will occur when two solutions are mixed and to write an equation for the reaction, we use the procedure that follows. The steps are outlined in the left column, and two examples illustrating how to apply the procedure are shown in the center and right columns.

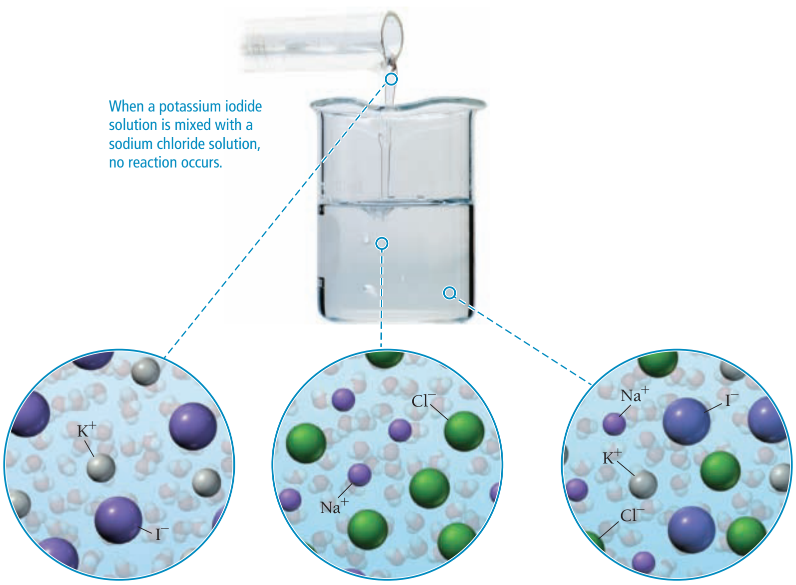


PbI_2(*s*) and KNO_3(*aq*)

No Reaction

KI(*aq*) + NaCl(*aq*) $\not\longrightarrow$ No reaction

◀ **FIGURE 5.14** **No Precipitation**



KI(*aq*) + NaCl(*aq*) $\not\longrightarrow$ No reaction

pgs. 180–181

Tro's multipart images help students see the relationship between the formulas they write down on paper (symbolic), the world they see around them (macroscopic), and the atoms and molecules that compose the world (molecular).

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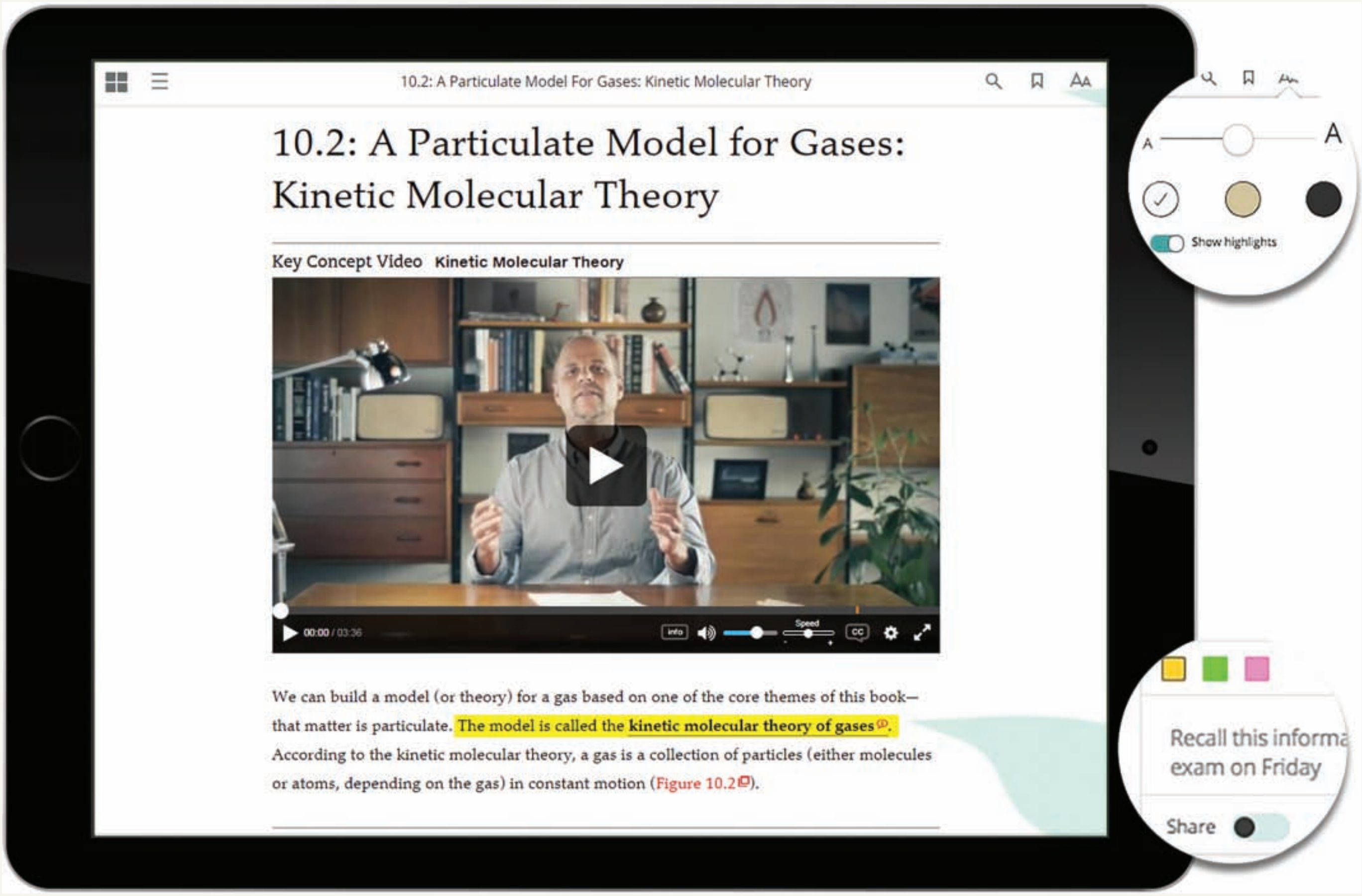

