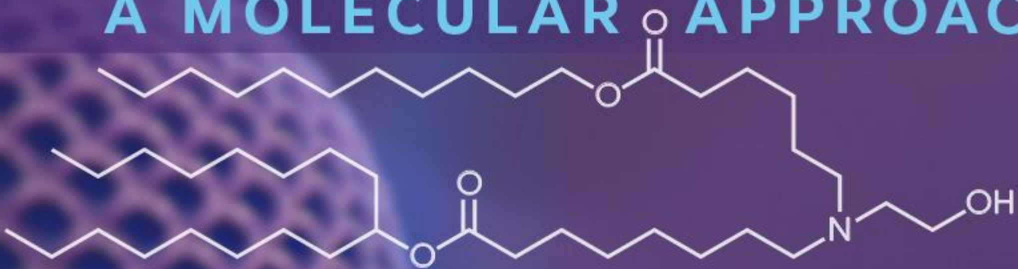
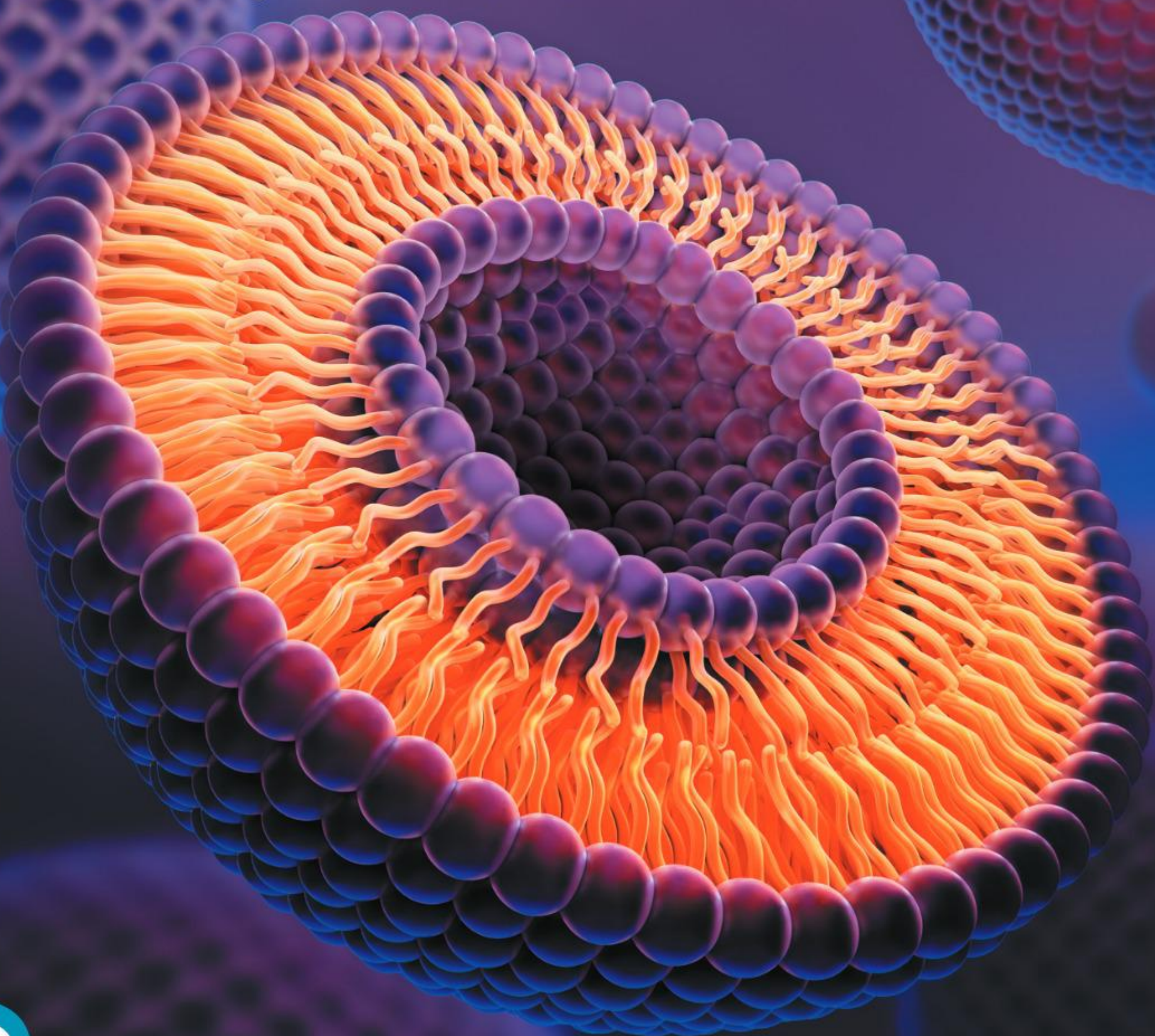
SIXTH EDITION

