

INSTRUCTOR'S GUIDE

Organic Chemistry:
Principles and Mechanisms

Second Edition

Joel M. Karty

Michelle Boucher

UTICA COLLEGE

Cliff Coss

NORTHERN ARIZONA UNIVERSITY

Stephen Pruett

JEFFERSON COMMUNITY AND TECHNICAL COLLEGE



W • W • NORTON & COMPANY • NEW YORK • LONDON

W. W. Norton & Company has been independent since its founding in 1923, when William Warder Norton and Mary D. Herter Norton first published lectures delivered at the People's Institute, the adult education division of New York City's Cooper Union. The firm soon expanded its program beyond the Institute, publishing books by celebrated academics from America and abroad. By midcentury, the two major pillars of Norton's publishing program—trade books and college texts—were firmly established. In the 1950s, the Norton family transferred control of the company to its employees, and today—with a staff of four hundred and a comparable number of trade, college, and professional titles published each year—W. W. Norton & Company stands as the largest and oldest publishing house owned wholly by its employees.

Copyright © 2018, 2014 by W. W. Norton & Company, Inc.

All rights reserved.

Printed in the United States of America.

Associate Media Editor: Arielle Holstein

Project Editor: Gabe Waggoner

Associate Managing Editor, College: Carla L. Talmadge

Production Manager: Eric Pier-Hocking

Assistant Media Editor: Doris Chiu

ISBN 978-0-393-64434-0

W. W. Norton & Company, Inc., 500 Fifth Avenue, New York, NY 10110
wwnorton.com

W. W. Norton & Company Ltd., 15 Carlisle Street, London W1D 3BS

1 2 3 4 5 6 7 8 9 0

CONTENTS

Preface v

Introduction ix

Chapter 1: Atomic and Molecular Structure 1

Interchapter A: Nomenclature: The Basic System for Naming Simple Organic Compounds—Alkanes, Haloalkanes, Nitroalkanes, Cycloalkanes, and Ethers 6

Chapter 2: Three-Dimensional Geometry, Intermolecular Interactions, and Physical Properties 9

Chapter 3: Orbital Interactions 1: Hybridization and Two-Center Molecular Orbitals 14

Interchapter B: Naming Alkenes, Alkynes, and Benzene Derivatives 18

Chapter 4: Isomerism 1: Conformers and Constitutional Isomers 21

Chapter 5: Isomerism 2: Chirality, Enantiomers, and Diastereomers 27

Interchapter C: Stereochemistry in Nomenclature: *R* and *S* Configurations about Asymmetric Carbons and *Z* and *E* Configurations about Double Bonds 33

Chapter 6: The Proton Transfer Reaction: An Introduction to Mechanisms, Thermodynamics, and Charge Stability 36

Chapter 7: An Overview of the Most Common Elementary Steps 42

Interchapter D: Molecular Orbital Theory, Hyperconjugation, and Chemical Reactions 48

Interchapter E: Naming Compounds with a Functional Group That Calls for a Suffix 1: Alcohols, Amines, Ketones, and Aldehydes 51

Chapter 8: An Introduction to Multistep Mechanisms: S_N1 and $E1$ Reactions and Their Comparisons to S_N2 and $E2$ Reactions 54

Chapter 9: Nucleophilic Substitution and Elimination Reactions 1: Competition among S_N2 , S_N1 , $E2$, and $E1$ Reactions 59

Interchapter F: Naming Compounds with a Functional Group That Calls for a Suffix 2: Carboxylic Acids and Their Derivatives 66

Chapter 10: Nucleophilic Substitution and Elimination Reactions 2: Reactions That Are Useful for Synthesis 68

Chapter 11: Electrophilic Addition to Nonpolar π Bonds 1: Addition of a Brønsted Acid 74

Chapter 12: Electrophilic Addition to Nonpolar π Bonds 2: Reactions Involving Cyclic Transition States 78

Chapter 13: Organic Synthesis 1: Beginning Concepts in Designing Multistep Synthesis 83

Chapter 14: Orbital Interactions 2: Extended π Systems, Conjugation, and Aromaticity 89

Chapter 15: Structure Determination 1: Ultraviolet–Visible and Infrared Spectroscopies 94

Chapter 16: Structure Determination 2: Nuclear Magnetic Resonance Spectroscopy and Mass Spectrometry 100

Chapter 17: Nucleophilic Addition to Polar π Bonds 1: Addition of Strong Nucleophiles 107

Chapter 18: Nucleophilic Addition to Polar π Bonds 2: Weak Nucleophiles and Acid and Base Catalysis 112

Chapter 19: Organic Synthesis 2: Intermediate Topics in Synthesis Design, and Useful Redox and Carbon–Carbon Bond-Forming Reactions 118

Chapter 20: Nucleophilic Addition–Elimination Reactions 1: The General Mechanism Involving Strong Nucleophiles 123

Chapter 21: Nucleophilic Addition–Elimination Reactions 2: Weak Nucleophiles 127

Chapter 22: Aromatic Substitution 1: Electrophilic Aromatic Substitution on Benzene; Useful Accompanying Reactions 132

Chapter 23: Aromatic Substitution 2: Reactions of Substituted Benzenes and Other Rings 136

Chapter 24: The Diels–Alder Reaction and Other Pericyclic Reactions 141

Chapter 25: Reactions Involving Free Radicals 146

Interchapter G: Fragmentation Pathways in Mass Spectrometry 150

Chapter 26: Polymers 152

Additional Resources 157

Sample Syllabi 161

Problem Correlation Table 177

PREFACE (Why this book?)

I met Joel Karty in 2005 at a conference. At that point, I had been teaching organic chemistry for more than 10 years. On the basis of students' success at other institutions and their reports of scores on standardized exams such as the PCAT, MCAT, and DAT, I felt that I was successful as an organic instructor. I was also content—though not necessarily happy—with the textbook I was using.

Joel and I spent hours at that conference talking about his work in progress, a new textbook for organic chemistry that would be structured around mechanism types rather than functional groups. I was a hard sell for his proposed reorganization of the material. Having been forced to teach out of books not of my choosing on several occasions, I had found that a “bad” textbook did not prevent me from teaching a good course. I therefore hesitated to believe that a “good” textbook would affect my teaching.

I had to admit, however, that not all was copacetic in the organic classroom. When my department hired another organic chemist, I handed over second-semester organic to him with relief. I had consistently had a “crisis of faith” in the midst of the second-semester course, struggling to get students to recognize the similarity between reactions in separate chapters, wondering about the relevance of several topics, and grappling with the content in the sections treating biological molecules. Toward the end of the second semester, I found that the course simply was not enjoyable to teach. Consequently, I suspected that a better way to present the material to students had to exist.

Joel's arguments for a book structured around mechanism types, as opposed to functional groups, came with two types of evidence. First, Joel had done quantitative studies that supported his proposals. Second, he had credibility as a teacher who actively considered students' needs. During our first meeting, as well as the many discussions we had later, I found Joel's insights as an instructor consistent with my own, to the point that when his position challenged mine, I felt I had to seriously consider his comments.

Fortunately, Joel and I met at a good time. One of my professional goals is to avoid becoming a fossilized professor. I wanted to shake things up and was willing to make a change. The organic class was ripe for a pedagogical revolution.

The initial draft of Joel's book was so different from anything I had seen that its sheer novelty fascinated me, and I was eager to try it. I suggested that I class-test the book and offer feedback. The first year's trial was bumpy for several reasons. By the second semester, though, his pedagogical revolution had clearly changed how my students looked at organic chemistry—and in a good way.

What were those changes? For one thing, the experience revealed that several of my assumptions about the course had been false. For example, I would have denied with my dying breath that I had expected my students to memorize organic chemistry. Yet that first year, experiences I had with students showed that, in some ways, I clearly *had* expected them to rely on memorization.

For all of us, students and instructor, the organization of the material led to a better experience. In the second semester, the progression from anions to cations and then free radicals created a semester that started with challenging, but doable, material, and concluded with material that students mastered readily. Each chapter's focus on reactions that were similar, without the “noise” from topics such as nomenclature and spectroscopy, was a major improvement.

Finally, students asked me the best questions I had ever encountered. Those were questions that I had never heard from other students, questions that reflected a strong understanding of organic chemistry—and questions that frequently stumped me. I often admitted, “I'll have to get back to you on that one.”

As teachers, we often discuss how students construct their learning from their experiences. What we discuss less often is that we construct our teaching from our experiences. Our goal in writing this *Instructor's Guide* is to improve your experience when you begin your own pedagogical revolution.

Steve Pruett
Jefferson Community and Technical College

What's different about *Organic Chemistry: Principles and Mechanisms*?

Several features set *Organic Chemistry: Principles and Mechanisms* apart from traditional chemistry texts.

Reactions are organized by mechanism instead of by functional group.

Yes, a simple review of the table of contents will tell you that. No, we cannot ignore the elephant in the room. That significant difference elicits strong and, often, emotional responses from people who examine the book. (“Gasp! But we’ve always taught organic chemistry by functional groups!”)

Explanations for elementary steps and organic reactions are based on thermodynamics and kinetics.

Although all organic chemistry textbooks emphasize kinetics and thermodynamics in the context of substitution and elimination reactions, those topics often fade into the background in later chapters. This textbook consistently discusses the reversibility or irreversibility of reaction steps, using bond energies and charge stability as the basis for qualitative evaluation. Those deceptively easy concepts do help students understand what occurs in reactions.

Chapter 7, “An Overview of the Most Common Elementary Steps,” is unique.

Chapter 7 introduces the elementary steps that students will see in practically all mechanisms in later chapters. To our knowledge, this chapter is unique to this book. The bad news is that you must incorporate it into the first-semester material, and it may seem to weight the division of material toward the first semester. The good news, and the reward for spending time with this chapter, is that it liberates you to discuss any organic mechanism with your students. Once they recognize the common elementary steps, most organic mechanisms are accessible to them.

Pedagogical issues are treated thoughtfully.

In many sections, the author has supplied simplifications that allow students to remove “noise” from the signal we are trying to send. For example, in describing organolithium, Grignard, and hydride reagents, he relegates the cations and aluminum and boron to the role of spectators, and shows simple carbanions and hydride anions as the reactants. That simplification allows students to see and understand the more reactive portion of the reagents and ignore ions and atoms that, at this level of presentation, can be readily omitted.

Another thoughtful treatment of pedagogical issues includes segregation of nomenclature. All the nomenclature topics are contained in five interchapters (Interchapters A, B, C, E, and F) spread throughout the textbook. That approach allows you to incorporate the material when and how you choose. For example, some instructors cover all the nomenclature material in the first semester—a benefit to those students who take only one semester of organic. Other instructors require students to basically learn nomenclature on their own, without devoting classroom time to it. The material is essentially paradigmatic, and students learn it easily. With this next edition of Joel’s textbook, nomenclature is spread out into more interchapters, making it easier for students to learn it on their own.

Cliff and Steve initially opposed that approach to nomenclature. Their rationale was that, as in a language class, students should be exposed to concepts one at a time; also, nomenclature was an “easy” part of each chapter. However, learning nomenclature is analogous to learning to conjugate verbs, and students simply need examples and exercises. There really is not anything to teach, except rules. They found that having students master that on their own, and testing them on quizzes or on a single exam at the end of the course, was at least as effective as the traditional approach. The organization of the nomenclature, based on functional group and similarities in rules, makes learning organic chemistry nomenclature easy for students. Moreover, we are happy not to have to spend time on the topic.

A further example is the segregation of biological topics at the ends of certain chapters. Textbooks traditionally include chapters on carbohydrates and proteins, and often chapters on nucleic acids and lipids. However, Joel has collected informal data indicating that most instructors do not get to those chapters in a normal course. Cliff is one such instructor. Though he has a passion for carbohydrates and synthesizing carbohydrate-based materials, enough time is never available to effectively incorporate that into undergraduate organic chemistry. In addition, in our experience, much of the material in such chapters does not belong in an organic chemistry course. For example, in my former textbooks, much of the protein chemistry and nucleic acid chemistry restated what students learn in biology courses.

What's in this *Instructor's Guide*?

For each chapter and interchapter in the textbook, you will find a chapter in the *Instructor's Guide* that contains all or most of the following sections:

- **Heads Up!** highlights differences between the author's presentation and what you may be familiar with in other textbooks.
- **Comments by Section** briefly outlines the material in the chapter, with suggestions for presenting concepts. The section also describes classroom activities you can incorporate into your classroom and offers other ways to describe specific concepts that may help your students grasp ideas more easily.
- **Students' Perspectives** contains examples of issues that students often wrestle with. The section also may include commentary from Joel or other instructors about a particular topic in the chapter.
- **Resources for Instructors** describes resources that may help you teach the material, such as sources of homework and exam questions, laboratory experiments, and classroom demonstrations. The section also includes suggested clicker questions available on wwnorton.com/instructors.

The introduction that follows this preface briefly discusses pedagogical issues relevant to organic chemistry. The end of the guide includes a list of general resources for instructors and sample syllabi from instructors teaching with Joel's textbook (Joel's syllabus is included as well). The course can be organized in many ways, and those resources offer suggestions. Finally, the guide includes a table that correlates problems from the Second Edition with those in the First Edition.

We hope that you will find useful information in this guide that will help you create a successful organic chemistry experience for your students. We welcome your comments, questions, and suggestions.

INTRODUCTION: A Discussion of Pedagogical Issues

This introduction discusses six issues that you may wish to consider as you design your course. Most issues are stated here as dichotomies—contradictory statements about our teaching goals and practices. Their purpose is to encourage you to step away from the course’s specific content and consider the overarching challenges that instructors and students face.

1. I want you to know everything, but I’d like you to learn something.

As an instructor, you determine the content of your course. That may seem obvious, yet some instructors feel compelled to teach every topic presented in a textbook.

Textbooks have to be able to work for a variety of users; they are not a consensus of what needs to be taught. As a result, chemistry textbooks generally contain more material than you can reasonably present. You have to use your judgment and experience to decide what your students need to know.

For example, although Steve remembers the sonorous name of the Chichibabin reaction and the significance of the Fischer proof of the structure of glucose, he does not lament the passing of either from the pages of organic textbooks. The information has simply not been useful to him. In contrast, because he used a Sandmeyer reaction in an undergraduate research project and knows the significance of diazotization in synthesizing the dyes used in Crayola crayons, his students will always learn about diazonium ions. Likewise, because Cliff spent most of his career attaching lipids and peptides to carbohydrates, he tests students in Organic Chemistry II heavily on acetal and hemiacetal chemistry (and their mechanisms). Michelle always spends extra time on enolate chemistry since those reactions fit well with how she likes to test students on both mechanisms and synthetic design.

We have found that *Organic Chemistry: Principles and Mechanisms* allows for easy editing of the material. Each chapter includes several reactions that proceed by similar mechanisms. We treat many of those chapters as surveys of a reaction type and can easily choose which reactions we expect our students to learn. You will find that approach particularly useful when navigating Chapters 7, 10, 12, and 15.

Furthermore, chapters can be rearranged to accommodate your preference as an instructor. Even though Joel’s textbook is written based on similarities in mechanisms, rather than functional groups, that organization still allows you the freedom to move chapters around. For example, Cliff covers Chapter 15 between Chapters 3 and 4 of his first-semester course, to introduce infrared spectroscopy before students use it in lab. He also prefers to cover conjugation and aromaticity (Chapter 14) in his second-semester course, as an introduction to aromatic substitution reactions (Chapter 22). Michelle uses both spectroscopy chapters (Chapters 15 and 16) in her laboratory sequence only and moves Chapter 14 to the second semester directly before Chapter 22.

In general, most instructors follow the textbook as it was intended. Different opinions occur in regard to what content should be included in the first and second semesters of organic chemistry. Aside from small adjustments, most instructors will spend the first half of the semester covering the fundamental concepts in Chapters 1–7. After that, most instructors will spend the rest of the first semester covering substitution, elimination, and addition reactions. From there, with not much time left in the semester, instructors may choose to introduce synthesis (Chapter 13) and/or instrumentation (Chapters 15 and 16). Either could be included in the first semester or saved for the second, being that both become more relevant in the second-semester course. You can find sample syllabi in the back of this guide.

2. I want you to understand this, so I’m going to lie to you.

One axiom of good teaching is “KISS: keep it super simple.” Implementing KISS requires us to cut out certain details that muddy the picture. Consider the existence of pentavalent carbon: although the isolation of pentavalent carbon is intriguing, we spend the whole year getting students to recognize that carbon can have only four bonds. Consequently, in our minds, pentavalent carbon has no place in a presentation to undergraduates.