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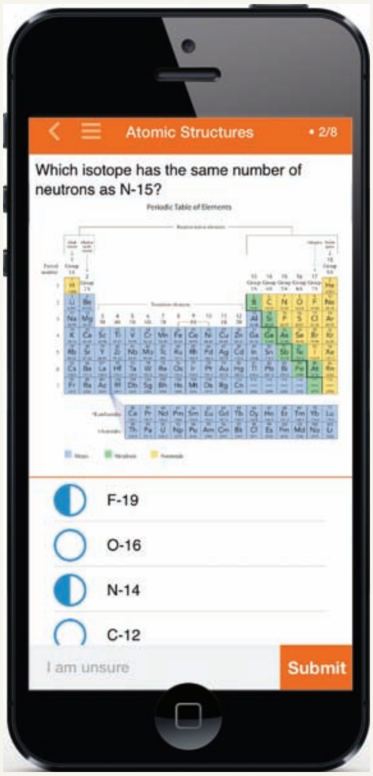

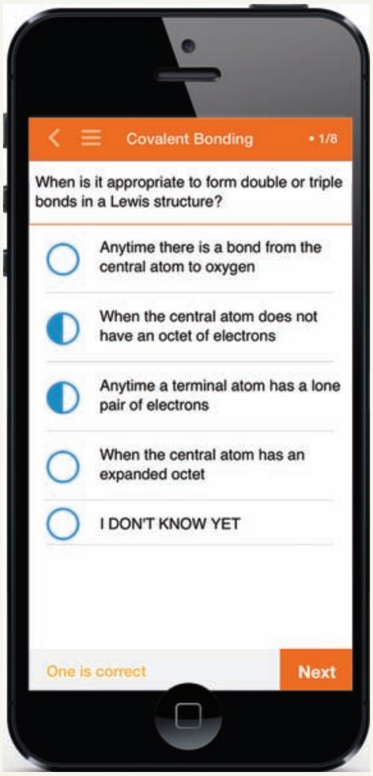

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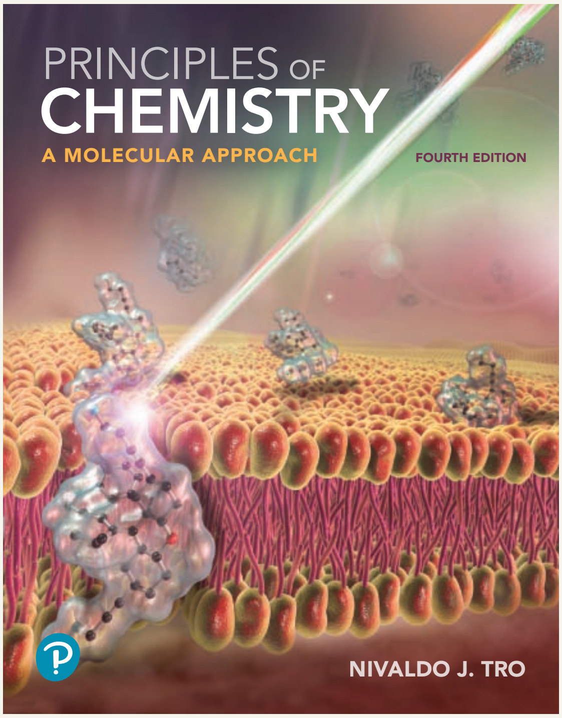
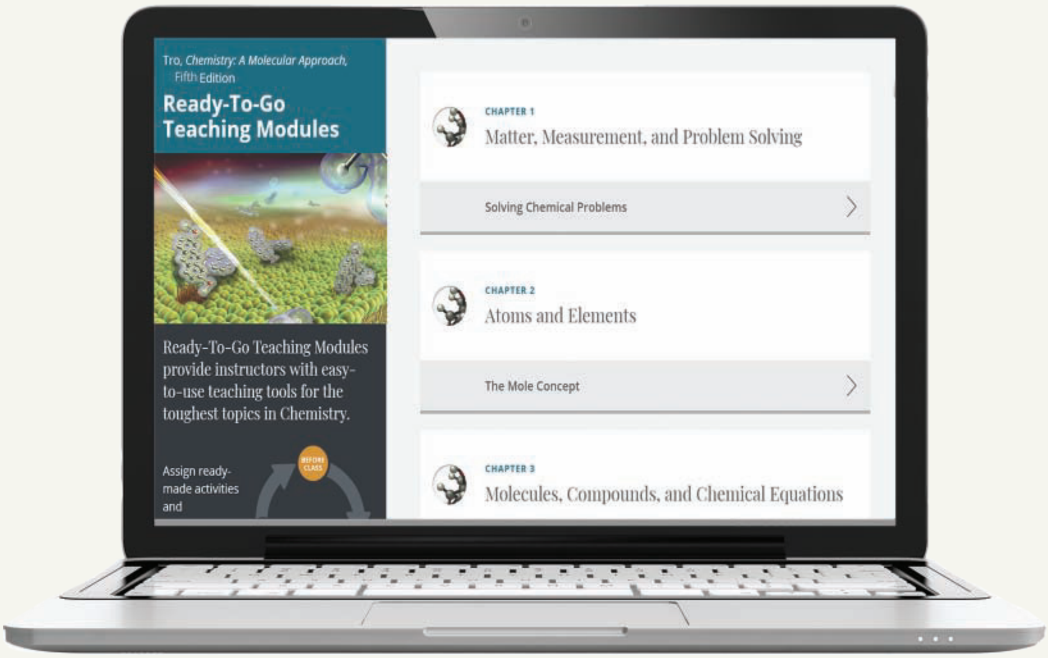


Principles of Chemistry: A Molecular Approach includes a full suite of instructor support materials in the Instructor Resources area in Mastering Chemistry. Resources include new Ready-to-Go Teaching Modules; accessible PowerPoint lecture outlines; all images and worked examples from the text; all Key Concept Videos and Interactive Worked Examples; plus an instructor resource manual and test bank.