CHEMISTRY

A MOLECULAR APPROACH





NIVALDO J. TRO

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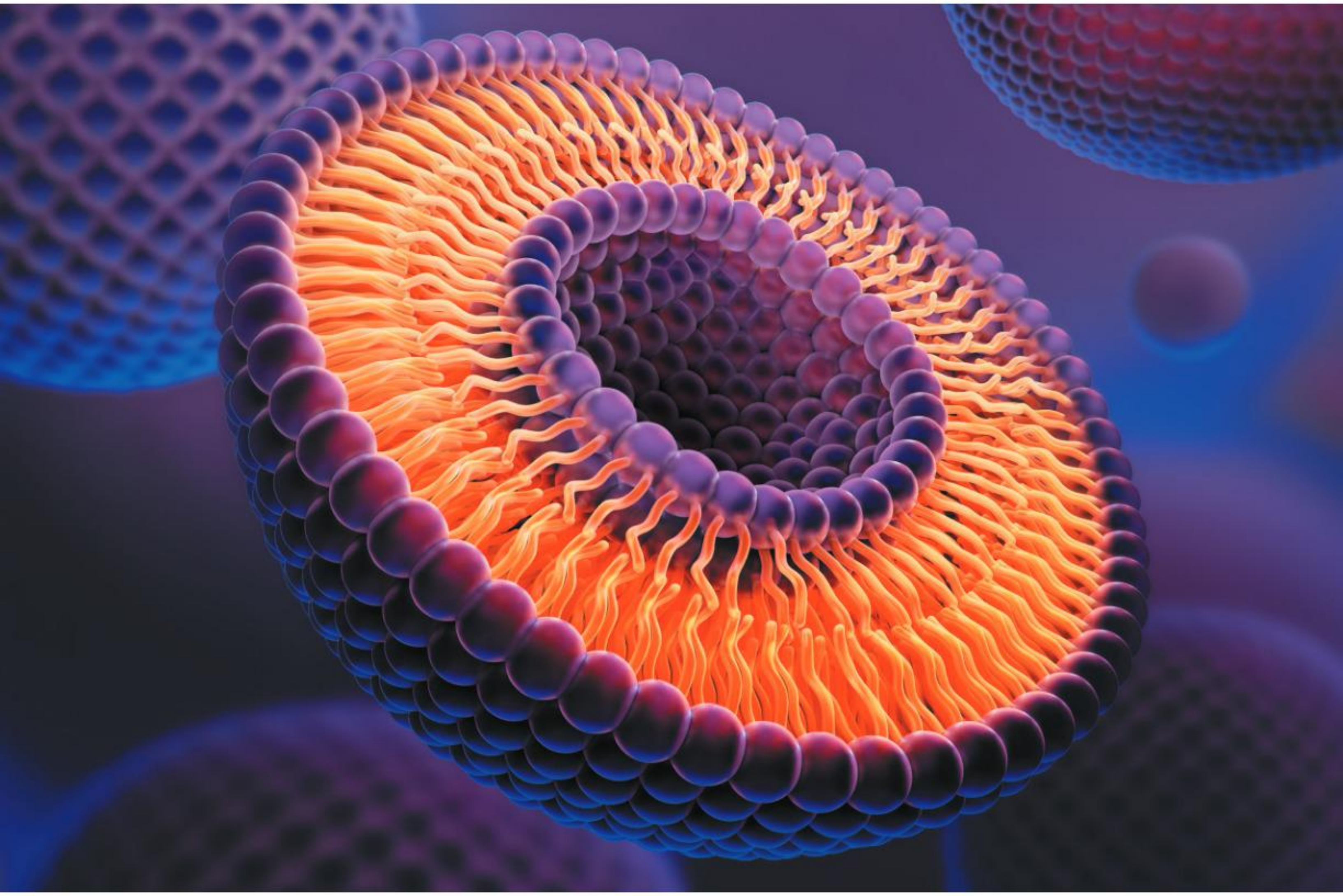