As an instructor, you have to decide what details to omit and which to include.

Joel has made a serious attempt at KISS in *Organic Chemistry: Principles and Mechanisms*. One example, mentioned in the Preface, is his description of organolithium, Grignard, and hydride reagents. He relegates the

cations and aluminum and boron to the role of spectators, and he shows simple carbanions and hydride anions as the reactants. That simplification allows students to see and understand the more reactive portion of the reagents and ignore ions and atoms that, at this level of presentation, can be readily omitted. The textbook also has sections in which Joel briefly mentions aspects of a reaction mechanism but concludes that the specifics are unknown or beyond the scope of the course—an excellent use of KISS.

Recognizing that some topics are presented in artificial contexts also helps. The classical presentation of nuclear magnetic resonance (NMR) is one example. In practice, chemists rarely run an NMR spectrum of a pure sample to obtain spectra similar to what our students see. In addition, chemists rarely use such a spectrum to determine the structure of an unknown compound.

Similarly, the synthesis problems students undertake fail to reflect the actual practice of organic synthesis. Synthetic chemists begin with an inexpensive, readily available starting material that can serve as a basis for the target molecule; few start with a compound with hydrocarbons or another molecule with four carbons or fewer.

Recognizing those artificial aspects of the course can help you improve your presentations. For example, in discussing NMR, we always point out the solvent peaks present in NMR spectra and explain to students how, in practice, we learn to ignore them. We are glad that most spectra in *Organic Chemistry: Principles and Mechanisms* contain solvent peaks and that, in the section on ^{13}C NMR, Joel labels and discusses the solvent peak. For synthesis, we always discuss briefly the motivations for organic synthesis—primarily economic ones—so students have a perspective on the significance of synthesis. With this new edition of the textbook, that topic becomes more relevant with the inclusion of green chemistry topics in Chapter 13. Such topics go beyond the scope of inexpensive reagents and solvents, such as less toxic and safer materials, atom economy, and increased yield.

3. Molecular orbital theory is state of the art, but that passé valence bond theory is so useful.

Organic Chemistry: Principles and Mechanisms gives a fairly detailed description of molecular orbital (MO) theory. Certainly, MO theory's significance in chemical research cannot be overstated, and the course includes topics that benefit greatly from MO theory, such as the Diels–Alder reaction and discussions of aromatic systems.

At the same time, valence bond theory continues to be the basis for teaching organic chemistry. Although Lewis dot structures and resonance contributors have their limitations, they are effective means of representing organic structures. Graduate-level texts continue to use them to explain reactivity and mechanisms.

Joel has designed *Organic Chemistry: Principles and Mechanisms* to allow you to include as much or as little MO theory as you want. A separate interchapter (Interchapter D), for example, describes MO theory in elementary steps. In the Diels–Alder chapter (Chapter 24), the MO discussion is at the end of the chapter and may be included or omitted as you choose.

4. Every organic molecule has at least three names. Can students really make do with just one?

You have to decide what dialect of organic chemistry your students will learn. Organic chemistry comes with serious linguistic issues. Is the active ingredient in vinegar acetic acid or ethanoic acid? Do welders use ethyne or acetylene? How many dicarboxylic acids should students be able to name?

You have to decide which “trivial” names are important for your students to learn. Again, that is a function of your experience and is not a topic that any two instructors will agree on completely.

Fortunately, the nomenclature sections in *Organic Chemistry: Principles and Mechanisms* are comprehensive in how they treat nomenclature and include trivial names for compounds.

5. Recognize this molecule? Good! Let me draw it in a way that will confuse you.

Organic chemistry is the science of multiple representations. A methyl group alone can be represented as CH_3^- , H_3C^- , Me^- , or a single line in a line structure. Benzene can be represented by three ring structures with a hexagon (two with double bonds and one with a circle), by the letters Ph, or by the Greek letter ϕ . Acetic acid appears in three ways in its condensed formula in general chemistry and organic chemistry texts: $\text{HC}_2\text{H}_3\text{O}_2$, CH_3COOH , and $\text{CH}_3\text{CO}_2\text{H}$.

Given the possible Lewis dot structures, line formulas, condensed formulas, Newman projections, and dash-wedge structures that students may encounter, we obviously expect them to interpret many representations.

As a result, organic chemistry's vocabulary and orthography (the written representation of language) can be challenging. Two approaches can help students with that challenge: first, we can be explicit about the representations we use; second, we can ask students to "translate" from one representation to another. I find *Organic Chemistry: Principles and Mechanisms* to be excellent at explaining representations, presenting them from different views, and asking students to translate.

6. Organic chemists count carbon atoms with great precision but are terrible bookkeepers.

The rule of correctly balanced chemical equations seems to go out the window when we teach organic chemistry. The fact is, we focus on the organic substrate and often ignore organic products of no interest and inorganic species that are produced.

Our journal entries are not entirely clear, either. In reaction sequences, we, as experts, know which species are reagents, which are solvents, and which are catalysts. Do we communicate explicit rules for identification? And what about those reactions in which we show no solvent? How do we explain those? More important, *do* we explain them?

In his first chapter on synthesis (Chapter 13), Joel takes time to explain synthetic notation and how it differs from a reaction mechanism. He distinguishes between the reagent and reaction conditions, and he notes that inorganic products are often ignored. He takes time to be explicit about the details that we often forget to explain to students. Let that example be your guide when you introduce students to reaction schemes versus reaction mechanisms. That approach becomes one of the key components of students' success.

CHAPTER 1 | Atomic and Molecular Structure

This first chapter introduces organic chemistry and begins an organic-centered review of relevant information from general chemistry. Chapter 1 reviews atomic structure, electron configurations, covalent and ionic bonds, electronegativity, bond dipoles, bond energy, bond length, formal charge, and oxidation numbers. The chapter summarizes the stepwise approach to drawing Lewis dot structures and then introduces a method for quickly generating Lewis dot structures for organic molecules. The chapter also includes a lengthy discussion of resonance structures, including visual clues that allow students to identify when resonance structures will exist for a species and an introduction to curved arrow notation. The chapter concludes with new topics for students, including the various representations of molecules (Lewis dot structures, condensed formulas, and line drawings) and a survey of functional groups.

HEADS UP!

The temptation is always to shortchange the “review” chapters because so much new information is waiting for students in later chapters. No matter how strong your students are from their general chemistry experience, some parts should not be skipped. In several places, Karty is setting up the rest of the semester by combining concepts or presenting them in particular ways, or going deeper than you might expect for an early chapter. For example, Section 1.9 presents formal charges from a molecular approach (which differs from the mathematical formula-based approach often used in general chemistry). In addition, Karty uses energy diagrams during his discussion of resonance theory (Section 1.10) and uses energy to justify stability (and then have students predict stability) in ways that most general chemistry courses do not. He leads from there directly into electron-pushing arrows (Section 1.11) and integrates them with his discussion on formal charges. The use of both energy diagrams (qualitative or quantitative) and curved arrow notation is vital to this text.

COMMENTS BY SECTION

1.1. What Is Organic Chemistry?

1.2. Why Carbon?

1.3. Atomic Structure and Ground State Electron Configurations

The first three sections of the chapter define organic chemistry, describe carbon’s unique properties, and review atomic theory, including wave functions and electron configurations. Even here, in the first few sections, the text is using complex structures (Figure 1-2, royal purple, for example) and branching systems to help students immediately become comfortable with larger molecules.

1.4. The Covalent Bond: Bond Energy and Bond Length

Section 1.4 discusses covalent bonds. It gives students an overview of bond length, strength, and energy and the types of bonds that occur in organic chemistry. The table of bond energies (Table 1-2) is worth noting because the text will use those values in discussing bond energy as a driving force (e.g., Section 7.8). The textbook generally provides bond energy values in the discussion; however, you may wish to send students to Table 1-2 to confirm the values or to use them in assignments.

1.5. Lewis Dot Structures and the Octet Rule

Section 1.5 summarizes the typical five-step process for drawing Lewis dot structures that students learn in general chemistry. A quick review of that process is a useful way to move students into the next section.

1.6. Strategies for Success: Drawing Lewis Dot Structures Quickly

This section is the first place where students often need to start working hard because they are applying what they have learned to new situations. Students are tempted to try to memorize the information presented in Table 1-4, which summarizes the numbers of bonds and lone pairs for H, C, N, O, X (where X = F, Cl, Br, or I), and Ne atoms

with no formal charge. I always advise my students to use that table as a tool to augment the five-step process (Section 1.5) and tell them that although they should not memorize the table, they will end up knowing it by heart through simple practice.

This section, and Table 1-4 in particular, helps students make the transition from the general chemistry approach of counting valence electrons and creating a structure to the faster method of creating a structure based on the number of bond and lone pairs expected for each first-row atom. That transition is not always presented explicitly in organic chemistry textbooks, and students find it useful.

1.7. Electronegativity, Polar Covalent Bonds, and Bond Dipoles

Section 1.7 introduces polar covalent bonds and electrostatic potential diagrams; however, net dipoles are not discussed until Section 2.4. Some instructors may expect those two topics to be treated together, but this chapter is focused on individual bonds (not geometry). This chapter has enough to cover without introducing geometry, and it allows a greater focus on bonds, formal charges, and electron movement. Net dipoles are deferred until the discussion of intermolecular forces in Chapter 2.

1.8. Ionic Bonds

Section 1.8 defines ionic bonds, provides guidelines for identifying ionic compounds, and describes polyatomic anions and cations, noting that most polyatomic cations contain a nitrogen atom.

1.9. Assigning Electrons to Atoms in Molecules: Formal Charge

Section 1.9 provides a simple method to calculate formal charges and does so without presenting it in a symbolic mathematical formula. The calculation is still there, and students work it out in Your Turn 1.8, but it is calculated as the valence electrons of the atom in the molecule (lone pairs and half-bonding pairs) versus the protons of that atom. In my experience, students are used to some variation of a mathematical presentation, such as “formal charge = valence electrons in the uncharged atom – (lone pairs of the atom in the molecule + $\frac{1}{2} \times$ bonding pairs).” Students may initially be concerned that they are not “using the formula,” but they quickly adapt to the commonsense approach of looking at valence electrons of the atom *in the molecular setting* versus the protons of that atom.

1.10. Resonance Theory

Section 1.10 provides six observations about resonance contributors, with examples, that students need to know. Those observations introduce students to how we interpret resonance contributors. The section does not compare structures with negative charges on atoms of different electronegativities; that topic appears in Sections 6.7 and 6.8. Although this section introduces the concept of equivalent/inequivalent resonance contributors (major/minor contributors), the idea is developed more fully later.

1.11. Strategies for Success: Drawing All Resonance Structures

Section 1.11 summarizes the situations in which resonance contributors are possible: lone pairs adjacent to π bonds, positive charges (or lacking an octet) adjacent to π bonds or lone pairs, and aromatic structures. Those are important visual clues that students can use to determine whether resonance contributors are possible for a chemical species.

The second aspect of this section is the introduction of curved arrow notation for drawing electron flow. To start using curved arrow notation at this point is extremely worthwhile. It is a natural way to indicate electron movement, it makes resonance forms easier for students to understand, and every bit of practice put into curved arrows now will pay off handsomely in later chapters.

1.12. Shorthand Notations

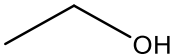
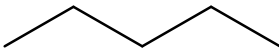
Section 1.12 compares condensed formulas, Lewis structures, and line drawings. That discussion explains to students how to translate one representation into another. Table 1-5 summarizes the types of formal charges students will see. Each results from the change of a lone pair to a shared pair (or vice versa) except the formation of

carbocations. That information, which expands on the information in Table 1-4 in Section 1.6, allows students to assess structures and provide the appropriate charges or lone pairs without calculating formal charge.

You may want to include examples with heteroatoms on the left end of the molecule and show that Hs attached to those generally do not follow the atom. Examples:

Ethylene glycol HOCH₂CH₂OH is preferable to OHCH₂CH₂OH.
 Glycine H₂NCH₂COOH is preferable to NH₂CH₂COOH.

If you use discovery learning in class, you can give students a table similar to the one below and have them fill in the empty cells, using the first line of entries as a guide. In general, the line structures are the most challenging.

Molecular Formula	Structural Formula	Condensed Formula	Line Drawing
C ₂ H ₆ O	$ \begin{array}{c} \text{H} \quad \text{H} \\ \quad \\ \text{H}-\text{C}-\text{C}-\text{OH} \\ \quad \\ \text{H} \quad \text{H} \end{array} $	CH ₃ CH ₂ OH	
	$ \begin{array}{c} \text{H} \quad \quad \text{H} \\ \quad \quad \\ \text{H}-\text{C}-\text{O}-\text{C}-\text{H} \\ \quad \quad \\ \text{H} \quad \quad \text{H} \end{array} $		
			
		CH ₃ CH ₂ CH ₂ CH ₂ NH ₂	

1.13. An Overview of Organic Compounds: Functional Groups

Section 1.13 introduces 17 functional groups (Table 1-6), as well as some comments about differentiating functional groups. You may wish to assess the list and modify it. The list is, as described, an overview and is not comprehensive. For example, sulfides and reactive carboxylic acid derivatives are absent. Even so, it is a useful table to start with, and I have found it worthwhile to hand out the table in class as a starting point of groups that students should be able to identify by the first exam.

Identifying functional groups can be a stumbling block for students, who often interpret some complex functional groups as combinations of multiple simple ones. An ester, for example, can appear to be a ketone and an ether. In a similar vein, acetals and hemiacetals are often the hardest groups for students to identify because of their similarities to ethers and alcohols. An aryl ring can appear to be three alkene groups. Using real-world molecules, and identifying groups with the help of some table (this one or one you produce), is good practice for this chapter.

The text helpfully does not include *alkane* as a functional group. Rather, the term indicates a molecule with no functional groups present.

1.14. An Introduction to Proteins, Carbohydrates, and Nucleic Acids: Fundamental Building Blocks and Functional Groups

Sections with the heading “The Organic Chemistry of Biomolecules” appear throughout the book, and Section 1.14

is the first of those. The sections serve several purposes.

For instructors, placing that information at the ends of chapters throughout the textbook gives them the option of covering the information they wish to include. Informal surveys of instructors indicate that, historically, most organic chemistry instructors minimize the coverage of biomolecules in their courses. (Doing so is understandable because that information usually appears in chapters at the end of the textbook.)

For students, the sections offer access to information they may need. For example, in its materials documenting the changes in the Medical College Admissions Test in 2015, the Association of American Medical Colleges detailed an expectation that students learn certain aspects of biochemistry in their organic chemistry courses. Other standardized exams, such as those of the American Chemical Society, have similar expectations.

For both students and instructors, these sections present an opportunity to apply the concepts presented in the chapter in the context of biomolecules. In Chapter 1, for example, students practice identifying functional groups (presented in Section 1.13) in proteins, carbohydrates, and nucleic acids.

STUDENTS' PERSPECTIVES

The text emphasizes how important it is for students to start using curved arrow notation and line structures starting with this chapter. Having two new concepts appear in the first chapter has helped my students build good study habits during the first week of classes. These new concepts often convince students to start studying right away! Pushing these new concepts so that they start using curved arrow notation as part of their determination of resonance structures (rather than something they draw in later as an afterthought) has overwhelmingly helped student outcomes in my course. If they start “thinking arrows now,” using arrows to help them figure out what is happening, they do better in the course overall.

Apart from their first exposure to arrows, students in my course have been most challenged by taking a neutral structure and providing resonance structures that result in charges on the molecule. It is difficult for them to take something that looks complete and “happy” and convert it to a form that appears incorrect to them (with formal charges on two atoms). This sometimes leads students to struggle with distinguishing simply-foreign-looking-but-correct structures from ones that are actually incorrect. Typical mistakes involve carbon with 5 or more bonds or oxygen with 10 electrons. We need to work through a number of examples of neutral molecules before all my students are able to trust their judgements.

RESOURCES

Pharmaceuticals are a rich source of molecules for questions that require students to identify functional groups. Although you can create your own molecules, students—particularly prepharmacy and premed students—will probably be more interested in pharmaceuticals. You can browse *The Merck Index* or *Chemical and Engineering News* for examples. The structures are generally available quickly on the Internet through an image search. In the past, students have brought me large collections of the informational sheets that accompany pharmaceuticals, and I have created exam questions from those sheets.