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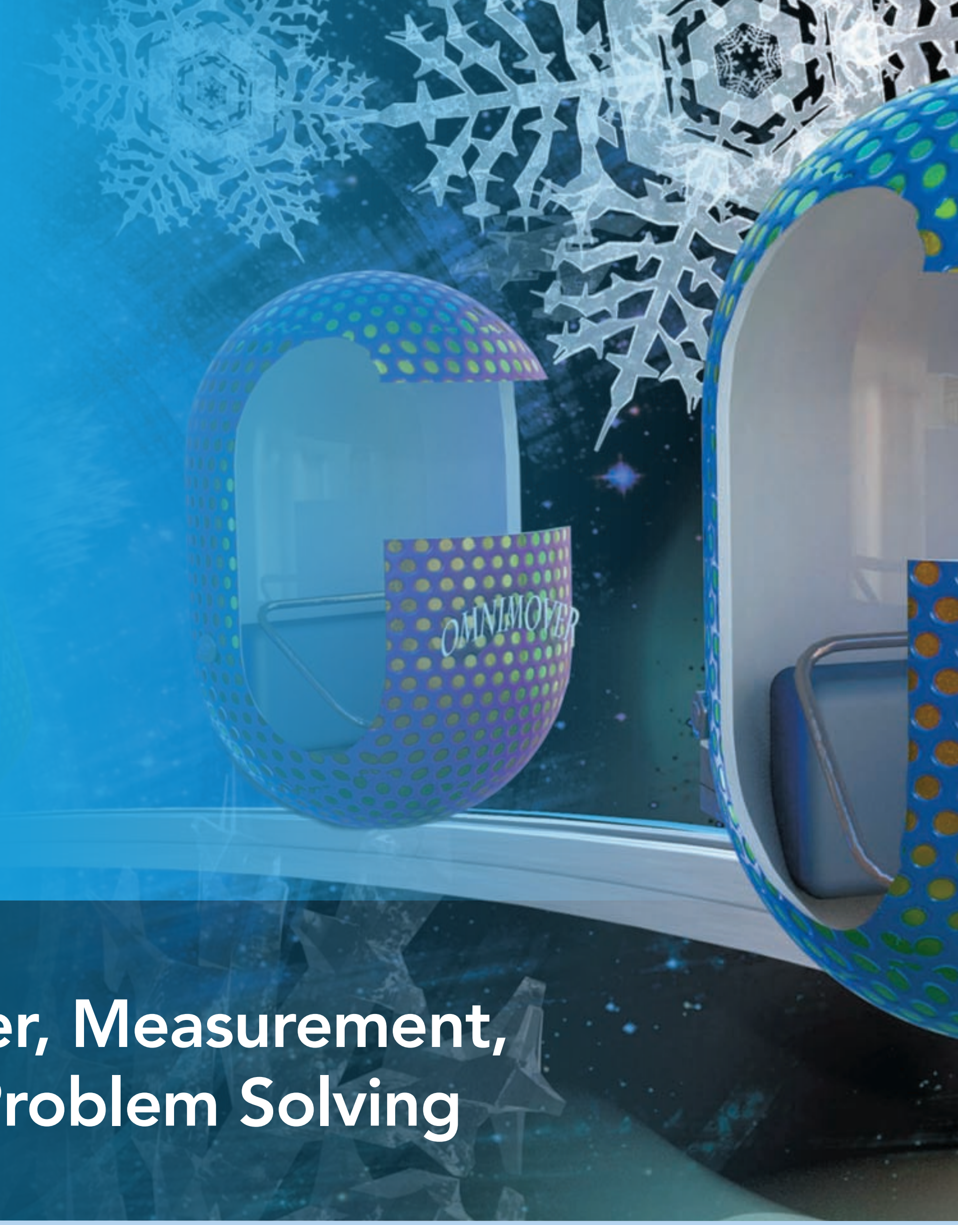
Principles of Chemistry

A MOLECULAR APPROACH

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

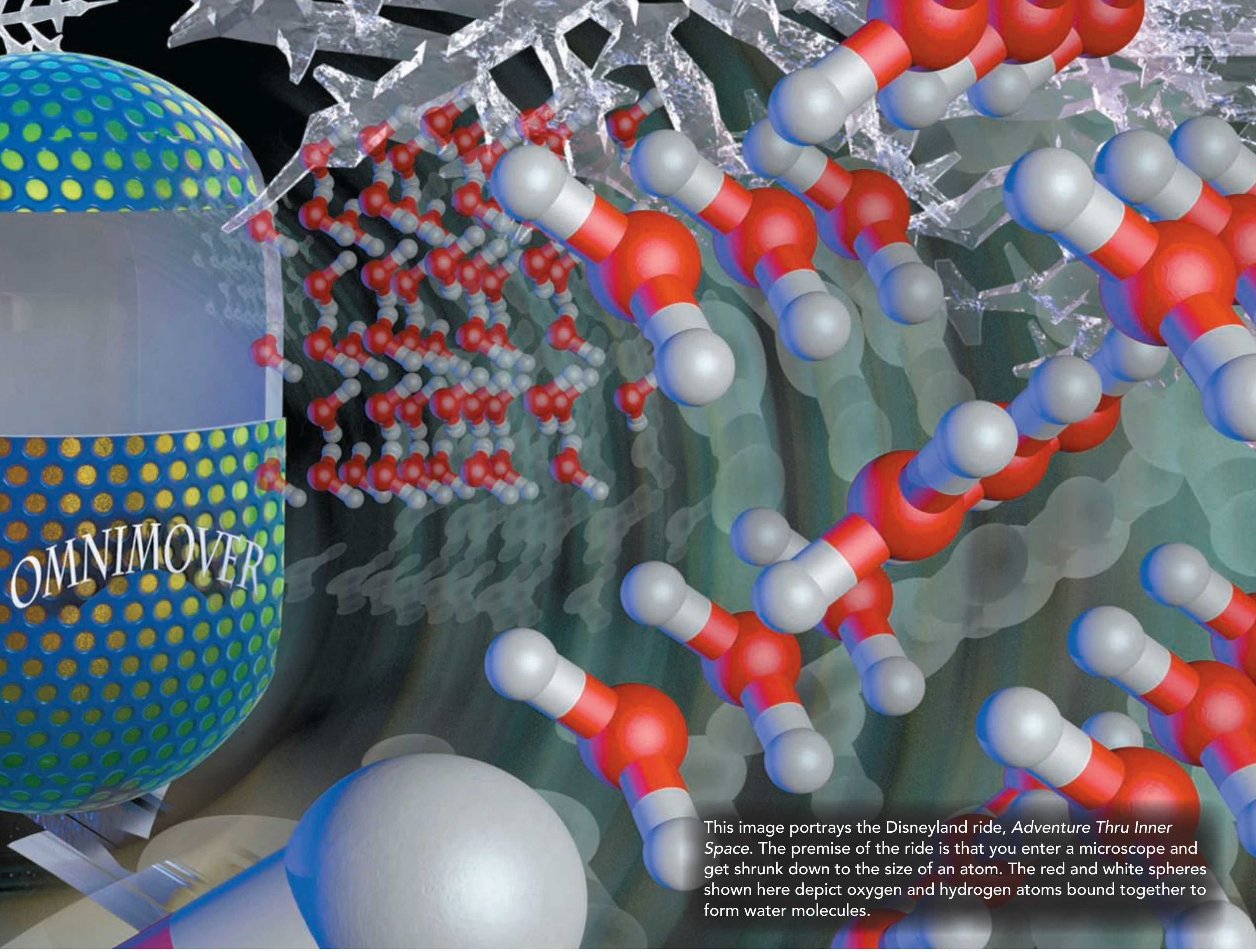
—ALBERT EINSTEIN (1879–1955)



CHAPTER 1

Matter, Measurement, and Problem Solving

What do you think is the most important idea in all of human knowledge? This question has many possible answers—some practical, some philosophical, and some scientific. If we limit ourselves 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.