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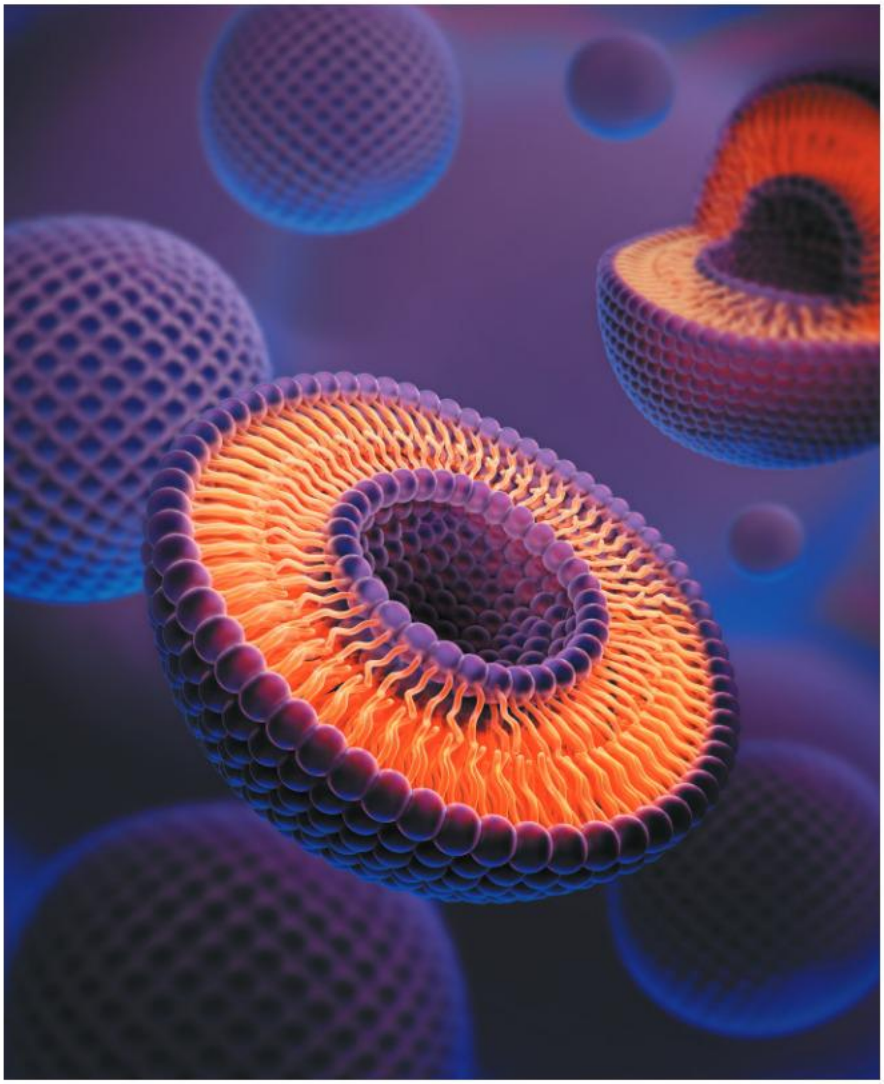
About the Author

Nivaldo Tro has been teaching college chemistry since 1990 and is currently teaching at the College of Creative Studies at the University of California, Santa Barbara, and 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. In his leisure time, Professor Tro enjoys cycling, surfing, and being outdoors.

To Michael, Ali, Kyle, and Kaden

About the Cover



The cover shows a lipid nanoparticle (LNP), a fat bubble that became central to the mRNA vaccines developed against COVID-19. These vaccines use lipid nanoparticles to house mRNA and transport it to cells. The molecule shown is 8-[(2-hydroxyethyl)[6-oxo-6-(undecyloxy)hexyl]amino]-octanoic acid, 1-octylnonyl ester, one of the components of the LNPs used in the Moderna vaccine. This molecule, and others like it, have a polar end and a nonpolar end, which results in the formation of the bilayers that compose the LNP shell.