You can also find examples at the American Chemical Society’s “Molecule of the Week” archive by going to <http://www.acs.org> and clicking “What molecule am I?” under “Molecule of the Week.”

Sometimes I find myself looking for molecules with specific functional groups for students to practice. The examples below represent a few interesting molecules and a list of the functional groups that they contain.

Molecule	Functional Groups
Atorvastatin (Lipitor)	Amide, amine, fluorine, hydroxy groups, aromatic rings, carboxylic acid
Lovastatin (Mevacor)	Esters, hydroxy group, alkenes
Zingerone (vanillylacetone)	Ketone, hydroxy group (phenol), ether, aromatic ring
Albuterol	Hydroxy groups (including phenol), amine, aromatic ring
Aspartame (NutraSweet)	Carboxylic acid, amine, amide, ester, aromatic ring
α -Damascone	Ketones, alkenes
Vanillin	Hydroxy group (phenol), ether, aldehyde, aromatic ring

Suggested Clicker Questions

The following clicker questions have been selected from the Chapter 1 Clicker Question PowerPoints available on wwnorton.com/instructors. More questions for each chapter are available at the website.

1.6. *Strategies for Success: Drawing Lewis Dot Structures Quickly*

“The connectivity of a particular molecule is shown below. Assuming that no atoms have a formal charge, how many double bonds are there in its completed Lewis structure?”

That problem asks students to apply Lewis dot rules quickly to a large (and imposing) molecule. The task is not that difficult once they consider that carbon needs to have four bonds, and it lets them see how approachable a difficult-looking problem can be with a few simple steps.

1.9. *Assigning Electrons to Atoms in Molecules: Formal Charge*

“What is the formal charge on the oxygen in the following compound?”

That problem forces students to “think outside the box” for a little bit because the formal charge on the oxygen is +1. That was often considered unusual in structures from general chemistry, but the situation is not unusual in organic chemistry.

1.10. *Resonance Theory*

“Which is not an acceptable resonance form of the boxed compound? (Choose 1–4)” and “Why is this form not acceptable? (Choose 5–8).”

That problem not only asks which resonance form is wrong but also delves deeper into why it is incorrect. The question and the follow-up question can be useful to students because sometimes they simply feel that a structure “looks wrong,” but they have no idea why.

INTERCHAPTER A | Nomenclature: The Basic System for Naming Simple Organic Compounds: Alkanes, Haloalkanes, Nitroalkanes, Cycloalkanes, and Ethers

The textbook covers nomenclature in separate interchapter sections rather than within the chapters. This section is placed right after Chapter 1 and introduces the IUPAC system as well as simple functional groups on alkanes. Students need to learn that material during the first part of the first semester because they will encounter alkanes and cycloalkanes in Chapter 4 in the context of conformation isomerism. Students will encounter haloalkanes (alkyl halides) as reactants in nucleophilic substitution and elimination reactions in Chapter 8.

HEADS UP!

Why does the text cover nomenclature in separate sections? Joel Karty explained that organization in his blog post “On Nomenclature” (posted October 16, 2012, at teachthemechanism.com). One reason is that it helps students focus as they learn. A second benefit is that separating nomenclature from the main chapters better enables students to see how the various nomenclature rules are related. Yet a third benefit comes when students review for an exam, especially a cumulative final exam. Doing so is much easier and more straightforward when the nomenclature rules are all collected together and organized logically.

COMMENTS BY SECTION

A.1. The Need for Systematic Nomenclature: An Introduction to the IUPAC System

This section sets up the reasoning behind the IUPAC system, which empowers students by letting them know that they can take an IUPAC name and use it to work out a compound’s structure once they know a few basic rules.

A.2. Alkanes and Substituted Alkanes

This section introduces the root words for alkanes (taking it to 10 carbons, Table A-1) and the concept of substituents.

A.3. Haloalkanes and Nitroalkanes: Roots, Prefixes, and Locator Numbers

This section introduces simple substituents (halogen and nitro groups) and then introduces naming substituted alkanes. Starting by using locator numbers and prefixes with halogens or nitroalkanes has been easier for me than starting with alkyl groups because alkyl groups add the complexity of locating the longest carbon chain.

A.4. Alkyl Substituents: Branched Alkanes and Substituted Branched Alkanes

This section brings alkyl substituents into play, from simple straight-chain substituents to substituted branched substituents. This section deals with all substituted branched systems by using IUPAC nomenclature, not common names (such as isopropyl), which Section A.7 deals with. If you intend students to use only common names in their branching, I advise dealing with that in class or in a handout.

A.5. Cyclic Alkanes and Cyclic Alkyl Groups

This section deals with cyclic alkanes, from three to eight carbons, as well as the rules surrounding when the cyclic is the root versus the substituent. Substituted rings, including ones with halogens or nitro groups, also are discussed. Now is a good time to introduce the idea that five-, six-, and seven-membered rings are favorable configurations for carbon.

A.6. Ethers and Alkoxy Groups

This section introduces –OR groups and the different ways that they can be named. Although including those groups now might seem unusual, this topic offers another example of substituents that do not change the suffix of the name.

A.7. Trivial Names or Common Names

The information on IUPAC nomenclature is fairly straightforward, and instructors will want students to learn most of the information. However, instructors will differ on which trivial (or common) names they wish students to learn. The list of names is extensive, and you may want to tell students that they can skip certain trivial names. You may also want to add some.

For example, I want students to use the common names for different propyl and butyl groups, especially because the *t*-butyl will be so useful synthetically, but I do not ask them to learn the names of the pentyl groups. If you choose to edit, giving students a small handout of common names that they are responsible for can be useful.

STUDENTS' PERSPECTIVES

Many instructors approach these interchapters as something that students should work through on their own. Overall, I have been surprised at how easily students master the material with minimal input from the instructor. I also recall occasions when students, having read and practiced the application of the relatively recent changes in IUPAC rules, knew more than I did about certain rules. I do recommend that you allow students the opportunity to ask questions about nomenclature during the course, and find a way (through quizzes or tests) to hold them accountable for the material to keep them honest in their independent work.

How you assess students' knowledge is up to you: a quiz for each nomenclature section, a page on an exam each semester, or the like. My colleague, for example, incorporates nomenclature into exam questions. Instead of giving students the structure of a starting material for a reaction, he supplies the IUPAC name.

If you have a small class, consider the following exercise: I give students a deliberately challenging quiz on a series of molecules, each of which the students have to name. While they complete the quiz, I put the molecules on the board. After the students turn in the quiz, I have them go to the board and name a single molecule. Then, working in groups, the students evaluate the names and recommend changes that will correct errors. I provide no input, but I do tell them what the score on the quiz would be according to what is on the board. We continue until the class comes up with names that earn a perfect score. Students have responded favorably to that approach, especially when I warn them that this level of difficulty is fair game for the exam but then surprise them with full credit to the class on that quiz after their hard work!

RESOURCES

William B. Jensen of the University of Cincinnati has written many short, historical pieces that deal with organic nomenclature and symbolism. Here is a selection of his articles:

- “The Origins of the Qualifiers Iso-, Neo-, Primary, Secondary, and Tertiary in Organic Nomenclature.” *J. Chem. Educ.* **2012**, *89*, 953–954. doi:10.1021/ed101192y.
- “Why Is ‘R’ Used to Symbolize Hydrocarbon Substituents?” *J. Chem. Educ.* **2010**, *87*, 360–361. doi:10.1021/ed800139p.
- “The Origins of the Ortho-, Meta-, and Para- Prefixes in Chemical Nomenclature.” *J. Chem. Educ.* **2006**, *83*, 356. doi:10.1021/ed083p356.
- “The Origin of Vinyl.” *J. Chem. Educ.* **2004**, *81*, 464. doi:10.1021/ed081p464.

Most textbooks don't address the pronunciation of names of organic compounds. Most spellings are created from words used in spoken language. The names of organic compounds are exceptions because these names are created first as written words through sets of rules. Consequently, instead of a spoken word's being represented by letters, a spoken word is generated from letters. That approach leads to ambiguities and variations. Some examples include the following:

- The multiple pronunciations of the functional group *amide*.
- The British pronunciations of *methyl* and other terms. For examples, view the videos by the University of Surrey on nucleophilic substitution, available on YouTube.
- The debate over the pronunciation of the *c* in *decyl*, documented by K. M. Reese in *Chem. Eng. News* **1987**, *65*, 64. doi:10.1021/cen-v065n022.p064.

You may wish to use one or more of those examples to show students that some variation is acceptable in pronouncing the names of organic compounds.

Suggested Clicker Questions

The following clicker questions have been selected from the Interchapter A Clicker Question PowerPoints available on www.norton.com/instructors. More questions for each chapter are available at the website.

A.4. Alkyl Substituents: Branched Alkanes and Substituted Branched Alkanes

“What is the IUPAC name for the following compound?”

This is a simple alkyl-substituted alkane that helps students work through prefixes and identifying the longest chain.

A.6. Ethers and Alkoxy Groups

“What is the IUPAC name for the following ether?”

This problem combines a cyclic (cyclopentane) with two methyl groups and a methyl ether, which is a nice combination of groups that students often find challenging but that become easy after a classroom explanation.

CHAPTER 2 | Three-Dimensional Geometry, Intermolecular Interactions, and Physical Properties

Chapter 2 reviews VSEPR theory, net dipoles, and dipole moments—concepts that students encountered in general chemistry. The polarity of molecules is used to explain intermolecular attraction (intermolecular forces), and the understanding of intermolecular attraction is then applied to melting points, boiling points, and solubility. In addition to those topics, the chapter explains dash–wedge notation (which students have seen in general chemistry but may not have been asked to use correctly), introduces protic and aprotic solvents, and describes the structures and functions of soaps and detergents.

HEADS UP!

Although this chapter may seem like the same simple general chemistry review (with an organic twist) that one sees in many textbooks, in several places Karty has introduced information now that many books wait until later to talk about in depth. For example, Karty explicitly defines protic and aprotic solvents for the first time here, providing discussions and pictures involving solubility, not just as an example of ion–dipole interactions but as a direct lead-in to mechanistic discussions later in the text. This chapter also emphasizes visualization, encouraging students not only to think in 3D but also to start looking at partial charges on a molecule (again with a view to reactivity in later chapters). Taking the time to set up a good foundation here makes later chapters easier.

COMMENTS BY SECTION

2.1. Valence Shell Electron Pair Repulsion (VSEPR) Theory: Three-Dimensional Geometry

VSEPR theory is introduced in general chemistry, and students should be familiar with it. The presentation in organic chemistry is simpler, much to the relief of students, because we can ignore trigonal bipyramidal and octahedral arrangements.

The term to describe the arrangement of electron pairs around a central atom is electron geometry; the term for the arrangement of atoms is molecular geometry. The designations vary from one text to another, so you may wish to be consistent with those terms or introduce synonymous ones that your students learned in general chemistry.

Table 2-2 summarizes electron geometry, and Table 2-3 summarizes the possible molecular geometries for each electron geometry. Section 2.1b introduces angle strain (in the context of ring strain). That concept will reappear in the discussion of stabilities and conformations of cycloalkanes in Sections 4.4 and 4.5.

In a lecture presentation or discussion, some simplifications can make discussing VSEPR less wordy. For example, you can define atoms attached to a central atom and lone pairs around a central atom as “things.” You can then ask students to determine the number of “things” and explain how that number determines the electron geometry. You can also simplify electron geometry to *geometry* and molecular geometry to *shape*. That approach simplifies a discussion of water, for example: How many “things” are around the oxygen? If there are four things, its geometry is tetrahedral. And its shape? Bent!

Tetrahedral arrangements are harder to illustrate and harder for students to visualize. A colleague gave me the best illustration I’ve found: a tetrahedron made of drinking straws and tape. It allows me to point to the center of the tetrahedron or actually put a model of methane inside it to point out the relationship between the molecule and the tetrahedron. It also clarifies the fact that the central atom is at the center of the tetrahedron.

The value for the bond angles in a tetrahedral arrangement also is not intuitively obvious. I tell students that the law of cosines or vector algebra would allow us to calculate the value. (See the “Resources” section for a relevant reference.) One year, I had a student who used the law of cosines to prove the value of 109.5° for extra credit.

2.2. Dash–Wedge Notation

This section describes dash–wedge (or dagger) notation explicitly. It describes the “V” formed by the normal lines and its orientation with respect to the V formed by the dash and wedge. It is important to start emphasizing dash–wedge notation, and 3-D visualization, in this chapter; the sooner students become comfortable with that notation, the easier the concepts will come to them.

I use my model kits (both a ball-and-stick model kit and a Darling model kit, see the “Resources” section for that reference) and draw a structure similar to the artwork from Figure 2-5. I hold both models directly up to the

drawing on the board, emphasizing which bonds are in the plane of the chalkboard (paper) to try to make the model kit and the drawing match in the students' eyes.

2.3. Strategies for Success: The Molecular Modeling Kit

The “Strategies for Success” sections do not have to be taught in class. They are generally either exercises that students can pursue outside class or methods that can be integrated into the lecture for the other sections (which is how I approach this section; I weave it throughout the chapter). The skills taught in those sections are important. Section 2.3 requires students to convert dash-wedge drawings into models, rotate the model, and then draw the correct dash-wedge representation of the model in its new position. That practice will help students learn to interchange two-dimensional and three-dimensional representations.

2.4. Net Molecular Dipoles and Dipole Moments

This section begins with the net dipole of a diatomic molecule (HF) and then defines a dipole moment. A discussion of vector algebra is followed by a qualitative assessment of net dipoles in linear and tetrahedral arrangements of atoms and lone pairs. Students need to leave this section with an understanding not only of direction but also of magnitude of the dipole.

2.5. Physical Properties, Functional Groups, and Intermolecular Interactions

Table 2-4 contains the physical properties of molecules of similar sizes but different functional groups. That context leads to a discussion of the difference in distribution of charge in various functional groups and the introduction of five types of intermolecular interactions:

1. Ion-ion interactions
2. Dipole-dipole interactions
3. Hydrogen bonding
4. Induced dipole-induced dipole interactions
5. Ion-dipole interactions

I confess that I organize those intermolecular interactions slightly differently because approaching hydrogen bonding first—oversimplifying it as a “special kind” of dipole-dipole interaction—has led to less confusion regarding hydrogen bonding's being an intermolecular interaction rather than an actual bond.

Regardless of what order you present the information in, Table 2-4 is an excellent start for discussing intermolecular interactions. *Note the box in the section summarizing the differences in those attractions:* “All else being equal, the greater the concentrations of charge that are involved in an intermolecular interaction, the stronger is the resulting attraction.”

2.6. Melting Points, Boiling Points, and Intermolecular Interactions

This section begins by contrasting solids, liquids, and gases and discusses the correlation between intermolecular interactions and melting/boiling points.

The discussion of intermolecular interactions continues, going from strongest to weakest:

1. Ion-ion interactions (ionic bonds; Section 2.6a)
2. Dipole-dipole interactions (Section 2.6b)
3. Induced dipole-induced dipole interactions (London dispersion forces; Section 2.6d)

Hydrogen bonding is discussed as a special form of dipole-dipole interaction in Section 2.6c. That section introduces hydrogen bond acceptors and donors.

Section 2.6d discusses the role of polarizability and surface area of molecules, something students often find challenging. Drawing long molecules on the board with a “squishy” electron cloud around them sometimes helps, as does an analogy of trying to squeeze into a bus seat next to another passenger. If both passengers are wearing big,

bulky fluffy coats and carrying large bags, rearranging to fit comfortably next to each other is easier (move the bags to each side, squish the coats) than if both passengers are trying to squeeze together in a small space and are wearing only shorts.

2.7. Solubility

This section introduces and elaborates on “like dissolves like,” discussing entropy’s role as a driving force. It also discusses ion–dipole interactions and how hydrocarbon groups affect solubility. *Note the highlighted box in Section 2.7a that relates the strength of ion–dipole interactions to the magnitude of the dipole moment.*

The differences among the motions and arrangements of molecules in solids, liquids, and gases can be explained by using John Fortman’s analogies of a military unit, a reunion party, and a soccer game, respectively:

Solids (Military Unit)	Liquids (Reunion Party)	Gases (Soccer Game)
Short distance between molecules	Short distance between molecules	Long distance between molecules
Rigid	Flowing	Diffusion
No disorder	Much disorder	Much disorder
No random motion	Some random motion	Much random motion

(See the “Resources” section for reference.)

Intermolecular interactions are synonymous with *intermolecular forces* (IMFs), which may be the term that your students learned in general chemistry.