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.

1.1 Atoms and Molecules

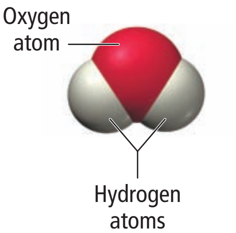
WATCH **NOW!**

KEY CONCEPT VIDEO 1.1
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 what it would be like to shrink 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.

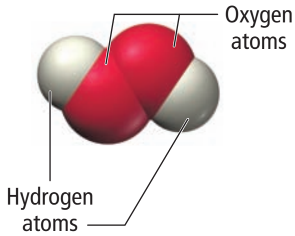
That ride sparked my interest in the world of atoms and molecules, an interest that has continued and grown to this day. I am a chemist because I am obsessed with the connection between the "stuff" around us and the atoms and molecules that compose that stuff. More specifically, I love the idea that 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 submicroscopic 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.

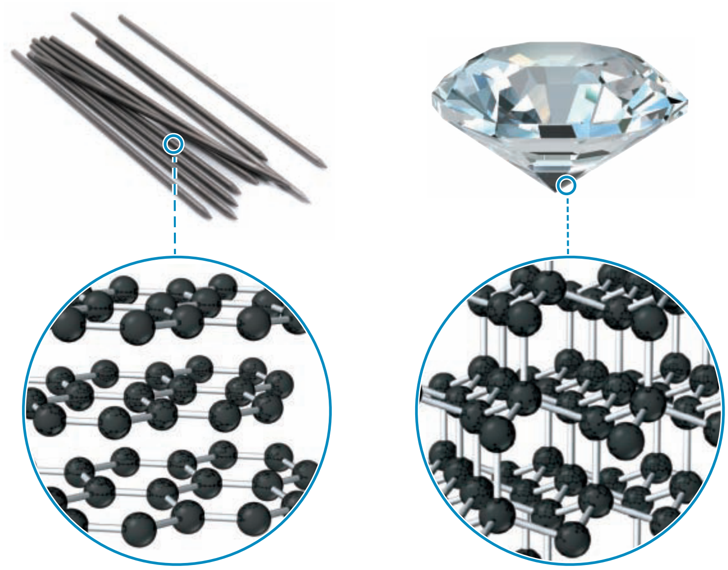
The details of how specific atoms bond to form a molecule—in a straight line, at a particular angle, in a ring, or in some other pattern—as well as the type of atoms in the molecule, determine everything about the substance that the molecule composes. If we want to understand the substances around us,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

> **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.

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.

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.



Graphite structure

Diamond structure

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.

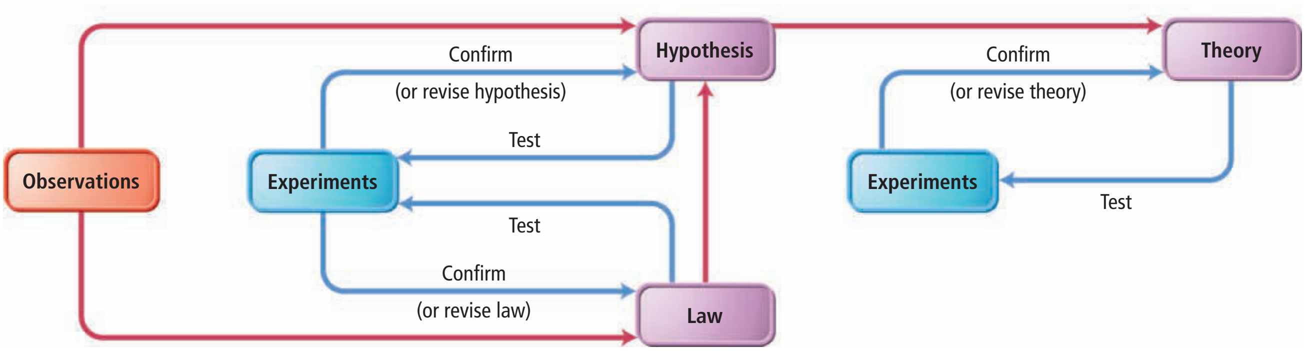
Finally, the scientific approach returns to observation to test theories. For example, scientists can test the atomic theory by trying to isolate single atoms or by trying to image them (both of which, by the way, have already been accomplished). Theories are validated by experiments; however, theories 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 key distinctions of science. Real science requires hard work, care, creativity, and even a bit of luck.

▼ FIGURE 1.1 The Scientific Approach to Knowledge

The Scientific Approach



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 accompanying box entitled *Thomas S. Kuhn and Scientific Revolutions*.)

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.

1.1 Cc Conceptual Connection

ANSWER **NOW!**

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

WATCH **NOW!**

KEY CONCEPT VIDEO 1.3
Classifying Matter

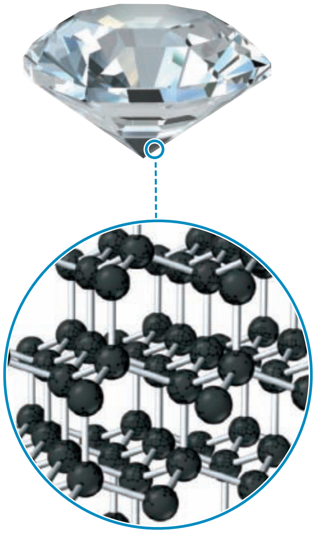
Matter is anything that occupies space and has mass. Your desk, your chair, and even your body are all composed of matter. Less obviously, the air around you is also matter—it too occupies space and has mass. We call a specific instance of matter—such as air, water, or sand—a **substance**. We classify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