Brief Contents

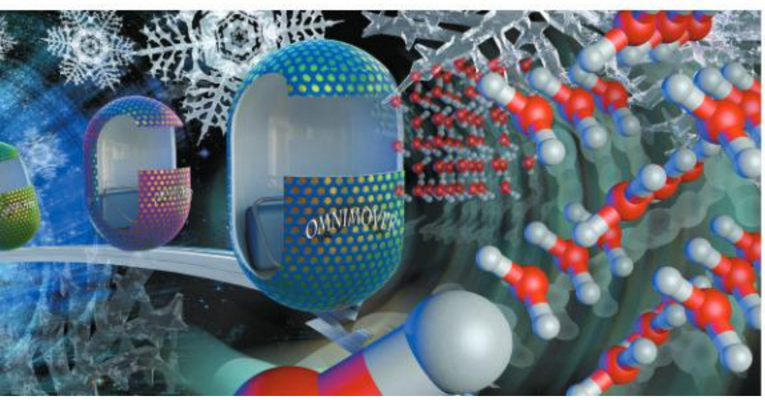
Interactive eText Media Contents

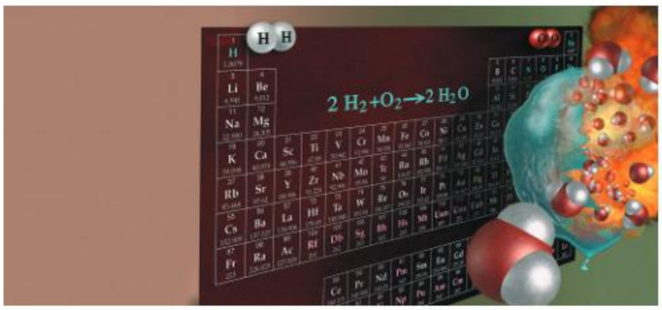
KEY CONCEPT VIDEOS (KCVs)

INTERACTIVE WORKED EXAMPLES (IWEs)

KEY CONCEPT INTERACTIVES (KCIs)

Contents

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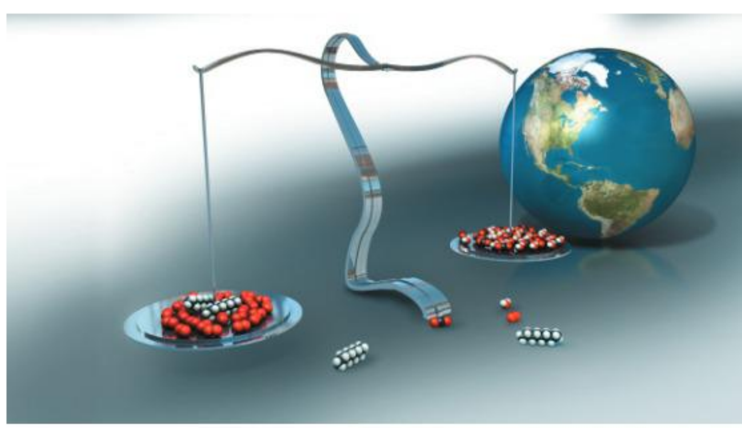
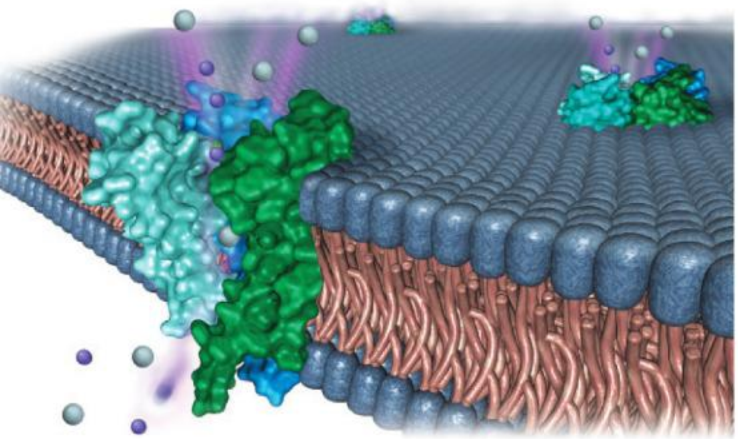
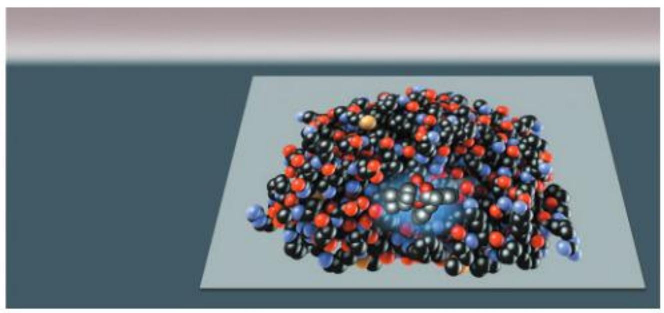
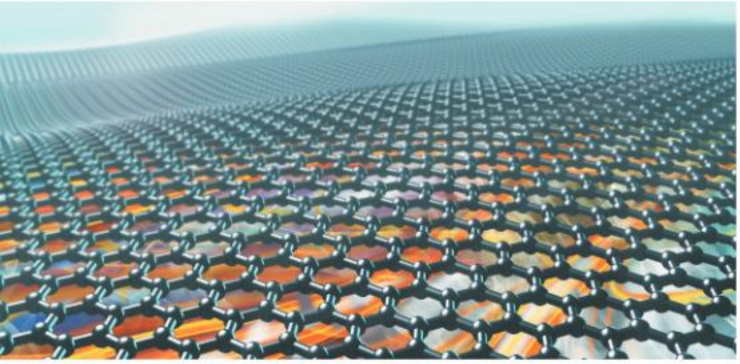