Ion–ion interactions are not, technically, intermolecular interactions because neutral molecules are not involved. You may wish to explain to students that ion–ion interactions are discussed here because of their relevance.

2.8. Strategies for Success: Ranking Boiling Points and Solubilities of Structurally Similar Compounds

As mentioned, this section can be assigned for out-of-class reading. It presents a detailed example in which students evaluate intermolecular attractions and use them to assign relative boiling points.

The excellent worked example thoroughly discusses a complex problem. I recommend requiring students to read and understand this section before class and then giving an in-class exercise to assess their understanding.

2.9. Protic and Aprotic Solvents

This section introduces the differences in solubility of ionic compounds in protic and aprotic solvents by comparing the solubility of NaCl in water and DMSO. Table 2-7 lists common protic and aprotic solvents and introduces abbreviations such as *DMSO* and *DMF*. *The difference between protic and aprotic solvents is presented here so that students will understand the role of solvents in substitution and elimination reactions. The higher solubility of ionic compounds in polar protic solvents serves as an easy introduction to the role that those solvents will play in facilitating the dissociation (heterolysis) of alkyl halides and other substrates in S_N1 and $E1$ reactions.*

This section introduces abbreviations for common solvents (DMSO and DMF). You may wish to discuss the prevalent use of abbreviations in organic chemistry and tell students whether you expect them to identify a specific abbreviation with the full name, structure, or both. To understand most problems (and for the American Chemical Society final exam in the second semester), students typically need to know DMSO, DMF, and THF.

2.10. Soaps and Detergents

This section discusses the structure and action of soaps and detergents. (Section 20.3 covers the synthesis of soap.) The discussion introduces and defines the terms *hydrophilic*, *hydrophobic*, *ionic head group*, *hydrocarbon tail*, *micelle*, *emulsify*, and *detergent*. The section also discusses hard water, precipitation of soap scum, and how detergents address the problem of soap scum.

Although most texts place that discussion with saponification of esters, the topic fits well with the coverage of intermolecular interactions. The discussion also introduces terms that allow students to better understand the structure and function of phospholipids, which are discussed in Section 2.11b.

2.11. An Introduction to Lipids

Because lipids are defined by their relative insolubility in water (or solubility in ether), this chapter is a logical place to introduce them. The section includes four subsections:

- 2.11a. Fats, Oils, and Fatty Acids
- 2.11b. Phospholipids and Cell Membranes
- 2.11c. Steroids, Terpenes, and Terpenoids
- 2.11d. Waxes

STUDENTS' PERSPECTIVES

This chapter is all about introducing new ways of viewing molecules and setting up good habits; with any luck, those visualization tools (dash-wedge notation, model kits) will become second nature. Introducing dash-wedge notation here, early, and forcing students to use it repeatedly seems to help them master the skill.

I agree with Joel Karty's blog post ("Molecular Model Kits," posted October 9, 2012, at teachthemechanism.com) about students' reluctance to use molecular model kits. Students need the time in the class periods to see not only how to use them but also how useful they are in solving certain types of problems. Karty has incorporated several of those lessons into the textbook sections marked "Strategies for Success." One such section shows how molecular models can be used to arrive at various dash-wedge representations of the same molecule.

Intermolecular attractions are, historically, hard for students to grasp. The difficulty arises from several sources.

First, we are trying to simplify a complex subject. For example, most organic chemistry texts omit the factors arising from crystallinity that affect melting points.

Second, students often think of *polar/nonpolar* and *soluble/insoluble* as discrete variables (i.e., yes-no) instead of continuous variables. That is, a compound is not actually inherently polar or nonpolar; it is polar or nonpolar in relation to another compound. For example, the solvents benzene and toluene are less nonpolar than acetone; however, toluene is more polar than benzene. Getting students to a point at which they can explain that relationship is challenging. Similarly, all organic compounds are soluble to some extent in water.

Third, the terminology can be confusing. *Hydrogen bonding*, for example, opens the door to confusion of intermolecular attractions with covalent and ionic bonds. Students often use the term *bonds* inaccurately in their descriptions and in their cartoon drawings. In addition, the multiple terms that may be (or may not be, according to some) synonymous (*London forces*, *dispersion forces*, *van der Waals attractions*) add confusion. Finally, *ion-ion attractions* and *ion-dipole attractions* cause a problem because they technically do not involve attractions between molecules. The terms logically fall with intermolecular attractions but contradict the strict definition of that term.

The study of intermolecular attractions requires students to visualize what is happening at a molecular level, and that presents a challenge. Using model kits early in the semester, and focusing on 3-D representations of molecules early in the semester, does help, as does asking conceptual questions (explain this, draw that) rather than simple identification questions (rank by boiling point).

RESOURCES

For a discussion of how to determine the 109.5° bond angle in a tetrahedral arrangement of atoms, see "Employing Vector Algebra to Obtain the Tetrahedral Bond Angle" by George H. Duffey. *J. Chem. Educ.* **1990**, *67*, 35. doi:10.1021/ed067p35.

For a history of dash-wedge notation, see "The Historical Origins of Stereochemical Line and Wedge Symbolism" by William B. Jensen. *J. Chem. Educ.* **2013**, *90*, 676–677. doi:10.1021/ed200177u.

Many instructors have their own preferences for which modeling kit their students use. I have found the most useful sets to be the ones produced by Steve Darling (www.darlingmodels.com) because the geometry is built into the structure. Students do need some instruction in how to assemble them correctly, however, and be careful to help students perceive the difference between trigonal planar carbon and tetrahedral carbon.

For details describing an analogy that compares solids, liquids, and gases to a military unit, a reunion party, and

a soccer game, respectively, see “Pictorial Analogies I: States of Matter” by John J. Fortman, *J. Chem. Educ.* **1993**, *70*, 56. doi:10.1021/ed070p56.

Napoleon's Buttons: 17 Molecules That Changed History by Penny Le Couteur and Jay Burreson (New York: Jeremy P. Tarcher/Penguin, 2004) has a chapter titled “Oleic Acid.” The chapter discusses the history of soap, the structure of fatty acids and triglycerides, saponification, and how soap functions.

The following classroom demonstration allows you to discuss intermolecular interactions, including the effect of alkyl chain length.

1. Combine approximately 10 mL of hexanes and 10 mL of methanol in a large test tube. At this point, the students will see two layers, although not of equal volume.
2. Add approximately 10 mL of 1-butanol and mix. The students will see that the contents of the tube are homogeneous.
3. Add approximately 10 mL of water and mix. A top layer of hexanes, approximately one-fourth of the total volume, will form at the top of the tube.

After each step, you can ask students to use IMFs to explain what they observe. The results in step 2 allow you to discuss the different roles of the hydroxyl group and the alkyl chain in 1-butanol.

In a follow-up activity, you can have students draw the intermolecular attractions at each step to explain what they observed. That activity, combined with the demonstration, allows for a discussion of IMFs that is based on experimental observation and asks students to depict what occurs at the molecular level.

Suggested Clicker Questions

The following clicker questions have been selected from the Chapter 2 Clicker Question PowerPoints available on wwnorton.com/instructors. More questions for each chapter are available at the website.

2.4. Net Molecular Dipoles and Dipole Moments

“How many of the following molecules are polar? (Consider 3-D geometry.)”

That question forces students to think in 3-D and involves substituted cyclobutane. As a bonus, the problem is much easier to solve if students use their model kits.

2.6. Melting Points, Boiling Points, and Intermolecular Interactions

“Which of the following compounds has the highest boiling point?”

That question deals with hydrogen bonding in a series of nitrogen-containing cyclic compounds.

“Which of the following compounds has the highest boiling point?”

That question has students compare symmetric systems and asks them to rely on size/polarizability to determine the molecule with the greatest IMFs.

CHAPTER 3 | Orbital Interactions 1: Hybridization and Two-Center Molecular Orbitals

Most topics in this chapter review information that students may have learned in general chemistry. This chapter reviews quantum mechanics, the shapes and characteristics of atomic orbitals (AOs), and how orbitals interact. Those ideas are used to develop molecular orbital (MO) theory. The chapter also introduces hybrid orbitals and discusses their relationship to VSEPR. Sigma bonds, π bonds, nonbonding orbitals, HOMOs, and LUMOs are then presented in the context of simple organic molecules. The effects of orbital overlap on bond rotation are discussed, introducing cis and trans isomerism about double bonds. Finally, differences in effective electronegativity due to hybridization are introduced.

HEADS UP!

Chapter 3 requires instructors to choose the extent to which they wish to include MO theory in the course. Because I generally omit MO theory from my presentations, the suggestions here will focus on simplifying the information students need from this chapter. Students will not need to be able to draw MO diagrams to understand the mechanistic approach of the Karty text, but they will have to understand hybridization and bond characteristics (including bond length, strength, and geometry). An understanding of relative energies of orbitals also would be useful later on in the text.

The textbook includes a fair amount of descriptive text to help students understand what occurs when MOs form. You may wish to minimize your classroom explanations and encourage students to follow the text's explanation.

COMMENTS BY SECTION

3.1. Atomic Orbitals and the Wave Nature of Electrons

This section reviews wave-particle duality, the Heisenberg uncertainty principle, electron density, and relative phases (plus or minus) of wave functions. The section also introduces $1s$ and $2p$ orbitals, their shapes, and the presence of nodes in the latter. As in most organic textbooks, however, this textbook includes no discussion of d and f orbitals; pointing that out to the students usually brings a sigh of relief.

3.2. Interaction between Orbitals: Constructive and Destructive Interference

This section uses the analogy of waves generated along a piece of rope to explain the two types of interference. Figures 3-4 and 3-5 show those concepts nicely. Bringing a rope to class for a short (1 minute) demonstration is usually enough to get that point across.

3.3. An Introduction to Molecular Orbital Theory and σ Bonds: An Example with H_2

This section introduces MOs, LCAOs, and nodal planes in MOs. It also introduces the important idea that mixing n orbitals produces n orbitals. The section goes on to define bonding, antibonding, and nonbonding MOs, as well as HOMOs and LUMOs.

3.4. Hybridized Atomic Orbitals and Geometry

This section introduces hybrid orbitals in the following order: sp , sp^2 , sp^3 . That initial presentation discusses the number of hybrid orbitals in each case, their relative s and p character, their geometry, and the number of “leftover” p orbitals. *The formation of π bonds from p orbitals is not mentioned until Section 3.6.*

The text starts with sp hybridization. However, if you wish to follow an approach similar to what students most likely received in general chemistry, I recommend starting with methane, progressing to ethene (ethylene) or formaldehyde, and then going on to ethyne (acetylene). You can ask students for the number of s bonds required between atoms, “generate” the necessary number of hybrid orbitals to create the σ bonds, and then discuss the π bonds that form. Using methane as a home base, with the tetrahedral geometry students are familiar with (from general chemistry), helps ground them when you introduce hybridization from an organic standpoint. You can

continue by assuring students that experimental evidence indicates that the hydrogens in methane are equivalent and the bond angle is 109.5° , not 90° .

I also emphasize, as the author does in the section on MOs, that mixing n orbitals produces n orbitals. I use the description “Number of orbitals in = Number of orbitals out” and emphasize that the unused p orbitals are “leftovers” that are used in π bonds.

Table 3-1 summarizes what students need to know. Because VSEPR and valence bond theory go hand in hand, having students count the “things” (attached atoms and lone pairs) around an atom allows them to determine the correct hybridization.

Although the author’s language in this chapter is correct, you may wish to simplify your explanation. For example, I describe unpaired electrons as being accommodated in hybrid orbitals instead of nonbonding MOs. I believe that students can more easily visualize an oxygen atom with four hybrid sp^3 orbitals, two of which contain lone pairs.

Students need to leave this chapter being able to recognize the hybridization of an atom fairly easily, which is something to keep in mind when presenting those concepts and giving students practice opportunities.

3.5. Valence Bond Theory and Other Orbitals of σ Symmetry: An Example with Ethane ($\text{H}_3\text{C}-\text{CH}_3$)

This section introduces valence bond theory and its application to ethane. The emphasis is on the number of bonding orbitals produced (7) from the number of AOs or hybrid AOs introduced (14). Figure 3-14 shows the overlap of orbitals to form the σ bonds.

3.6. An Introduction to π Bonds: An Example with Ethene ($\text{H}_2\text{C}=\text{CH}_2$)

The discussion here is analogous to that in the previous section, with the introduction of π symmetry and π bonds. The relative energies of σ and π bonding orbitals also are discussed.

Figure 3-16 shows and describes the components of a double bond (a σ bond and a π bond).

One analogy for a double bond is a hot dog on a hot dog bun. The hot dog is the σ bond, and the bun is the π bond. The analogy for a triple bond is a hot dog surrounded by two hot dog buns. The hot dog is the σ bond, the first bun is the first π bond, and the second bun is the second π bond.

3.7. Nonbonding Orbitals: An Example with Formaldehyde ($\text{H}_2\text{C}=\text{O}$)

Analogous to the previous section, the discussion includes a description of the nonbonding MOs for the lone pairs from oxygen. Those sections (3.5–3.8) are great to work through together in class to apply the concepts presented in Section 3.4. I find it useful to remind students that we are working through examples together (formaldehyde, etc.), reinforcing what they know, not introducing new concepts.

3.8. Triple Bonds: An Example with Ethyne ($\text{HC}\equiv\text{CH}$)

This section extends the previous discussions, describing and showing the triple bond in ethyne (acetylene) in Figure 3-23. If you are presenting that structure in class, students should be able to deduce that example almost completely on their own at this point.

3.9. Bond Rotation about Single and Double Bonds: Cis and Trans Configurations

This section compares single and double bonds between carbons and the ease or difficulty of rotation about the carbon–carbon bond. It also discusses planarity of the atoms in a double bond and those attached to it.

The section concludes with an algorithm for determining whether cis–trans isomers exist for a compound with a double bond: A molecule with a double bond will have two distinct structures that differ by a hypothetical 180° rotation about the double bond only if *neither* of the atoms connected by the double bond is singly bonded to two identical atoms or groups.

Because students will encounter cis and trans in the context of ring systems, you may wish to emphasize that the terms describe a spatial relationship between two groups.

You may also choose to explain that cis and trans are applied to alkenes only when no ambiguity exists in determining which groups are cis or trans, and that further nomenclature (such as E/Z) will appear later in the text.

3.10. Strategies for Success: Molecular Models and Extended Geometry about Single and Double Bonds

This section asks students to use molecular models to construct allenes and evaluate the planarity of the atoms in allenes with different numbers of carbon–carbon double bonds. Those exercises often amaze students because they must think in three dimensions to solve them.

3.11. Hybridization, Bond Characteristics, and Effective Electronegativity

Figure 3-32 summarizes how hybridization affects bond strength and bond length. *Although the author does not use the expression bond order, using that term to describe the difference between single, double, and triple bonds may be helpful.*

The section also introduces effective electronegativity and explains how it varies with hybridization. *Effective electronegativity's effects on acidity are discussed not in Chapter 3, but in Chapter 6.* I suggest using *bond order* in explanations because students should be familiar with that term from general chemistry. Doing so also allows you to explain how bond lengths vary with bond order as well as with hybridization. For example, the sp – sp single bond length in butadiyne is 138 pm, whereas the triple bond length in acetylene is 118 pm.

The following analogies explain change in bond length and strength with the change in bond order:

- A single bond is analogous to a couple holding hands.
- A double bond is analogous to a couple slow dancing.
- A triple bond is analogous to a couple in a passionate embrace.

As the “points of contact” (or bonds) between the two people increase, the distance between them decreases, and the energy required to separate them increases.

STUDENTS' PERSPECTIVES

Students encounter difficulties visualizing σ and π bonds in double and triple bonds; triple bonds in particular are hard to depict in two dimensions. You may want to search for diagrams that you think depict such bonds most clearly, or bring both the art from Figure 3-23 in the Karty text and a ball-and-stick model of ethyne that clearly shows the three bonds.

Some molecular model sets can present problems. For example, they may not represent double and triple bonds in a way that reflects the σ and π bonds present (some simply have the linear geometry for the triple bond and a short connector). You may want to explain the difference between how the models create double and triple bonds and how students should perceive the multiple bonds. Reminding students of the geometry is useful as an anchor to help them figure out what is going on.

RESOURCES

One way to present the necessity of hybrid orbitals (or molecular orbitals) is to show students models of the $2s$, $2p_x$, $2p_y$, and $2p_z$ orbitals. Challenge students to imagine the structure of methane if the carbon atom could use only those orbitals for overlap with the $1s$ orbitals of hydrogen.