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

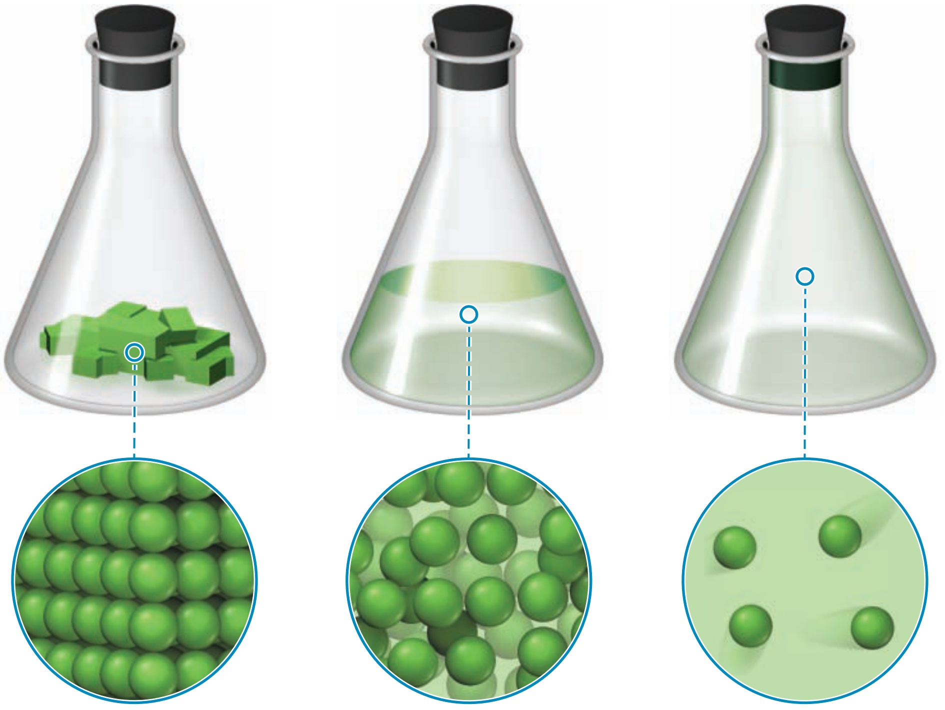
Glass and other amorphous solids can be thought of, from one point of view, as intermediate between solids and liquids. Their atoms are fixed in position at room temperature, but they have no long-range structure and do not have distinct melting points.

The States of Matter: Solid, Liquid, and Gas

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.

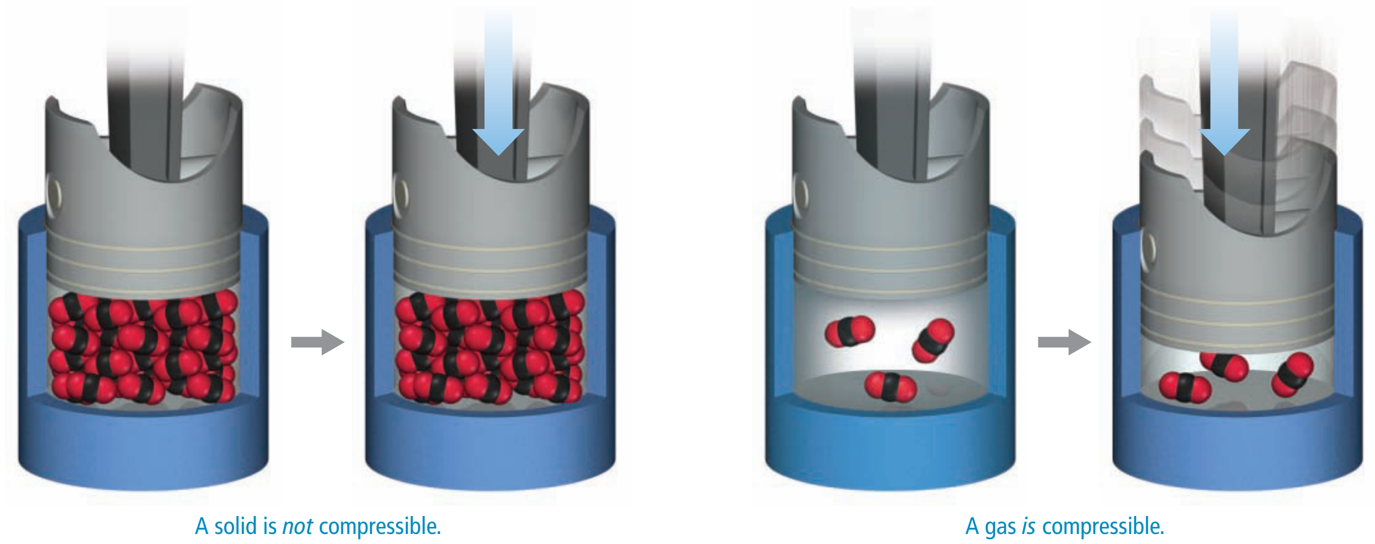


▲ **FIGURE 1.2 Crystalline Solid** Diamond (first discussed in Section 1.1) is a crystalline solid composed of carbon atoms arranged in a regular, repeating pattern.



▲ 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).

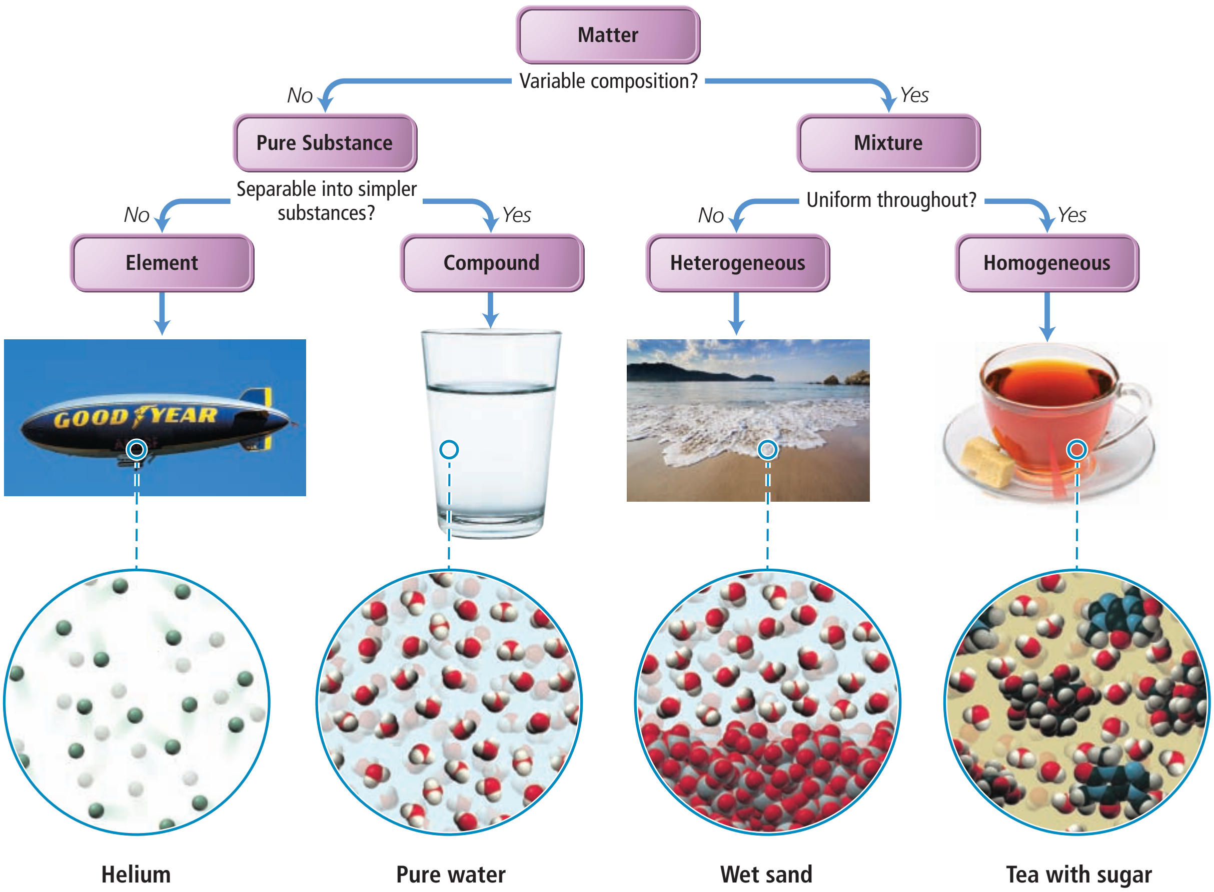
In *gaseous matter*, atoms or molecules have a lot of space between them and are free to move relative to one another, making gases *compressible* (Figure 1.3▶). When you squeeze a balloon or sit down on an air mattress, you force the atoms and molecules into a smaller space so that they are closer together. 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 by 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.