FREEFALL: 4 MINUTES 27 SECONDS
Top speed 1,322 km/h
JUMP 41,400 METERS


Schrödinger's Cat



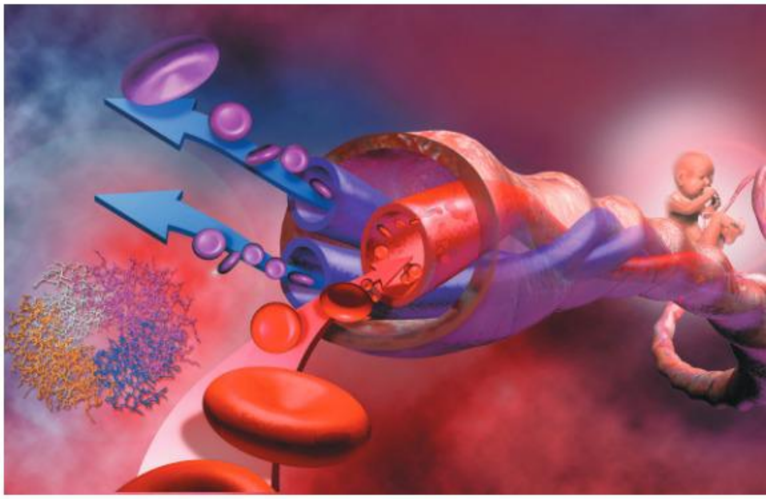




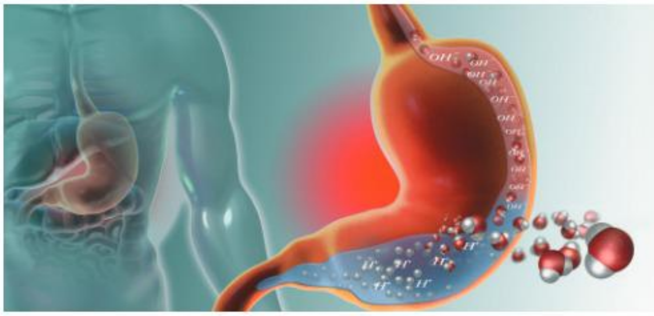
14 Solutions 588

15 Chemical Kinetics 642

16 Chemical Equilibrium 696

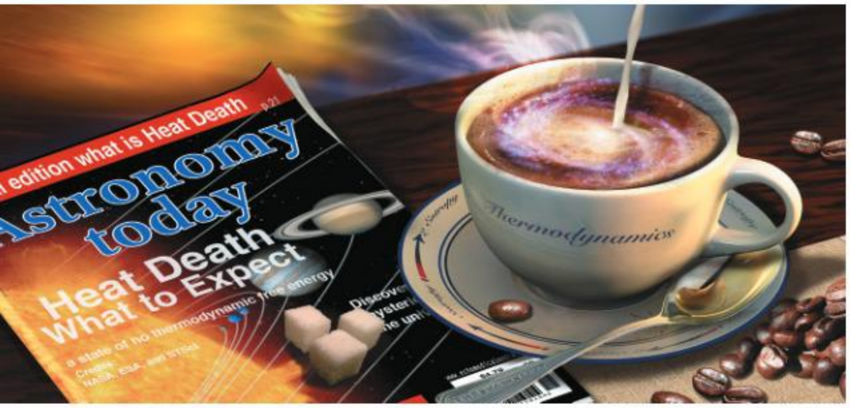


17 Acids and Bases 746