Models of s and p orbitals (and d and f orbitals) are available from Klinger Educational Products (<http://www.klingereducational.com/>). The orbital lobes are painted wood and mounted on narrow iron rods that connect to a wooden base. The models are relatively small; the lobes are only a few inches in diameter. However, with a set of three p orbitals, you can show their orientations in space.

Suggested Clicker Questions

The following clicker questions have been selected from the Chapter 3 Clicker Question PowerPoints available on www.norton.com/instructors. More questions for each chapter are available at the website.

3.4. Hybridized Atomic Orbitals and Geometry

“How many sp^3 -hybridized atoms are there in this hypothetical species?”

That question has several good features that make it an appropriate (and tricky) hybridization question for this level. Along with the ring (visually intimidating) and heteroatoms, it also has a carbocation.

3.9. Bond Rotation about Single and Double Bonds: Cis and Trans Configurations

“For which of the following molecules do cis and trans configurations exist?”

Answering that question requires a slightly tricky analysis of possible isomers; the question asks students to visualize from a condensed drawing of the compound to see whether multiple forms of the structure can exist (which is true for neither molecule).

3.11. Hybridization, Bond Characteristics, and Effective Electronegativity

“Which H atom has a larger concentration of positive charge?”

That question has students compare hydrogens that are Csp^2 -H and Csp^3 -H.

INTERCHAPTER B | Naming Alkenes, Alkynes, and Benzene Derivatives

This chapter immediately follows Chapter 3 and introduces information that will be directly useful for Chapter 4. The nomenclature of unsaturated molecules, alkenes, and alkynes, is introduced along with that of simple benzene derivatives. Students will be able to use the nomenclature of alkenes to help determine whether two molecules with the same formula are constitutional isomers, an approach described in Section 4.11.

HEADS UP!

The approach used for nomenclature in this chapter follows the most current IUPAC system rules, which use placement of the double or triple bond as an infix between the root and the suffix—for example, Solved Problem B.3 shows 4,4-dichloro-3-(1-methylethyl)hex-2-ene. Most of the end-of-chapter problems follow those newer rules (e.g., B.21), but some still use the older IUPAC guidelines (e.g., Problem B.26, part c, asks students to draw “2,3-dimethyl-2-butene,” not “2,3-dimethylbut-2-ene”). *Z* and *E* configurations around double bonds are not covered until Interchapter C, which deals with stereochemistry in nomenclature.

I have students learn the alkene and alkyne portions of this material where it appears in the text, directly before Chapter 4. One year I chose to reserve the section on benzene derivatives until the class reached Chapter 14, which discusses aromatic systems. That approach had benefits, most notably that students could focus more on the complexities of finding the longest carbon chain. The main drawback was that by withholding the nomenclature of benzene, I missed the opportunity to introduce early on how benzene is different from other systems with multiple bonds. Also, presenting small carbon chain substituents on benzene is a good way to practice naming the different isomers of three- and four-carbon chains.

No matter which approach you take, the names of heterocyclic compounds are not in Interchapter B but are in Section 14.8. Pyridine, pyrrole, and furan are mentioned in that section. Solved Problem 14.19 shows thiophene, although its name is not given.

COMMENTS BY SECTION

B.1. Alkenes, Alkynes, Cycloalkenes, and Cycloalkynes: Molecules with One C=C or C≡C

Students are introduced to using suffixes beyond *ane* in this section, learning *ene* for alkenes and *yne* for alkynes. Students often miss that the root is the longest chain or ring *that contains the entire double or triple bond*. The example using cyclobutene as the root is a useful one to present in class to clarify that point.

The section then presents numbering of the root and placement of the substituents, and it goes on to show applications with fairly complex systems using the halo and nitro groups from Interchapter A. Solved Problem B.3 is a good example of a problem with a deliberately tricky drawing (the longest chain runs top-to-side) and two chloro groups.

Although geometry is not part of the chapter explicitly, emphasizing it at this stage is worthwhile. Students often struggle with visualizing and drawing triple bonds by using just the line notation, and they sometimes struggle with simply counting how many carbons are in the molecule. For some students, carbons are hard to perceive in a structure if the 180° bond angle is present. Problem B.1, part c, is a good example for in-class work because it offers not only the challenge of finding the root for an alkyne with a cyclic attachment but also practice in counting the carbons.

B.2. Molecules with Multiple C=C or C≡C Bonds

This section addresses the rules regarding multiple double or triple bonds in a molecule, including how to number the chain and the use of prefixes such as *di* or *tri* to indicate the number of double or triple bonds. It also notes that C=C and C≡C bonds are of equal priority so that numbering minimizes the locator number for the double and triple bond groups.

Even though students know only a few groups at this stage, the problems in this section quickly become complex. Problem B.7 combines all the groups that students have learned, and either assigning it or working through it in a classroom setting is worthwhile.

B.3. Benzene and Benzene Derivatives

Benzene is introduced in this section as aromatic, a class of compound apart from alkenes, and thus it is not named the tempting-but-incorrect “cyclohexa-1,3,5-triene.” Aromaticity is covered only briefly here, in just enough depth to introduce it and justify it as a unique class of compounds. Chapter 14 presents aromaticity in depth.

The *ortho*, *meta*, and *para* prefixes are introduced and applied in several problems using the carbon chains and other substituents (halogens, nitro groups) the students have learned. This section is a great place to practice some of the small carbon chain nomenclature presented in Interchapter A (isopropyl, *t*-butyl).

B.4. Trivial Names Involving Alkenes, Alkynes, and Benzene Derivatives

Common names for alkenes and alkynes such as ethylene and acetylene are presented in this section, as well as common names for aromatic compounds such as toluene and anisole. Also presented is the way to use alkene and alkyne common names when those groups serve as substituents. It is worth pointing out that the aromatic common names include only those that have groups that students have already learned; for example, because students haven't studied nomenclature of amines, aniline is not presented at this point.

This is another section for which a handout of the common names I want students to know is useful. I add to that list once we introduce other benzene derivatives.

STUDENTS' PERSPECTIVES

This chapter can get confusing in a hurry if students are still struggling with the simple nomenclature from Interchapter A. Other times, students think that this is easy because most examples start straightforwardly, but then they get confused and intimidated when structures become more visually complex. A strength of the approach of these interchapters is that it is not bound by the “functional group of the chapter” but instead integrates multiple groups. Alkenes and alkynes appear together, and are practiced together, so that students who struggle with concepts can get better reinforcement while students who need challenges can see more complex structures (double and triple bonds together in one molecule).

Just as understanding a foreign language is often easier than producing grammatically correct prose in that language, students often find reading a name and drawing a structure easier than giving a name for a drawn structure. Mixing problems in which students draw structures, as in B.21, with problems in which students have to supply names, such as B.23, helps students see both sides of nomenclature communication. Giving students some small amount of class time to work through those problems together is a good approach.

Chapter 4 deals primarily with alkanes when discussing conformers and constitutional isomers, but Section 4.11 introduces unsaturated systems. This section calls back directly to Interchapter A to help students determine whether two molecules with the same formula are constitutional isomers. Encouraging students to use the naming of the compounds to help them determine differences between compounds is a wonderful way to reach students who are still struggling with visualizing line drawings. Of course, use of the model kits should still be encouraged.

RESOURCES

Two of the William B. Jensen history of nomenclature articles cited in this guide's Interchapter A, on the origins of the prefixes *ortho*, *meta*, and *para*, as well as the origin of vinyl, are directly useful in this chapter.

For students interested in practicing nomenclature on their own, this interchapter offers the perfect opportunity to introduce them to chemical databases and to chemical sketching software. For example, students could create structures in SciFinder, try to name them on their own, and then search for the structure to get the correct name. Drawing programs such as ChemDraw have features through which you can have the program produce the name of a sketched compound, again allowing students to draw something on their own and then practice naming it.

Suggested Clicker Questions

The following clicker questions have been selected from the Interchapter B Clicker Question PowerPoints available on wwnorton.com/instructors. More questions for each chapter are available at the website.

B-1. Alkenes, Alkynes, Cycloalkenes, and Cycloalkynes: Molecules with One C=C or C≡C

“What is an appropriate IUPAC name for the following compound?”

That problem asks students to name an alkyne. For this stage, the carbons on either side of the triple bond are usefully drawn out as letters, modifying the line structure to make counting the carbons in the molecule easier.

B-3. Benzene and Benzene Derivatives

“What is an acceptable IUPAC name for the following compound?”

That problem requires students to name a benzene derivative, 1,3-dimethyl-2-nitrobenzene. One challenge for students is to determine where on the ring to start counting.

CHAPTER 4 | Isomerism 1: Conformers and Constitutional Isomers

The chapter introduces isomerism and then addresses three principal topics:

- Conformers in straight-chain systems, using Newman projections to represent conformers, and analyzing the relative energies of different conformers
- Conformers' isomers and analyzing cyclic systems, focusing on cyclohexane, monosubstituted cyclohexanes, and disubstituted cyclohexanes
- Identifying and generating constitutional isomers

The chapter concludes by discussing amino acids and monosaccharides that are constitutional isomers of one another, as well as how unsaturation affects fatty acids.

HEADS UP!

In books organized by functional group, this material appears in chapters on alkanes or cycloalkanes or in an introductory chapter. In this text, however, the types of isomerism are presented together in two dedicated chapters.

COMMENTS BY SECTION

4.1. Isomerism: A Relationship

Figure 4-1 introduces (and summarizes) the relationship between types of isomers. This chapter covers conformers and constitutional isomers, the two isomers shown in red in the figure. Chapter 5 covers the configurational isomers (diastereomers and enantiomers).

The text makes the point that the relationship term *isomer* always describes two molecules and that you cannot call just one molecule an “isomer.”

4.2. Conformers: Rotational Conformations, Newman Projections, and Dihedral Angles

This section introduces conformers, rotational conformations, Newman projections, and dihedral angles and then relates three-dimensional structures to Newman projections.

Section 4.2 has multiple examples to help students with the difficult leap from two-dimensional representations to three-dimensional visualization. Figure 4-2 shows an interpretation of a Newman projection from a dash-wedge 3-D representation of the molecule to the 90° rotation to the Newman projection. Your Turn 4.1 is a problem in which students can apply Figure 4-2 to an example on their own. Figure 4-3 depicts conformational isomers with various dihedral angles as Newman projections for a generic molecule XCH_2-CH_2Y . Unlike in many texts, instead of working through the full rotation from 0° to 360°, the figure sets the total eclipsed conformer at 0° and moves right and left 180°. That approach of working left and right rather than “around the clock” is often easier for students. The figure also shows each isomer as a ball-and-stick model from two perspectives: down the side and down the C—C bond.

One goal of Sections 4.2 and 4.3 is to enable students to see the relationship between three-dimensional models and two-dimensional representations. Either you or the students need to construct and rotate models and establish the relationship between the models and the corresponding Newman projections.

4.3. Conformers: Energy Changes and Conformational Analysis

Conformational analysis is introduced as a way to help students understand the nature of rotation around a given bond. The text makes the important point that the energy values are all given in relation to the molecule's lowest-energy conformation.

In Section 4.3a, staggered and eclipsed isomers are presented in terms of the various dihedral angles between two hydrogens, one on each carbon of ethane. Torsional strain from eclipsed bonds is defined and used to explain

the difference in energies of staggered and eclipsed conformers. The availability of thermal energy to overcome the rotational barrier between staggered conformers is also discussed. Here again, the 0° conformation is the total eclipsed conformer—as will continue to be the case.

Section 4.3b presents a conformational analysis of 1,2-dibromoethane and explains the difference in the energies of the gauche and anti conformations in terms of steric strain. Problem 4.30 at the end of the chapter, which asks students to rank Newman projections from least to most stable, is useful here.

Section 4.3c describes the all-anti conformation of alkanes that leads to the zigzag conformation. Using model kits in class throughout this section is worthwhile, but especially so for this subsection, in which students should see at least one full model of a long-chain alkane.

4.4. Conformers: Cyclic Alkanes and Ring Strain

This section introduces cycloalkanes and offers an analysis of heats of combustion as a way to measure ring strain in rings smaller and larger than cyclohexane. That analysis is useful to introduce here, where many students intuitively appreciate that cyclohexane is more stable than cyclobutene simply by trying to build the models of each by using tetrahedral carbon. Using numbers to make a case for what students perceived from their model kits helps them appreciate the use of numbers later in the text. A similar analysis of thermodynamic data will appear in Section 14.3's discussion of heats of hydrogenation as a measure of resonance energy in aromatic systems, in which stability is not as intuitive to students.

Students should leave this section knowing that six-membered rings are the most favorable and that five- and seven-membered rings are reasonably stable.

4.5. Conformers: The Most Stable Conformations of Cyclohexane, Cyclopentane, Cyclobutane, and Cyclopropane

This section explains that ring strain arises from a combination of angle strain, torsional strain, and steric strain. Those characteristics are used to explain the relative stabilities of cyclohexane through cyclopropane. The concept of a chair conformation for cyclohexane is introduced here. Figure 4-12 nicely shows representations of cyclohexane from ball-and-stick models to a Newman projection. Problems 4.26 and 4.28 at the end of the chapter, which deal with complex Newman projections including cyclics, are good problems to assign at this stage.

Although models are the best way to demonstrate the conformations of cyclic hydrocarbons, be careful with cyclobutane and cyclopropane. Some models cannot accommodate making rings with such constrained bond angles. The Darling model set, for example, includes special, flexible pieces for making small rings—the regular pieces will break. You may want to warn your students about how best to make those small rings with their model sets.

4.6. Conformers: Cyclopentane, Cyclohexane, Pseudorotation, and Chair Flips

This section introduces pseudorotation to explain the equivalency of the carbons in cyclopentane. An analysis of the equatorial and axial positions in cyclohexane follows. The section concludes by discussing chair flips and higher-energy conformers (half-chair, twist-boat, and boat).

One way to demonstrate the conversion of axial groups to the equatorial position is to bring to class a model similar to Figure 4-20. You can put six atoms of one color in the axial positions and six atoms of another color in the equatorial positions. Changing from one chair to another will show students how the positions convert and how the axial hydrogens become equatorial hydrogens and vice versa: It is useful to either project Figure 4-20 or draw the figure in color on the board as you manipulate the model kit.

You may want to cite experimental evidence for the distinction between axial and equatorial positions of hydrogen atoms in cyclohexane. The Connections side box refers to using nuclear magnetic resonance (NMR) to detect axial and equatorial hydrogens. Lambert cites the work of Bovey and colleagues (see “Resources” for the reference), in which the ^1H NMR spectrum of cyclohexane- d_{11} gave two distinct signals at low temperature: one for cyclohexane with the single H in the axial position and one for cyclohexane with that H in the equatorial position. I don't discuss the NMR phenomenon in lecture but simply mention that distinguishing the two conformers at low temperatures is possible.

4.7. Strategies for Success: Drawing Chair Conformations of Cyclohexane

This section gives step-by-step directions for drawing cyclohexane chairs correctly. Figure 4-23 shows the progression from ball-and-stick to dash-wedge to shorthand notation. Figures 4-24 and 4-25 use color coding to help students understand and visualize the shorthand notation. Taking class time to work through Your Turn 4.17, a step-by-step tutorial for drawing a chair, is useful.

4.8. Conformers: Monosubstituted Cyclohexanes

This section defines nonequivalent chairs as conformers of each other. The energy difference between the two chair conformers is explained in terms of 1,3-diaxial interactions, which are shown as both Newman projections and chair conformations. The 1,3-diaxial interactions are not limited to carbon-containing substituents; heteroatoms such as bromine appear in the text, and a nitrogen-containing ring (with either a hydrogen or a methyl group) appears in Problem 4.39.

Again, if you wish to cite experimental evidence, March's text (see "Resources" for reference) cites low-temperature NMR studies by Jensen and Bushweller. Those researchers isolated pure equatorial conformers of chlorocyclohexane and trideuteriomethoxycyclohexane.

4.9. Conformers: Disubstituted Cyclohexanes, Cis and Trans Isomers, and Haworth Projections

The evaluation of 1,3-diaxial interactions continues and is used to predict the relative stability of disubstituted cyclohexanes. Haworth projections are introduced as representations of a planar cyclohexane, in which students can clearly see the cis or trans relationship of the substituents. However, this section includes no examples with carbohydrates, the usual context for using Haworth projections, and the biomolecules covered in Section 4.14 are part of a discussion of constitutional isomers and are shown only in dash-wedge notation. Haworth projections of carbohydrates will be shown in later sections, such as mutarotation of monosaccharides in Section 18.13.