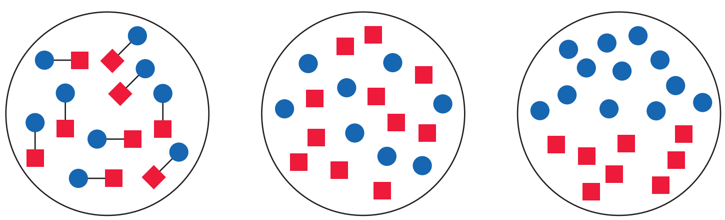
We also categorize mixtures into two types—heterogeneous and homogeneous—depending on how *uniformly* the substances within them mix. Wet sand is a **heterogeneous mixture**, one in which the composition varies from one region of the mixture to another. Sweetened tea is a **homogeneous mixture**, one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

ANSWER **NOW!**

1.2 Cc Conceptual Connection

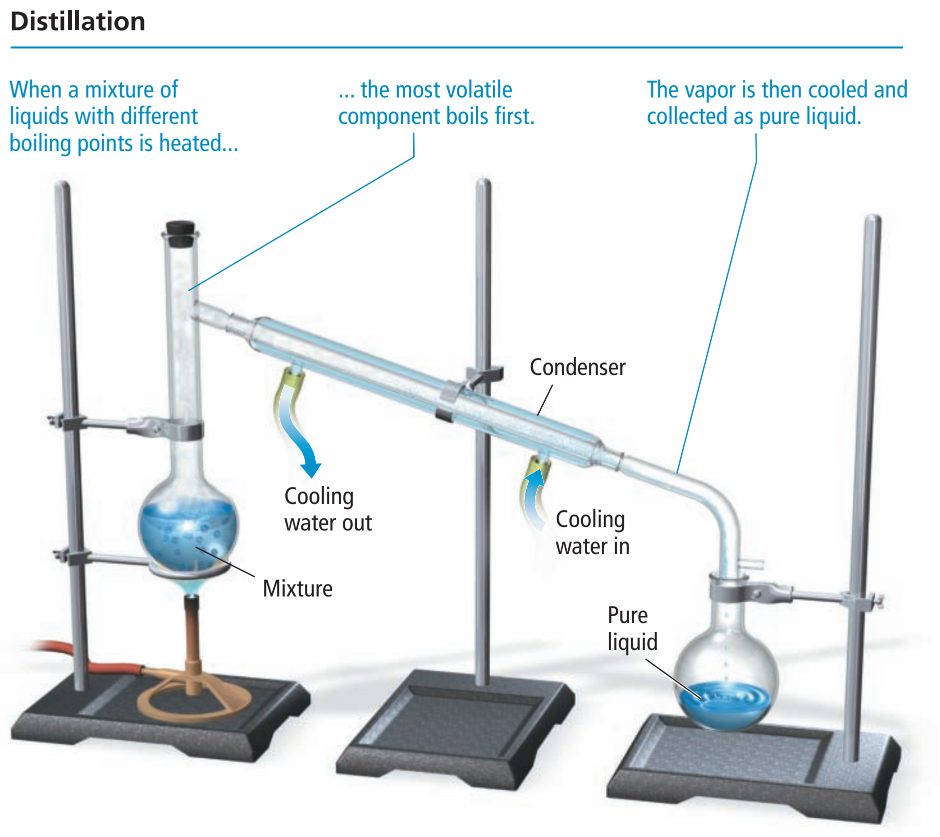
PURE SUBSTANCES AND MIXTURES In these images, a blue circle represents an atom of one type of element, and a red square represents an atom of a second type of element. Which image is a pure substance?



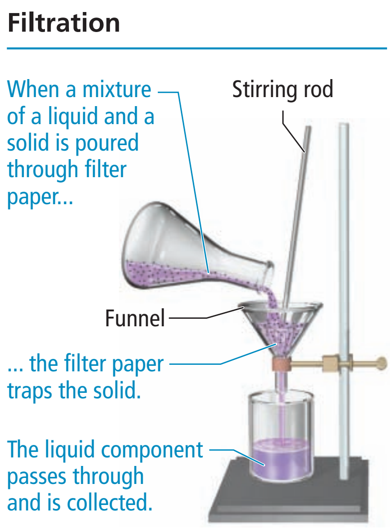
(a) **(b)** **(c)** None of the these **(d)**