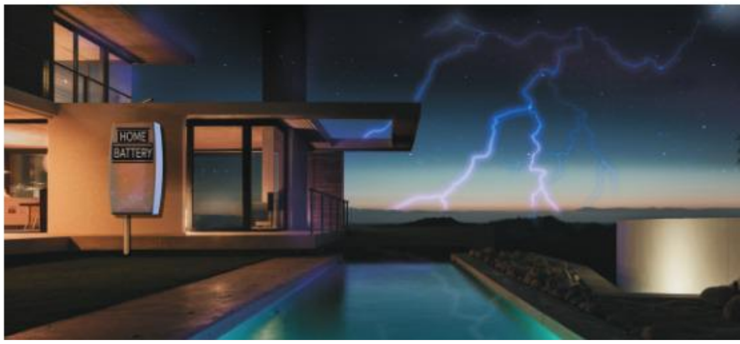


18 Aqueous Ionic Equilibrium 802

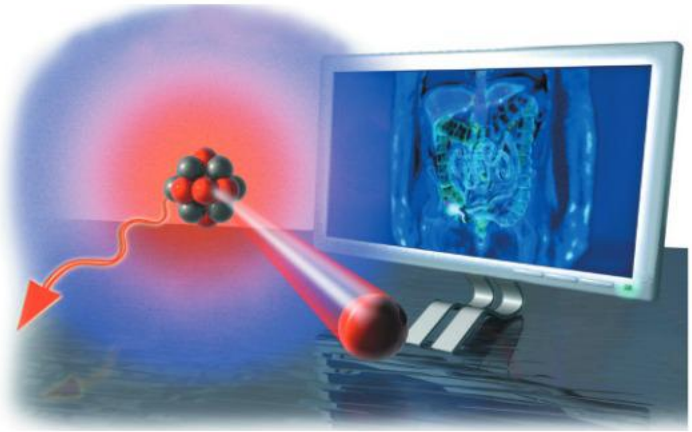
19 Free Energy and Thermodynamics 864



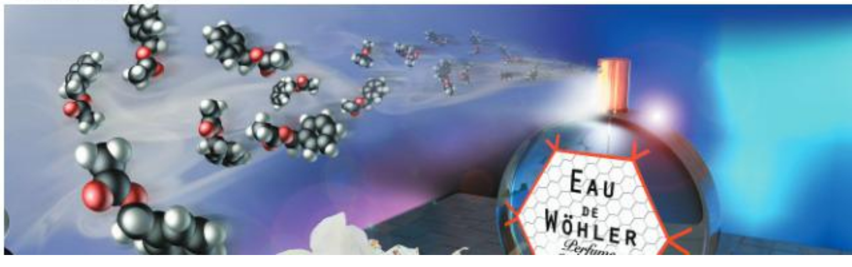
20 Electrochemistry 914



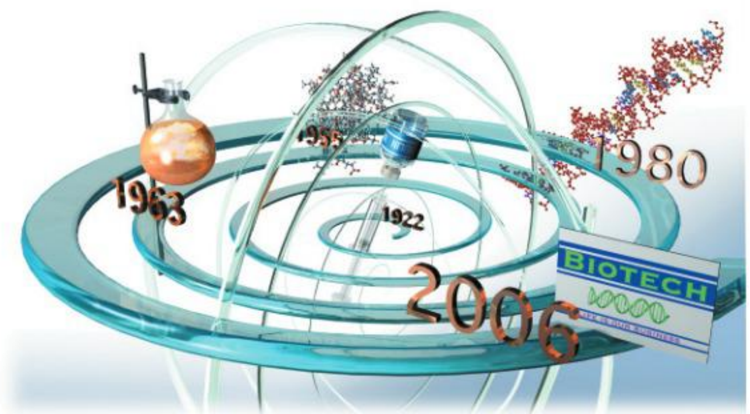
21 Radioactivity and Nuclear Chemistry 966