Students generally have trouble distinguishing whether substituents are cis or trans when one is in the equatorial position. Cyclic models with color-coded positions such as those in Figure 4-20 (Section 4.6), are helpful here. I use them to demonstrate the "up" and "down" nature of the equatorial position: a flattened ring in which the carbons are in the same plane and all six "up" positions are equivalent (as are all six "down" positions). I also show the second chair conformation, in which the axial or equatorial position has changed for each substituent but the cis-trans relationship is maintained.

It is worth mentioning to students multiple times that the cis-trans relationship is maintained in both chair conformers. What was axial becomes equatorial, what was equatorial becomes axial, but the substituents are cis (or trans) with respect to each other in both conformers because that does not change with a chair flip.

4.10. Strategies for Success: Molecular Modeling Kits and Chair Flips

This section encourages students to use molecular modeling kits to evaluate chair conformers and uses an example to show the value of models. The focus is on the axial groups because axial up and axial down are much easier to see than equatorial "up" and "down." I find it useful at this stage to have students make a model with two substituents different from the rest and each other. That model lets them track those two both in terms of each conformer's position and in relation to each other.

4.11. Constitutional Isomerism: Identifying Constitutional Isomers

This section begins by defining constitutional isomers and then uses an example of two structures that are identical (but depicted differently) to introduce steps for determining whether two structures represent constitutional isomers. The steps focus on a nomenclature-centered approach to help students build on what they already know when identifying different drawings of the same structure. Problem 4.16 in the text, which asks students to determine constitutional isomers, is good but also a little tricky because one pair is not an isomer set at all (a great forest-for-the-trees example).

The text also introduces *structural isomer* as a synonym for *constitutional isomer*.

4.12. Constitutional Isomers: Index of Hydrogen Deficiency (Degree of Unsaturation)

This section defines saturation and presents the structural features that produce saturation in organic molecules. After introducing the formula C_nH_{2n+2} for determining the formula of saturated hydrocarbons, the section uses example problems to show students how to deal with the presence of nitrogen and halogen atoms.

The designation *IHD* or *DU* varies from author to author; no truly “correct” designation exists. For a survey of different terms, see Klemm’s article in the “Resources” section. That article also explains how to deal with functional groups that require special consideration in calculating IHD/DU, such as nitro, sulfoxide, sulfone, and sulfonyl groups.

4.13. Strategies for Success: Drawing All Constitutional Isomers of a Given Formula

This section helps students by explicitly explaining traps that lead to redundant structures. As with other “Strategies for Success” sections, you should encourage students to read and understand the material, but you do not necessarily have to cover it in class. When I use those sections, I typically convert them into worksheets or small-group work or some other in-class activity instead of lecturing on the material.

You may want to refer students to Section 4.11, which illustrates that identical structures can be identified by using nomenclature. If students apply the rules properly, two identical structures, regardless of how they are drawn, will generate the same name. That property is useful when students are struggling with drawing redundant structures.

4.14. Constitutional Isomers and Biomolecules: Amino Acids and Monosaccharides

This short section, part of the “Organic Chemistry of Biomolecules” series, presents simple cases of biomolecules that are constitutional isomers: leucine/isoleucine, cyclic and acyclic forms of ribose and glucose, and glucose/fructose. Figure 4-43, showing the structures of leucine and isoleucine, is a great example of constitutional isomers. The section also introduces terms related to monosaccharides, such as *aldose*, *ketose*, *pentose*, *hexose*, *aldopentose*, and *ketopentose*.

4.15. Saturation and Unsaturation in Fats and Oils

A second short section discusses monosaturated and polyunsaturated acids and how unsaturation affects the melting points of fatty acids. It ends the chapter with a clear structure–behavior relationship.

STUDENTS’ PERSPECTIVES

This chapter begins the material in organic chemistry that is typically completely new to students. Students who feel comfortable in chemistry because of strong math skills often feel betrayed by this chapter, which is highly visual and requires them to relate two-dimensional representations to three-dimensional molecules. Some students will adore this chapter because it clicks quickly for them, whereas others will need to try various techniques before they can picture molecules in three dimensions and then use those pictures to predict relative energy, stability, and behavior.

Teaching students to draw the chair representations of cyclohexanes is a challenge. Section 4.7 is designed to help students with that task, but students may continue to struggle. Some students find starting with templates for chairs to be a useful stepping-stone leading to drawing them freehand. I have occasionally lent students templates for practice (see the “Resources” section for suppliers). Other instructors produced cyclohexane chairs in ChemDraw with dotted lines for students who felt that a connect-the-dots approach would be helpful. Most students succeed fairly quickly once they genuinely practice and try. Sometimes the only way to get that genuine effort is one-on-one in the office with a great deal of positive reinforcement.

When students are practicing chair flips with model kits, they often lose their chair along the way. I suggest that they focus on the axial groups, reminding themselves that their model should have a repeating pattern of axial up–axial down–axial up around the ring. If their model cannot stand on their desks with three axial groups acting as “legs” and three axial groups pointing up, they have a mistake in their model and need to pull the axial groups to where they belong (three acting like legs on the desk, three pointing up). Manipulating the axial groups, and focusing on them, seems to help students who get confused when the model kit is between-chairs.

Students sometimes ask, “Is there a way to predict the number of constitutional isomers for a given formula?” The answer is yes; however, the basis for predictions is graph theory, which is beyond the scope of what most instructors wish to discuss. The “Resources” section lists articles with some background on that topic.

RESOURCES

For a different perspective on the flowchart in Figure 4-1, see “Flow Chart Determination of Isomeric Relationships” by Kersey A. Black, *J. Chem. Educ.* **1990**, *67*, 141; doi:10.1021/ed067p141. The chart provides examples for each possible outcome of the questions posed in the flowchart, including the possibility of identical structures.

If you wish to incorporate models and the significance of zigzag conformations in your laboratory course, consider an experiment in which students evaluate the solubility of dicarboxylic acids by titrating saturated solutions. The experiment is presented in “Studying Odd–Even Effects and Solubility Behavior Using α , ω -Dicarboxylic Acids” by Hugh D. Burrows, *J. Chem. Educ.* **1992**, *69*, 69; doi:10.1021/ed069p69. Dicarboxylic acids with even numbers of carbons adopt a zigzag conformation, which maximizes hydrogen bonding in the solid and decreases solubility of the acid in water.

For details about the ^1H NMR spectrum of cyclohexane- d_{11} as a function of temperature, referred to in Section 4.6, see F. A. Bovey et al., *J. Chem. Phys.* **1964**, *41*, 2042. That work also appears in *Introduction to Organic Spectroscopy*, by J. B. Lambert, H. F. Shurvell, D. A. Lightner, R. G. Cooks, and G. H. Stout (Macmillan: New York, 1987, pp. 33–35).

Templates that allow students to draw chair conformations are available from the following sources:

- Kenemak is a Canadian company that sells a plastic template for organic structures. It includes a template for cyclohexane chairs and the appropriate lines for bonds to substituents in the axial and equatorial positions. It also provides stencils for Newman projections, boat conformations of cyclohexane, Haworth projections, Fischer projections for monosaccharides, dash–wedge drawings for carbons, and polygons for line structures of cycloalkanes up to cyclooctane. At this writing, the price was Can\$19.95 plus shipping. See www.kenemak.com.
- Rapidesign produces templates for drafting. Its R-83 template for “chemical rings” includes two sizes of cyclohexane chairs (although not the lines for the bonds to the axial and equatorial substituents) and cyclohexane boat conformers. The rest of the template contains polygons of various forms and sizes for drawing line structures for cycloalkanes. It lists for around \$18 on Amazon.com and is available from other online sellers.

For details about isolating equatorial conformations of monosubstituted cyclohexanes at low temperatures, referred to in Section 4.8, see *March’s Advanced Organic Chemistry: Reactions, Mechanisms, and Structure*, 6th ed., by Michael B. Smith and Jerry March (John Wiley & Sons: Hoboken, NJ, 2007, p. 204).

For a discussion of different terms authors use to describe IHD/DU, calculations of IHD/DU for molecules with heteroatoms, and the limitations of the concept, see “Use of Degrees of Unsaturation in Solving Organic Structural Problems” by LeRoy H. Klemm, *J. Chem. Educ.* **1995**, *72*, 425; doi:10.1021/ed072p425.

For background on using graph theory to determine the number of possible isomers for a given formula, see the following articles:

- “Chemical Applications of Graph Theory: Part II. Isomer Enumeration” by Peter J. Hansen and Peter C. Jurs. *J. Chem. Educ.* **1988**, *65*, 661. doi:10.1021/ed065p661.
- “The Enumeration of Isomers—with Special Reference to the Stereoisomers of Decane” by J. R. C. Whyte and M. J. Clugston. *J. Chem. Educ.* **1993**, *70*, 874. doi:10.1021/ed070p874.

Suggested Clicker Questions

The following clicker questions have been selected from the Chapter 4 Clicker Question PowerPoints available on wwnorton.com/instructors. More questions for each chapter are available at the website.

4.3. Conformers: Energy Changes and Conformational Analysis

“What is the dihedral angle between H_a and H_b? (Enter 1–3.)” and “What relationship does this portray? (Enter 4–6.)”

Those questions ask students to read a Newman projection and assign both geometry and name to a relationship. Knowing early in this chapter whether students can visualize the molecule from the drawing is useful.

4.4. Conformers: Cyclic Alkanes and Ring Strain

“Which compound has the greatest (most exothermic) heat of combustion?”

That question deals with the stability of rings, using the correlation of ring strain with increased heat of combustion. It is a quick gut-check–style question.

4.9. Conformers: Disubstituted Cyclohexanes, Cis and Trans Isomers, and Haworth Projections

“Identify which of the following can have both substituents in the equatorial position. (Choose 1–4.)” and “In a chair–chair ring flip, which is true? (Choose 5–7.)”

The first question, dealing with which combination of cis–trans substitutions can lead to a fully equatorial chair, is more challenging than the second question, which is a definition-style question. Both questions are useful for checking in, but the first question is typically more challenging for students than the second question.

CHAPTER 5 | Isomerism 2: Chirality, Enantiomers, and Diastereomers

Chapter 5 deals with organic stereochemistry. The chapter defines relevant terms: *enantiomer*, *diastereomer*, *chiral*, *achiral*, *plane of symmetry*, *stereocenter*, *meso*, *optical activity*, *specific rotation*, *racemic mixture*, and *enantiomeric excess*. It also describes how to apply those terms correctly to organic molecules. The chapter introduces Fischer projections, inversion of nitrogen atoms, the behavior of enantiomers in chiral environments, techniques for separation of stereoisomers, the diastereomeric relationship of cis–trans alkenes, and how alkyl substitution affects the stability of carbon–carbon double bonds.

HEADS UP!

One significant difference between this presentation and that in other books is that this chapter doesn't include the Cahn–Ingold–Prelog rules for assigning *R* and *S* configurations. Instead, they are the principal topic in Interchapter C, which follows Chapter 5 in the text. By holding back on the *R/S* nomenclature until the next chapter, Karty can focus the text on structure and shape. Students have to engage with what each molecule looks like and determine relationships visually instead of simply by having the same or opposite nomenclature designation. Although that approach can be challenging for the instructor, it is ultimately rewarding because it constantly forces the conversation to be about what the molecule looks like in three-dimensional space.

Consider the following comments as you prepare to discuss this chapter's material:

1. Stereochemistry requires sequential presentation of important definitions. Ideally, once students understand each definition and the accompanying examples, they see the relationship between different classes of stereoisomers.
2. Because students must see the relationships between three-dimensional objects, using models in this chapter is crucial. The goal is to get students to understand the relationships that the definitions describe. In a small class, you can scan students for nonverbal signs of understanding.
3. As mentioned, the chapter stresses the spatial relationships between stereoisomers over using assigned configurations.

COMMENTS BY SECTION

5.1. Defining Configurational Isomers, Enantiomers, and Diastereomers

Figure 5-1 is the same flowchart presented in Chapter 4, Figure 4-1, but with the concepts relevant to this chapter highlighted in red. That highlighted path follows isomers down to stereoisomers (isomers with the same connectivity) to configurational isomers to diastereomers and enantiomers. I draw this figure on the board for this section, as I do when teaching Chapter 4, using it as an outline and a way to tie the two chapters together. This section explains that enantiomers and diastereomers differ from each other in ways other than rotation about single bonds, defines *enantiomer* and *diastereomer*, and uses the biological activities of the enantiomers of thalidomide to illustrate the importance of configurational isomers. *The discussion of thalidomide continues in Section 5.12.*

5.2. Enantiomers, Mirror Images, and Superimposability

This section expands on the definition of enantiomers by introducing the concept of nonsuperimposable mirror images and uses examples of substituted methanes and their mirror images to illustrate the concept. Figure 5-2 compares a pair of enantiomers, whereas Figure 5-3 shows a compound without an enantiomer and how with rotation the mirror image is superimposable on the original molecule. Both examples encourage students to get out their molecular model kits, build models, and confirm the relationships between the images.

From this section forward, most figures in the text include some type of rotation of a three-dimensional image. Reproducing Figures 5-2 and 5-3 with model kits in class and demonstrating those rotations physically will help your students pick up that skill. Question 5.36 from the end of the chapter asks students to determine planes of symmetry in conformers of 1,2-dichloroethane. That question is a useful one to do in class with model kits and leads nicely into Section 5.4.

5.3. Strategies for Success: Drawing Mirror Images

The “Strategies for Success” sections are primarily for students to read and apply and not necessarily a topic for lecture. At the same time, the goal of this section is to impart a skill that students must have to understand stereochemistry. Some of the examples from this section are perfect to use in breakout small-group settings or for class workdays.

This section gives explicit rules for drawing mirror images and a clear step-by-step example that inserts bonds and atoms progressively into the diagram of a mirror image (Figure 5-4). A solved problem illustrates the same rules applied to a Newman projection. The section repeats this exercise in Problem 5.3, which contains an allene, two examples with a three-membered ring, and another Newman projection. Later problems ask students to identify mirror images that are superimposable and match structures that are mirror images.

5.4. Chirality

This section defines chirality:

- A molecule is **chiral** if it *has an enantiomer*.
- A molecule is **achiral** if it *does not have an enantiomer*.

Section 5.4 also offers examples of common objects that are chiral. The “Resources” section has additional examples of chiral and achiral objects (taken from *Alice in Wonderland* as well as problems from the text). Solved Problem 5.6 applies the definitions of chiral/achiral to an organic molecule as well as again showing clear examples of how to draw mirror images and then use stepwise rotations to determine superimposability.

The text goes further into three-dimensional analysis, showing how a mirror image of a conformer can be shown to be identical to the original molecule through rotation of single bonds. The section also demonstrates how Haworth projections can show clearly whether two substituted cyclohexanes are identical structures or enantiomers.

This section goes on to assert that a molecule that has a plane of symmetry must be achiral. Convincing students that a molecule with a plane of symmetry is one that will have an identical mirror image can be time-consuming. The more I use model kits in class, the more likely students are to believe me and use model kits themselves.

You may want to clarify for your students that the plane of symmetry test works only for a three-dimensional representation of a molecule—for example, a model, a figure with dashes and wedges, a chair drawing, or a Haworth projection. Having students actually use model kits in this section is useful because they can prove to themselves that they produce the correct answer with models but often cannot find the correct answer when simply using line structures.

Technically, human beings are asymmetric because the right and left sides do not match exactly. However, if you are willing to overlook that technicality, students make excellent demonstrations of the mirror plane test for chirality. To accomplish that, I bring two students of about the same height to the front of the class. I ask them to face each other and to stand normally or to give the signal for a football touchdown, with one being the mirror image of the other. I then take one student and rotate him or her 180° to show that the two students are essentially superimposable. I then ask the students to pose in John Travolta’s stance in *Saturday Night Fever* (which sometimes takes some convincing). In this case, rotating one of the students shows that the two are no longer superimposable.

The section introduces a good bit of vocabulary at this point. Many books and homework sites use vocabulary interchangeably, but Karty is careful with defining his terms. At this point in the text he introduces the following:

- A *stereocenter* is an atom with the property that interchanging any two of its attached groups produces a different stereoisomer.
- A *tetrahedral stereocenter*, called a *chiral center*, is bonded to four different groups.
- A chiral carbon center is called an *asymmetric carbon*.
- A molecule is *meso* if it contains at least two chiral centers but has a plane of symmetry that makes it achiral overall.