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

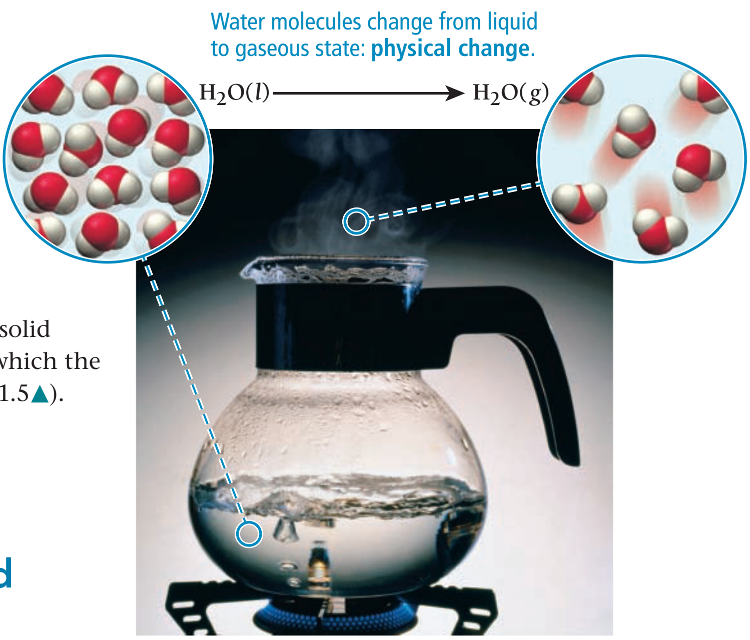


▲**FIGURE 1.4** **Separating Substances by Distillation**



▲ **FIGURE 1.5** **Separating Substances by Filtration**

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 1.6** **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.

1.4 Physical and Chemical Changes and Physical and Chemical Properties

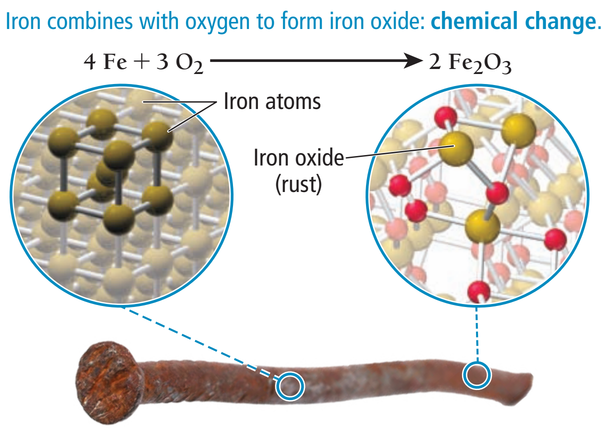
Every day we witness changes in matter: ice melts, iron rusts, gasoline burns, fruit ripens, and water evaporates. What happens to the molecules or atoms that compose these substances during such changes? The answer depends on the type of change. Changes that alter only state or appearance, but not composition, 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▲).

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

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 1.7◀). Figure 1.8▶ illustrates other examples of physical and chemical changes.

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.

The differences between physical and chemical changes are not always apparent. Only chemical examination can confirm whether a particular change is physical or chemical. In many cases, however, we can identify chemical and physical changes based on what we know about the changes. Changes in the state of matter, such as melting or boiling, or changes in the physical condition of matter, such as those that result from cutting or crushing, are typically physical changes. Changes involving chemical reactions—often evidenced by temperature or color changes—are chemical changes.



▲ **FIGURE 1.7 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 a chemical change, and the tendency of iron to rust is a chemical property. A more detailed exploration of this reaction can be found in Section 20.9.

EXAMPLE 1.1 Physical and Chemical Changes and Properties

Determine whether each change is physical or chemical. What kind of property (chemical or physical) is demonstrated in each case?

(a) the evaporation of rubbing alcohol
(b) the burning of lamp oil
(c) the bleaching of hair with hydrogen peroxide
(d) the formation of frost on a cold night

SOLUTION

(a) When rubbing alcohol evaporates, it changes from liquid to gas, but it remains alcohol—this is a physical change. The volatility (the ability to evaporate easily) of alcohol is therefore a physical property.

(b) Lamp oil burns because it reacts with oxygen in air to form carbon dioxide and water—this is a chemical change. The flammability of lamp oil is therefore a chemical property.

(c) Applying hydrogen peroxide to hair changes pigment molecules in hair that give it color—this is a chemical change. The susceptibility of hair to bleaching is therefore a chemical property.

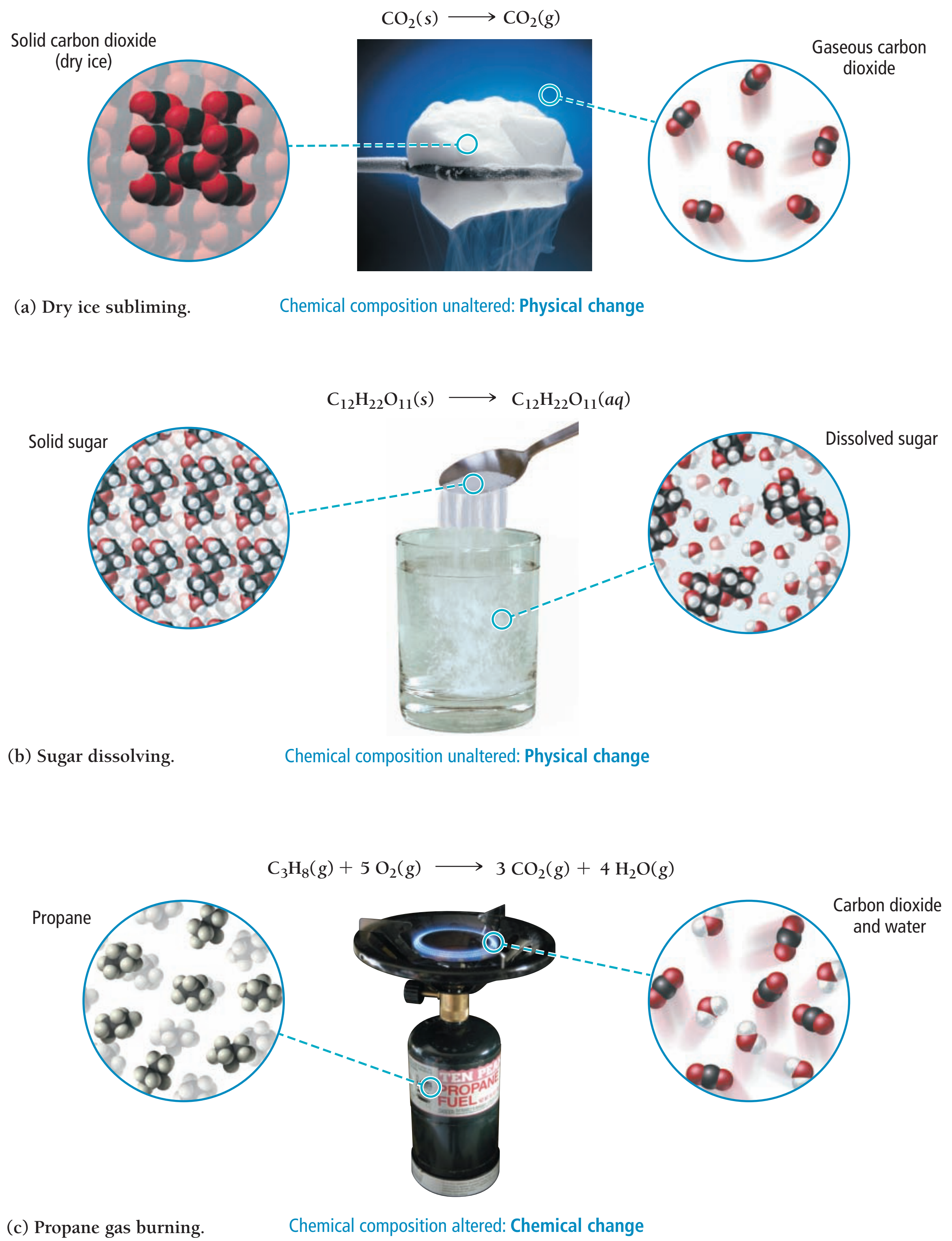
(d) Frost forms on a cold night because water vapor in air changes its state to form solid ice—this is a physical change. The temperature at which water freezes is therefore a physical property.