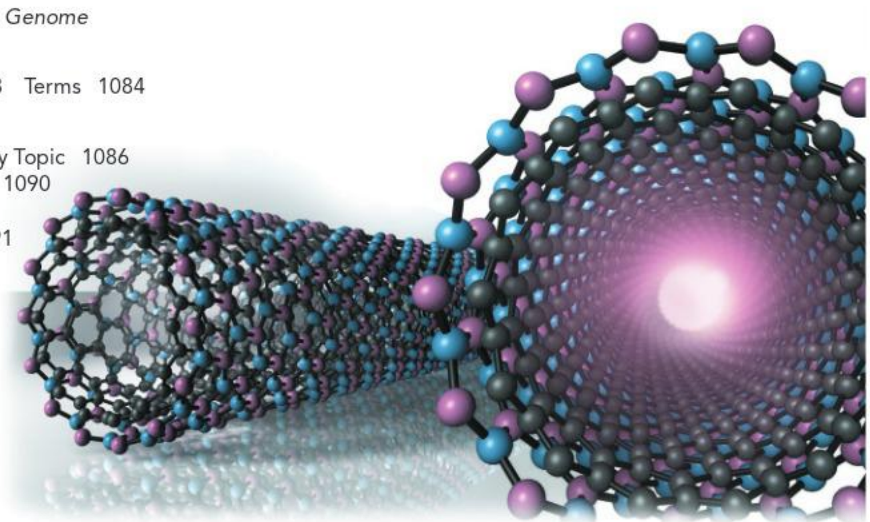
22 Organic Chemistry 1008



23 Biochemistry 1058



24 Chemistry of the Nonmetals 1092



25 Metals and Metallurgy 1130

26 Transition Metals and Coordination Compounds 1156

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

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.

This revision comes out in the midst of a pandemic and after a challenging year, for both the world and for higher education. Most of us taught remotely during the 2020–2021 academic year, lecturing into a Zoom meeting of often faceless students. The year demonstrated the power of technology for learning and also its shortcomings. I learned two important lessons: (1) Face-to-face teaching continues to be the superior mode for college instruction; and (2) technology can deliver learning experiences that are more valuable than passive studying. This revision focuses on lesson 2.

Technology can transform passive learning into active learning, which has been repeatedly demonstrated to be more effective. One of my main goals in this revision is to continue to expand tools to engage students in active learning. Although the term *active learning* has been applied mainly to in-class learning, the principal idea—*that we learn better when we are actively engaged*—applies to all of learning.

For this edition, I have worked with Pearson to develop 50 *Key Concept Interactives (KCIs)*. Each KCI guides the student through a key concept in that chapter. However, rather than passively reading a book, the student must continually interact with the material as they navigate through it. In the KCI on nomenclature, for example, students first learn how to categorize compounds as ionic, molecular, or acid. Before they advance, they are given a compound to categorize. If they categorize it incorrectly, they are provided with feedback to lead them in the right direction. If they categorize it correctly, they can advance. In this way, the student is completely active in the learning process, which we know from education research results in much greater retention than passive reading. In addition, each KCI has an associated follow-up question that can be assigned using Mastering Chemistry.

Other active learning tools, presented in previous editions, have been expanded in this edition. For example, the library of 3- to 6-minute *Key Concept Videos (KCVs)* now spans 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.

Also expanded in this edition is the 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 KCV, 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. Together, the library of KCVs and IWEs now comprises approximately 250 interactive videos.

Although we have added these 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 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, and 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, it applies a consistent approach (Sort, Strategize, Solve, and Check), 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. 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, *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 contact me with any questions or comments about the book.

Nivaldo J. Tro
nivatro@gmail.com

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, Elizabeth Bell. I have known Lizzy for many years, first as my marketing manager and now as my editor. Lizzy is a constant source of good, market-informed ideas. She is creative, energetic, and always follows through on her ideas and commitments. I am fortunate to work with such a skilled and insightful colleague. Thanks, Lizzy. Thanks also to Coleen Morrison, my new developmental editor on this project. Coleen has helped me to develop the new material in this edition. She is careful, organized, and always improves my work. Thanks, Coleen, for your attention to detail and all your hard work. Thanks also to my project manager, Shercian Kinosian. She has managed the many details and moving parts of producing this book with care and precision. I appreciate her steady hand and hard work. Thanks also to my media editor, Jackie Jacob. Jackie and I have been working together for many years to produce innovative media pieces that are pedagogically sound and easy to use. She is simply the best in the business, and I am lucky to get to work with her. I am also grateful to Ian Desrosiers and Chloe Veylit who have helped tremendously with the development of the new Key Concept Interactives and have stepped in at different stages to offer their talent and expertise.

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 product management in Science 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 the Lachina Creative, Inc. team and Jerilyn DiCarlo for their creativity and hard work in crafting the cover illustration and design of this text. I also thank Francesca Monaco and her coworkers at Straive. 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.

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 Kyle Tro, who put in many hours proofreading changes in the manuscript, working problems, and organizing appendices. Kyle, you are an amazing person—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 32 years as a professor. You have taught me much about teaching that is now in this book, and you are the motivation that keeps me inspired to develop the best learning tools possible.

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 also grateful to the accuracy reviewers who tirelessly checked page proofs for correctness.