Something confusing to students that Karty addresses immediately is that the presence of stereocenters does not guarantee chirality (meso compounds) and that the absence of a stereocenter does not guarantee that a molecule is achiral. Any molecule that contains exactly one chiral center must be chiral, but with no chiral centers or more than one chiral center further analysis is needed. Multiple problems in this section demonstrate the use of the plane of symmetry test to determine whether groups attached to a potential stereocenter are identical (Figure 5-7 and Solved

Problem 5-9 are two good examples). Figure 5-10 illustrates a chiral molecule with no chiral centers, again through providing a mirror image and then rotating the original molecule to be on top of (but not superimposed on) the mirror image. The end-of-chapter Problem 5.44, asking students to identify all chiral centers in Taxol, is an excellent problem to assign at this stage.

At this point the text refers to, but does not discuss, stereochemical configurations. Instead, the discussion refers the reader to Section C.1 in Interchapter C directly after this chapter.

Earlier in this section, nitrogen is introduced as an atom that can be a chiral center if it is bound to four different groups (and consequently has a +1 formal charge). The last part of this section deals with molecules that can rapidly interconvert, such as those with single-bond rotation or nitrogen inversion. Figure 5-13 shows a worked-through example of 1,2-dibromoethane in different conformations, and that rotation around the carbon–carbon bond leads to an achiral molecule. Your Turn 5.11 asks students to apply those concepts to prove to themselves that *trans*-1,2-difluorocyclohexane is chiral. The last part of this section deals with inversion of nitrogen atoms that possess lone pairs and how those nitrogen centers are not chiral. *Most other heteroatoms that can be stereocenters do not undergo that type of rapid inversion.*

5.5. Diastereomers

This section restates the definition of diastereomers—*stereoisomers that are not mirror images of each other*—and applies it to examples that include *cis* and *trans* double bonds, *cis* and *trans* isomers of disubstituted cyclohexane, and molecules with two and three stereocenters.

Diastereomers are identified by inversion of some but not all stereocenters in two stereoisomers. The discussion relies on visually identifying the inversion of configuration and does not use R/S designations to identify inversion. At first, discussing configurational isomers without using *R/S* designations was hard for me because I had relied on deriving the maximum configurational isomers symbolically with strings of *R*s and *S*s. But then I made a variety of models ahead of class (for example, all the stereoisomers discussed in Solved Problem 5.16 and Solved Problem 5.17). Once I did that, showing all the possible configurational isomers structurally rather than simply symbolically with *R/S* designations was easier.

The section also introduces the following rule: The maximum number of configurational isomers that can exist for a molecule with n stereocenters is 2^n .

Solved Problem 5.19 encourages students both to rotate molecules to identify identical structures and to use the plane of symmetry test to identify a structure that is achiral (and cannot have an enantiomer).

Problem 5.20 (b) involves a compound with pseudoasymmetric carbon. The example contains two stereocenters and has four stereoisomers: a pair of enantiomers and two meso forms. Encourage your students to use models if Problem 5.20 (b) confuses them. Naming the meso forms involves rules beyond the scope of the Cahn–Ingold–Prelog rules presented in the text; you may want to sidestep questions from students about how to name the stereoisomers.

A similar compound that you can use as an exercise is 3,4,5-trimethylheptane.

Students find this section's applications box dealing with nanocars particularly appealing. It helps them understand structure and symmetry visually.

5.6. Fischer Projections and Stereochemistry

This section introduces the conventions of Fischer projections from dash–wedge notation and demonstrates their application to monosaccharides. Your Turn 5.14 works through how to convert a Fischer projection to a dash–wedge structure in conventional orientation. Many students find it stressful to have yet another representation presented to them at this stage, and focusing on how Fischer projections make visualizing molecules with multiple asymmetric carbons (such as monosaccharides) much easier will make many students more willing to engage with the material.

Figure 5-22 shows D-allose, D-glucose, and L-glucose and how much easier it is to see the relationships (diastereomers or enantiomers) with the Fischer projections than it would be with dash–wedge notation. Once students answer a few questions such as end-of-chapter Problem 5.73, which asks for specific relationships between pairs of molecules drawn in Fischer projection form, the usefulness of this notation becomes clear.

5.7. Strategies for Success: Converting between Fischer Projections and Zigzag Conformations

The exercises in this section encourage students to use models to interpret Fischer projections in two ways: (1) to

draw the correct Fischer projection of a given molecule for a model and (2) to construct the correct model of a given molecule from a Fischer projection. All those examples start with cartoons of model kits (and strong encouragement to use the model kits) followed with zigzag depictions or Fischer projections.

Sometimes I have saved this section and its emphasis on producing Fischer projections for later in the year, focusing instead on being able to use Fischer projections to determine relationships between pairs of compounds. Whenever you assign it, repeatedly emphasizing how useful model kits are at this stage is worthwhile.

5.8. Physical and Chemical Properties of Isomers

This section introduces what insights are provided in terms of physical differences and chemical properties once the relationship (constitutional isomer, enantiomers, diastereomers) is known. Although the text presents that information in the order of constitutional isomers, enantiomers, and finally diastereomers, I find teaching diastereomers before enantiomers to be more useful for my students. I find the progression from greatly different (constitutional) to somewhat different (diastereomers) to identical in achiral environments (enantiomers) to be the most natural for me. The progression given in the text, with diastereomers last, does have the benefit of leading seamlessly into Section 5.9 (Stability of Double Bonds and Chemical Properties of Isomers).

Constitutional isomers are often the most intuitive for students because early pairs chosen to illustrate them often look so completely different. The text shows an example that has different connectivities and different melting and boiling points (but-3-ene-2-ol and tetrahydrofuran), but it also shows an example of two similar molecules (pent-1-ene and *trans*-pent-2-ene) that have closer boiling points. Similar connectivities lead to similar properties, whereas different connectivities lead to different properties.

Enantiomers exhibit physical and chemical differences in chiral environments and exhibit identical physical and chemical properties in achiral environments. The text defines chiral and achiral environments and uses an analogy involving socks and shoes, presenting the sock as an achiral environment for a foot and a shoe as a chiral environment (Figure 5-25). Medicinal chemistry offers multiple examples of enantiomers that behave differently in biological systems. Brad Chamberlain mentions several in his blog post (see “Resources”). Another interesting example is baclofen, one enantiomer of which is in testing for treatment of autism. (See *Chem. Eng. News*, **2010**, 88, 16–17; doi:10.1021/cen-v088n037.p016.)

Because *diastereomers* are not mirror images of each other, they have to have different physical and chemical properties. The text here introduces the difference in physical properties of diastereomers, including *cis* and *trans* alkenes and diastereomers with stereocenters. Solved Problem 5.25 and Problem 5.26 ask students to evaluate similarities in chemical reactivity and acidity on the basis of similarities and differences in stereochemistry.

5.9. Stability of Double Bonds and Chemical Properties of Isomers

This section uses differences in heats of combustion (Table 5-1) to explain the increase in stability in double bonds as substitution increases. It also uses those data and steric strain to explain *trans* isomers' greater stability than that of *cis* isomers. *The text uses similar thermodynamic data to discuss ring strain (Section 4.4) and resonance energy in aromatic systems (Section 14.3).*

The text briefly introduces hyperconjugation to explain the stability of substituted alkenes.

5.10. Separating Configurational Isomers

After noting the ability of common laboratory methods to separate diastereomers but not enantiomers, the discussion here describes Pasteur's separation of enantiomeric crystals of sodium ammonium tartrate (Figure 5-27 is a useful one showing “handedness” in crystals). The discussion also gives examples of modern methods of separation of enantiomers: chromatography with a chiral stationary phase and the conversion of enantiomers into diastereomers followed by separation of the diastereomers and then regeneration of the enantiomers.

5.11. Optical Activity

Some textbooks introduce optical activity earlier in the discussion of stereochemistry. If you wish to move the topic to earlier in your discussion, you can do so easily. Another natural place for this section to appear would be after Section 5.4, chirality, especially if you intend to use this section qualitatively rather than quantitatively. This section gives enough information that a student could be expected to do calculations, or you could use it to simply introduce the concept of using instruments to measure enantiomeric excess (and purity).

The section defines the relevant terms: *plane-polarized light*, *dextrorotatory*, *levorotatory*, *angle of rotation*, *specific rotation*, *racemic mixture*, and *enantiomeric excess*. It also gives examples of calculations that involve specific rotation and enantiomeric excess.

Plane-polarizing filters are available from science supply companies. Using two of them together allows you to show how a polarimeter works. In a pinch, rotating two pairs of polarized sunglasses works well enough. If the filters are too small for students to see the light that passes through them, you can shine a flashlight through them to improve visibility.

5.12. The Chirality of Biomolecules

The section, another special section on the organic chemistry of biomolecules, describes the thalidomide tragedy and the different activities of the two enantiomers. That description leads to a discussion of the body as a chiral environment, as well as the chirality of many biomolecules (L-amino acids, D-monosaccharides, nucleotides, and steroids).

5.13. The D/L System for Classifying Monosaccharides and Amino Acids

This section explains the origin and evolution of the D/L designations for monosaccharides and amino acids. The discussion points out that the D/L designation for a sugar other than glyceraldehyde is part of the name and does not indicate the direction in which the sugar rotates plane-polarized light.

5.14. The D Family of Aldoses

Many textbooks present this material in a separate chapter dealing with carbohydrates. Many instructors have found this textbook's placement of relevant biochemical topics helpful because the topics are not delayed until the end of the course or not taught as a result of insufficient time. For a discussion of that arrangement, see the Teach the Mechanism blog.

This section provides Fischer projections for each of the D-aldoses, notes that they share the same configuration at the highest-numbered carbon stereocenter, and introduces the term *epimer*.

If you believe your students need to know the names of the aldohexoses, you might share with them the mnemonic “All altruists gladly make gum in gallon tanks.”

STUDENTS' PERSPECTIVES

This chapter can be incredibly difficult for some students who simply cannot easily picture in three dimensions from a two-dimensional representation. In my experience, it is vital that students start using model kits to solve problems. Many students can make it through Chapter 4 without actually using their kits as tools; students can build models as afterthoughts after having solved the problem (or answered through memorizing systems) without the help of their visualization tools. But in Chapter 5, students have nowhere to hide. They simply need to be able to use those tools and to deal with stereochemistry in terms of three-dimensional models. They need to be discouraged from depending on two-dimensional representations and assignments of configurations.

The challenge is to convince students of that idea. Joel has commented on his blog (see “Resources”) that students use models with reluctance. Reflecting (as Joel does) on why students use those models only with reluctance can help in finding ways to encourage them. One of the biggest barriers I have seen is that the kits can be simply another confusing set of visuals. Many students simply cannot initially see the differences in structures, even with models. Two tactics that worked well for me: helping students through the solved problems in the text and making them assemble the models with my encouragement.

RESOURCES

If you wish to pursue a literary introduction of stereochemistry, browse Martin Gardner's *The Annotated Alice*. In his notes to Chapter 1 of Lewis Carroll's *Through the Looking Glass*, Gardner touches on the left–right reversals of asymmetric objects in mirrors. Examples include references to corkscrews (with their asymmetric helices), the White King's singing about squeezing a right foot into a left shoe, and the images and language of Tweedledee and Tweedledum. Question 5.35 at the end of the chapter, asking students to identify chiral and achiral objects, is a

useful one to couple with those examples. Gardner also points out the foreshadowing of organic stereochemistry when Alice comments, “Perhaps Looking-glass milk isn’t good to drink . . .” Gordon T. Yee’s article builds on that perspective. See the following resources:

- *The Annotated Alice: The Definitive Edition*; W. W. Norton, 1999. See particularly pages 142, 144, and 182.
- “Through the Looking Glass and What Alice Ate There,” by Gordon T. Yee. *J. Chem. Educ.* **2002**, 79, 669; doi:10.1021/ed079p569. The author documents an intriguing stereochemical problem he posed to his students: “What foods can looking-glass Alice eat without ill effects?”

The *Teach the Mechanism* blog has several posts reflecting on the teaching of chirality and stereochemistry within the context of this text. A selection of those posts includes the following:

- Brad Chamberlain of Luther College reflected on a traditional nomenclature approach versus an emphasis on spatial relationships in “*R,S* Nomenclature: Help or Hindrance in Teaching Configurational Isomerism?” (December 4, 2012). That blog post also has several good examples of enantiomer pairs with different biological responses.
- In “Molecular Modeling Kits” (October 9, 2012), Joel Karty offers thoughts on why students are so resistant to the use of model kits and why model kits would help them so much if only they would use them.
- Anne Wilson explains how she reorganized the text to integrate Interchapter C (chirality nomenclature) into Chapter 5 because that approach suited her class needs and teaching style in “Stereochemistry and Adaptability” (October 16, 2015).

Small polarizable filters are available from Educational Innovations (<http://www.teachersource.com>) for around \$3 each at the time of this writing.

Suggested Clicker Questions

The following clicker questions have been selected from the Chapter 5 Clicker Question PowerPoints available on www.norton.com/instructors. More questions for each chapter are available at the website.

5.4. Chirality

“How many stereocenters are in the following molecule?”

That problem may seem like a simple stereocenter problem, but because it involves both a cyclic and two equivalent methyl groups on the same carbon, it poses a challenge to many students.

5.6. Fischer Projections and Stereochemistry

“What is the relationship between the following compounds?”

That problem shows two compounds that are identical but might initially look different to students because of how the molecules are rotated in relation to each other.

INTERCHAPTER C | Stereochemistry in Nomenclature: *R* and *S* Configurations about Asymmetric Carbons and *Z* and *E* Configurations about Double Bonds

This section is unlike the other nomenclature interchapters because it deals with stereochemistry (not functional groups) and introduces the Cahn–Ingold–Prelog priority rules. Students will learn how to derive *R/S* designations by prioritizing groups around an asymmetric carbon, to integrate *R/S* designations into IUPAC names, to use those tools with Fischer projections, and to use the *R/S* designations to help determine the relationship between pairs of molecules. As noted in the discussion of Chapter 5 in this guide, some instructors have found it advantageous to have students learn that material during or after the discussion of stereochemistry.

HEADS UP!

Approaching nomenclature of asymmetric carbons only after dealing with chirality, enantiomers, and diastereomers might seem strange at first. But that approach is completely in keeping with the philosophy of teaching *understanding*, not *memorization*. Teaching stereochemistry without Cahn–Ingold–Prelog rules leads to discussions focused more on shape/structure and less on a nomenclature crutch. Students spend Chapter 5 learning about molecular shape and symmetry/asymmetry. They should leave Chapter 5 with the ability to visualize and produce enantiomers and diastereomers as well as how to determine a molecule's chirality. After students have mastered those concepts, teaching stereochemical nomenclature is much easier.

This interchapter also deals with *Z/E* configurations, something that a text arranged by functional group typically introduces in a chapter on alkenes. Introducing it here makes sense, however, because it follows the same priority rules as the *R/S* designations do. Bundling those two topics together, because they are connected in terms of both stereochemistry and prioritization rules, makes for a cohesive unit that helps students understand.

COMMENTS BY SECTION

C.1. Priority of Substituents and Stereochemical Configurations at Asymmetric Carbons: *R/S* Designations

This section begins by explaining the basic steps for *R/S* configuration for an asymmetric carbon:

1. Assign a priority, 1 through 4 (where 1 is the highest and 4 is the lowest), to each of the four substituents bonded to the asymmetric carbon.
2. Orient the molecule so that the lowest-priority substituent is pointed away from you.
3. If the substituents having the first, second, and third priorities are arranged clockwise, then the stereocenter is assigned the *R* configuration. If they are arranged counterclockwise, then the stereocenter is assigned the *S* configuration.

Figure C-1a and C-1b show, using a steering wheel as a visual aid, how the substituents 1–3 could be arranged clockwise versus counterclockwise.

The relative priorities of atoms are discussed, starting with atomic number (the greater atomic number has the greater priority) and isotopes (greater atomic mass has greater priority). The other methods of prioritization are presented as “tiebreakers.” Those tiebreakers are integrated throughout this section, and examples of each tiebreaker appear as worked-through problems with follow-up examples for students to try on their own. Compiled as one list for the instructor, the tiebreakers are as follows:

First Tiebreaker. Examine each substituent's atom at the point of attachment. If those atoms are different, assign the higher priority to the substituent that has the higher-priority atom.