FOR PRACTICE 1.1 Determine whether each change is physical or chemical. What kind of property (chemical or physical) is demonstrated in each case?

(a) A copper wire is hammered flat.
(b) A nickel dissolves in acid to form a blue-green solution.
(c) Dry ice sublimes without melting.
(d) A match ignites when struck on a flint.

Answers to For Practice and For More Practice problems can be found in Appendix IV.

Physical Change versus Chemical Change

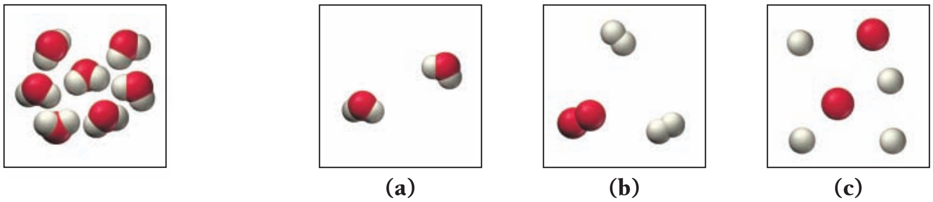


▲ **FIGURE 1.8 Physical and Chemical Changes** **(a)** The sublimation (the state change from a solid to a gas) of dry ice (solid CO_2) is a physical change. **(b)** The dissolution of sugar is a physical change. **(c)** The burning of propane is a chemical change.

ANSWER **NOW!**

1.3 Cc Conceptual Connection

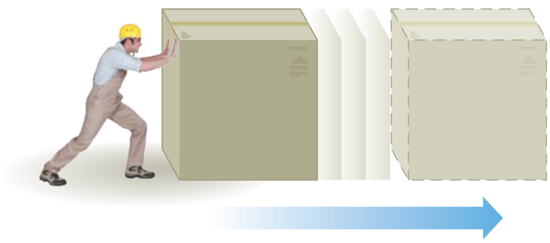
CHEMICAL AND PHYSICAL CHANGES The diagram on the left represents liquid water molecules in a pan. Which of the three diagrams (a, b, or c) best represents the water molecules after they have been vaporized by boiling?

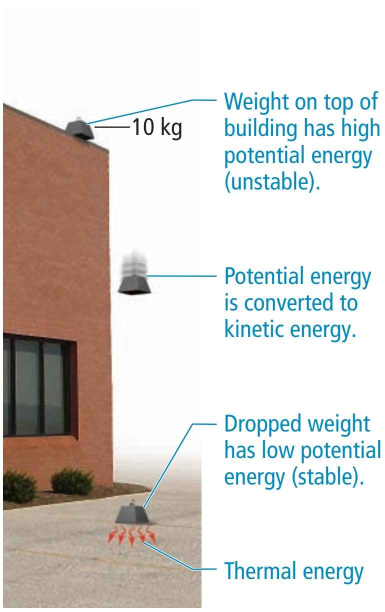


1.5 Energy: A Fundamental Part of Physical and Chemical Change

The physical and chemical changes discussed in Section 1.4 are usually accompanied by energy changes. For example, when water evaporates from your skin (a physical change), the water molecules absorb energy from your body, making you feel cooler. When you burn natural gas on the stove (a chemical change), energy is released, heating the food you are cooking. Understanding the physical and chemical changes of matter—that is, understanding chemistry—requires that you understand energy changes and energy flow.

The scientific definition of **energy** is *the capacity to do work*. **Work** is defined as the action of a force through a distance. For instance, when you push a box across the floor or pedal your bicycle across the street, you have done work.





▲ **FIGURE 1.9 Energy Conversions** Gravitational potential energy is converted into kinetic energy when the weight is dropped. The kinetic energy is converted mostly to thermal energy when the weight strikes the ground.

The *total energy* of an object is a sum of its **kinetic energy** (the energy associated with its motion) and its **potential energy** (the energy associated with its position or composition). For example, a weight held several meters above the ground has potential energy due to its position within Earth's gravitational field (Figure 1.9◀). If you drop the weight, it accelerates, and its potential energy is converted to kinetic energy. When the weight hits the ground, its kinetic energy is converted primarily to **thermal energy**, the energy associated with the temperature of an object. Thermal energy is actually a type of kinetic energy because it is associated with the motion of the individual atoms or molecules that make up an object. When the weight hits the ground, its kinetic energy is essentially transferred to the atoms and molecules that compose the ground, raising the temperature of the ground ever so slightly.

The first principle to note about how energy changes as the weight falls to the ground is that *energy is neither created nor destroyed*. The potential energy of the weight becomes kinetic energy as the weight accelerates toward the ground. The kinetic energy then becomes thermal energy when the weight hits the ground. The total amount of thermal energy that is released through the process is exactly equal to the initial potential energy of the weight. The idea that energy is neither created nor destroyed is known as the **law of conservation of energy**. Although energy can change from one type into another, and although it can flow from one object to another, the *total quantity* of energy does not change—it remains constant.

In Chapter 21 we will discuss how energy conservation is actually part of a more general law that allows for the interconvertibility of mass and energy.