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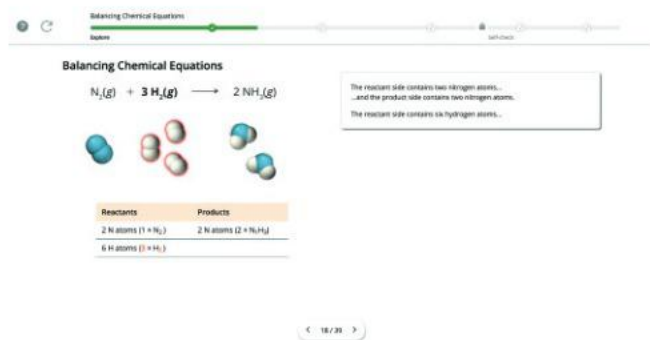
Servet M. Yatin, *Quincy College*
Kazushige Yokoyama, *SUNY Geneseo*
Lin Zhu, *IUPUI*
Jim Zubricky, *University of Toledo*

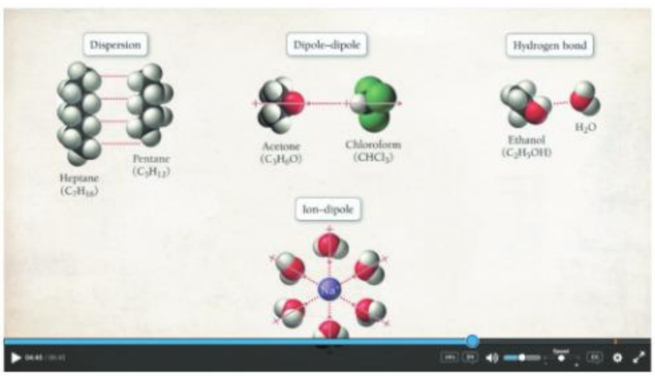
What's New in This Edition?

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 KEY CONCEPT INTERACTIVES

50 new *Key Concept Interactives (KCIs)* have been added to the eText and are assignable in Mastering Chemistry. Each interactive guides a student through a key topic as they navigate through a series of interactive screens. As they work through the KCI, they are presented with questions that must be answered to progress. Wrong answers result in feedback to guide them toward success.



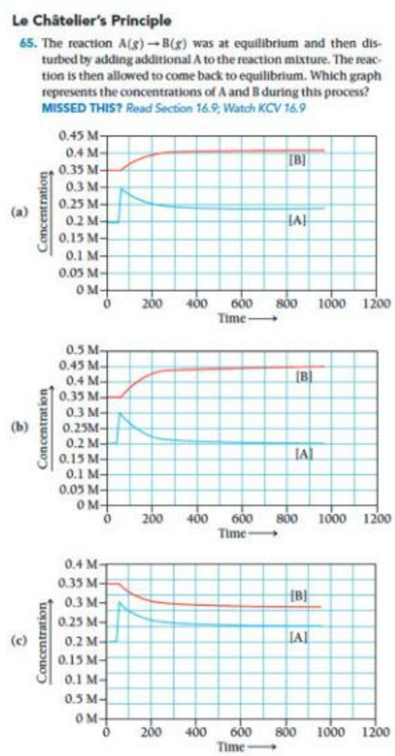


NEW INTERACTIVE VIDEOS

15 new *Key Concept Videos (KCVs)* and 25 new *Interactive Worked Examples (IWEs)* have been added to the media package that accompanies the book. All videos are available within the eText and assignable in Mastering Chemistry. *The video library now contains approximately 250 interactive videos.* These tools are designed to help professors engage their students in active learning.

NEW AND REVISED END-OF-CHAPTER PROBLEMS

176 New End-of-Chapter questions have been added throughout the book, and **378 have been revised**. Many new End-of-Chapter questions involve the interpretation of graphs and data. All new End-of-Chapter questions are assignable in Mastering Chemistry.



NEW ONLINE PROBLEM SETS

Online problem sets are web-based, online-only problems that are algorithmically randomized. They provide answer-specific feedback and will be continually updated and expanded.

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 Concentrations in the Atmosphere*; Figure 4.3: *Global Temperature*; the unnumbered figure in Section 7.10 of *U.S. Energy Consumption by Sector*; Figure 7.12: *Energy Consumption by Source*; Table 7.6: *Changes in National Average Pollutant Levels, 1990–2019*.

DIVERSITY, EQUITY, AND INCLUSION REVIEW

As mentioned in the Preface, the entire book went through a detailed review to ensure the content reflects the rich diversity of our learners and is inclusive of their lived experiences.