Second Tiebreaker. For each substituent, identify the set of three atoms one bond away from its point of attachment. In each set, arrange the three atoms from highest priority to lowest. Compare each set's highest-priority atom. If they are different, then the atom that has the higher priority corresponds to the higher-priority substituent. If the highest-priority atoms from each set are the same, compare each set's second-highest-priority atom to break the tie. If the second-highest-priority atoms from each set are the same, compare each set's lowest-priority atom to break the tie.

Third Tiebreaker. If sets of atoms one bond away from the point of attachment are identical, apply the second tiebreaker to the sets of atoms one additional bond away from the point of attachment. If a tie persists, continue to move farther from the point of attachment until a difference is evident. If the substituent's backbone is branched, follow the chain on which the higher-priority atoms are encountered first. If two atoms being compared are the same and one of them is a substituent's terminal atom, the substituent to which it belongs has the lower priority. If a point of difference is never found, the substituents must be identical.

The examples integrated around the tiebreaker discussion help students through assigning *R/S* designations, show what to do when the molecule's fourth-priority group is not in the dash position (pointing away from the reader), and show how to incorporate *R/S* designations into IUPAC nomenclature. In-text Problems C.3 and C.4 are straightforward molecules that students have to either name or supply a structure for when given a name, and they prepare students for the more complex end-of-chapter problems.

This section goes on to address how to deal with substituents that have a double or a triple bond. Figure C-2 shows nicely how students can imagine that a double bond can be treated as having two of the same atom. Typically that rule is easy for students to understand, and one example is plenty for most to be able to apply it on their own.

If you intend for students to derive *R/S* designations from Fischer projections at this stage, a short section explains how to determine the configuration and gives an example of a molecule with two asymmetric carbons. The text does not review dash-wedge structures from Fischer projections, but rather starts from a Fischer projection and shows the derivation with the fourth position on either the horizontal or the vertical axis.

This section concludes with how to use *R/S* designations to determine whether the relationship between a pair of molecules is enantiomeric (inversion of all chiral centers) or diastereomeric (inversion of some of the chiral centers). Presenting that method of relationship determination *after* students have made those determinations by using model kits is always rewarding; suddenly, nomenclature seems like a powerful tool for them and becomes something they are happy to do. The end-of-chapter Problem C.21 is a great example of a problem that would have seemed difficult to students before this interchapter but is now straightforward and easy.

C.2. Stereochemical Configurations of Alkenes: *Z/E* Designations

This section follows naturally from the previous section, even though it would not appear anywhere near *R/S* designations in a functional group-organized text. Because *Z/E* designations rely on prioritization, and the prioritization rules for those stereoisomers are the same as for groups around an asymmetric carbon, students typically have no trouble switching gears to groups around a double bond.

The examples start with assigning priorities for the two substituents on each carbon participating in a double bond. Students find that step refreshing because each carbon has only two groups to prioritize. If both higher-priority groups are on the same side of the double bond, the molecule is the *Z* (*zusammen*, or together) configuration; if the higher-priority groups are on the opposite side of the double bond, the molecule is in the *E* (*entgegen*, or opposite/opposed) configuration. The book offers the mnemonic of “Zame” side or “Epposite” side. The examples become more complex until students have been shown how to deal with multiple bonds that require *Z/E* designations and how to deal with larger cyclic molecules.

STUDENTS' PERSPECTIVES

My students have found this material easier to master as a stand-alone section after they have struggled with and ultimately mastered the concepts from Chapter 5. Using *R/S* nomenclature to help define enantiomer pairs and diastereomeric relationships is much more intuitive after those relationships are well understood from a molecular visualization approach.

Because the text introduces nomenclature after discussing chirality, you might be tempted to breeze through this chapter and not spend enough time on the fundamentals of prioritization. Spending a bit of time on priorities is worthwhile because those assignments are often the only sticking point for students in this interchapter (because the hope is that they already understand chirality). In-text Problems C.1, C.2, and C.6 are great examples of basic prioritization drills.

In addition to using *clockwise* and *counterclockwise*, simply telling students that *R* is for priorities arranged 1 through to the right (arrow pointing right) and *S* (sinister) with arrangement to the left can be useful for students who, in the age of digital clocks, aren't comfortable with *clockwise*. Students have typically not confused that explanation of prioritization with optical rotation, so I have kept using it.

Some of this interchapter's shortcuts for nomenclature are less useful for my students, and I keep the focus on using model kits from Chapter 5. For example, the text box offering suggestions for “Assigning *R* and *S*

Configurations When the Fourth-Priority Substituent Does Not Point Away” gives strategies to use if the fourth priority points toward the student or if the fourth priority is in the plane of the page. For situations in which the fourth priority points toward the student, I present the material the same way that the text does, but I also use the rotation of a molecular model (and the example of me in front of the classroom for “my right, your left”) to lead to how the rotation of what you “see” is the opposite of what it actually is. For situations in which the fourth priority is in the plane of the page, I have students practice rotating the molecule and redrawing it until the fourth priority is in either the wedge or the dash position. Not only is that a foolproof method to assign *R/S*, because it relies on deriving it rather than remembering swapping rules (presuming they get the rotation correct), but it also forces students to use their model kits.

RESOURCES

Although not an external resource, the integrated end-of-text problems (C.27–C.37) are useful and challenging problems that do not exist in many other textbooks (which present *R/S* and *Z/E* nomenclature separately and so do not have integrated problems). Problem C.37 asks students whether a name represents a single stereoisomer unambiguously; answering that requires students to think about what information the name has provided (and potentially omitted) as well as whether the molecule could be drawn as two or more stereoisomers from the information given.

The rotations in this chapter lend themselves to using the ball-and-stick model. Molymod Molecular Model Kits, available from Carolina Biological Supply, Indigo Instruments, and Amazon.com, can be useful for classroom demonstrations. One enantiomer pair is enough for two to three students to share as we work together in class. One complete set of the Molymod MMS-008 Organic Chemistry Molecular Model (at the time of this writing, about \$21 from Amazon.com) would supply enough material for six enantiomer pairs.

Suggested Clicker Question

The following clicker question has been selected from the Interchapter C Clicker Question PowerPoints available on wwnorton.com/instructors. More questions for each chapter are available at the website.

C.1. Priority of Substituents and Stereochemical Configurations at Asymmetric Carbons: R/S Designations

“What is an appropriate name for the following compound?”

That problem asks students to determine the entire name, including the *R/S* designation, for a cyclic alcohol that also contains a carbon–carbon double bond. Because students often have difficulty prioritizing double bonds, the question is great for this chapter.

CHAPTER 6 | The Proton Transfer Reaction: An Introduction to Mechanisms, Thermodynamics, and Charge Stability

The chapter uses acid–base reactions to review topics students learned in general chemistry: K_{eq} , K_{a} , $\text{p}K_{\text{a}}$, Le Châtelier’s principle, ΔG° , ΔH° , and ΔS° . The chapter also introduces new concepts such as curved arrow notation, using $\text{p}K_{\text{a}}$ values to predict the outcome of an acid–base reaction, the leveling effect, and reaction free energy diagrams. Much of the chapter is devoted to evaluating acid strength on the basis of the presence or absence of charge, periodic trends in acidity, hybridization of the atom to which the atom is attached, resonance effects, and inductive effects. The chapter concludes with discussions of the placement of charge in resonance contributors, the structure of amino acids as a function of pH, and electrophoresis and isoelectric focusing.

Most concepts in the first part of the chapter are topics that students learned in general chemistry *except for the extremely important concept of curved arrow notation, which is probably new to them*. One approach is to touch on many of the review topics only briefly in lecture, leaving more time for the new topics and concepts. For example, students learned the Brønsted–Lowry definitions in general chemistry. To drive home the point that this is review material, you may want to start with an unlabeled example (without products) and ask students to identify the acid and the base, predict the products of the reaction, and, finally, provide the correct designation of each product (conjugate base or conjugate acid). Starting with that review makes introducing curved arrow notation much less intimidating.

HEADS UP!

I recommend that you read the chapter introduction, which explains how concepts presented here will be used in future chapters. This is the chapter that introduces, with simple and familiar examples as reactants, curved arrow notation. The chapter also introduces acid strength as a function of conjugate base stability and then moves on to look at base strength (setting the stage for nucleophile strength). You might be tempted to hold off on curved arrow notation until Chapter 7, but introducing it here makes Chapter 7 much easier.

To elaborate on the introduction, note the following:

- The discussion of acidity here is comprehensive and allows students to evaluate species they will see in future chapters, such as protonated alcohols and carbonyls, enolates, and acetylide anions. Introducing so many species traditionally seen as advanced topics in a functional group–organized approach may seem strange at this stage. Those species are not inherently more advanced; they were simply arbitrarily held till later in the text, so instructors often thought of them as advanced. Teaching all those examples together helps students understand the reasoning behind acid strength.
- In Chapter 7, students will be expected to already have some comfort level with curved arrow notation, so the examples and practice in this chapter are vital for the next stage of learning.
- In future chapters, charge stability will be the primary means of predicting whether a reaction is reactant favored or product favored. Consequently, the discussion of charge stability is extensive.
- The chapter also introduces the regular use of reaction free energy diagrams. Multiple reaction steps are depicted in a single diagram so students can compare the steps. For example, similar diagrams will be used to compare $\text{S}_{\text{N}}2$ reactions, electrophilic additions, and other situations in which students evaluate competing reactions.

COMMENTS BY SECTION

6.1. An Introduction to Reaction Mechanisms: The Proton Transfer Reaction and Curved Arrow Notation

This section reviews Brønsted–Lowry acid–base reactions and introduces several fundamental concepts, including the idea of an elementary step, concerted reactions, and curved arrow notation (arrow pushing). Introducing those new concepts with the example of acid–base reactions that students are probably familiar with is much easier; students typically understand the chemical reaction taking place, and therefore they can more easily see what the arrow pushing notation is “telling” us.

The reaction of water and ammonia to form the hydroxide and ammonium ions may seem trivial, but it is the basis of several problems that are actually perfect examples to have students gain confidence with arrow pushing

notation. In-text Problems 6.2 and 6.3 ask students to look at permutations of that reaction and are useful to assign or ask students to work through in class. End-of-chapter Problems 6.38 and 6.39 are great exercises to have students draw what the products will look like (from reagents and arrows) or provide arrows when given products and reactants.

6.2. Chemical Equilibrium and the Equilibrium Constant, K_{eq}

This section offers a comprehensive review of concepts from general chemistry, and how deep to take that review is up to you. Certainly students will need to understand how to use $\text{p}K_{\text{a}}$ to determine the direction of a reaction by the end of this section, but whether students need to derive the values as shown in the chapter, produce from memory those values as is encouraged later in the chapter, or simply look them up from a table is a personal course choice. I typically lean toward simply using the values from tables and skip much of the derivations and almost all the $\text{p}K_{\text{a}}$ value memorization, but having those topics covered in the text is useful for students' future reference.

The section begins by reviewing the convention for writing K_{eq} and how to interpret its magnitude. The section then defines K_{a} and $\text{p}K_{\text{a}}$ and explains how to compare the values to determine the stronger of two acids. It also describes the relationship between the strengths of a base and its conjugate acid, as well as how to use K_{a} and $\text{p}K_{\text{a}}$ values to compare the basicity of two species. *That is where you will find the table of K_{a} and $\text{p}K_{\text{a}}$ values (Table 6-1) for various acids. Appendix A lists additional values.*

From here, students learn how to predict whether an acid–base reaction favors the reactants or products: Proton transfer reactions favor the side opposite the strong acid. The stability of the conjugate base will be dealt with extensively later in this chapter, starting in Section 6.5.

The leveling effect is introduced in this section, discussing the strongest acid and strongest base that can exist in a solvent, using water as an example and then generalizing. That topic does not appear in some texts and receives only passing mention in others. It will be important, however, in future chapters in which students will need to recognize synthetic traps. In-text Problem 6.9 foreshadows that concept, asking students to pick the appropriate solvent for a reaction using acetylide anion.

This section ends with both a qualitative discussion of Le Châtelier's principle and quantitative applications of the Henderson–Hasselbalch equation. Those topics relate to the discussion of gel electrophoresis in Section 6.10.

6.3. Thermodynamics and Gibbs Free Energy

This section reviews material that students learned in general chemistry: the definitions of Gibbs free energy, standard conditions, spontaneous reactions, exergonic and endergonic reactions, and the significance of the sign of ΔG° . I find that reassuring students that we are looking at using those concepts qualitatively, in terms of orders of magnitude and sign, helps students engage with the material more comfortably.

The section includes a review of ΔS° and ΔH° , their relationship to ΔG° , and endothermic and exothermic reactions. The discussion points out that, in general, ΔH° determines the magnitude of ΔG° . It mentions that ΔS° is sometimes significant and points out temperature's role in such cases (such as elimination reactions). This section also explains free energy diagrams, particularly the nature of the reaction coordinate, and points out their relevant aspects: the overall change in energy, the free energy of activation ($\Delta G^{\circ}_{\text{rxn}}$ and $\Delta G^{\circ\dagger}$), the transition state, and the overall energy barrier in a change. Again, students will see free energy diagrams throughout the text, so presenting them in some level of detail at this stage is useful. A useful example of the level of understanding students will need from this section would be end-of-chapter Problem 6.49, which asks students to evaluate two reaction diagrams to predict product abundance.

The relationship between $\Delta G^{\circ\dagger}$ and k , the rate constant, will be discussed in Chapter 8.

Most students learn about the energy of activation in the Arrhenius equation, E_{a} , in general chemistry. You may want to tell students that $\Delta G^{\circ\dagger}$ and E_{a} are similar, each representing an energy barrier that must be overcome as reactants form products. Elaborating on the difference between the two quantities is beyond the scope of the course.

6.4. Strategies for Success: Functional Groups and Acidity

This section starts with the question of what to do if you need the $\text{p}K_{\text{a}}$ for a compound that is not on your $\text{p}K_{\text{a}}$ table. Students are then shown how to estimate a $\text{p}K_{\text{a}}$ value by comparing a compound with an unknown $\text{p}K_{\text{a}}$ with a similar compound with a known $\text{p}K_{\text{a}}$. After comparing the similarities in the $\text{p}K_{\text{a}}$'s of ethanol and isopropyl alcohol and of acetic acid and benzoic acid—pairs with identical functional groups—the section contrasts acetic acid with trichloroacetic acid and then ethanol with phenol to show how additional functional groups affect a molecule.

Students begin to use structure, looking at the molecule as a whole and comparing it with another molecule, to determine acidity. That technique will lead them to be able to determine acidity completely from structure.

In the end-of-chapter Problems 6.50 and 6.51, students examine molecules, determine the important feature—the appropriate functional group—that indicates the acidity of the molecule, and find pK_a 's of similar structures in Table 6-1. Specifically telling students to use Table 6-1 is useful because the problem does not instruct them to do so.

6.5. Relative Strengths of Charged and Uncharged Acids: The Reactivity of Charged Species

This section introduces a theme that appears repeatedly throughout the text: Creating charged species is thermodynamically unfavorable. Using K_{eq} , ΔG° , and energy diagrams, the section shows how charged products are less stable than uncharged reactants. The discussion begins with autoionization of water and goes on to the reactions of ammonia and ammonium ion with water. This is the section that introduces a structural argument as to *why* acidity trends exist.

6.6. Relative Acidities of Protons on Atoms with Like Charges

This section explains the periodic trends in acidity that Section 6.7 will neatly summarize with the simplification of the priorities following the “CARDIN”-al rule:

Charge > Atom > Resonance Delocalization > Inductive effects.

I find it useful to start with that rule, instead of introducing it only in the next section, because doing so helps keep the conversation focused on what we are looking at and trying to accomplish.

The text examines periodicity by first introducing protons on different atoms in the same row of the periodic table and then protons on different atoms in the same column of the periodic table. Students continue to use energy diagrams to compare acidity; similar reactions are shown on the same diagram, and students use the difference in energy to determine which reaction is more product favored. This is the section that also fully discusses the relative stabilities of the conjugate base and brings all the concepts together.

Anions tend to become more stable across a row. For across the row, the key notion is electronegativity: Within a row, the stability of the negative charge increases as the electronegativity of the atom increases. The same concept is applied to positively charged species, in which case the less electronegative atom can better stabilize a positive charge.

Anions tend to become more stable down a column. For down a column, the larger the atom, the more stable it is with a negative charge. This section points out the apparent contradiction in the trends (electronegativity not being the determining factor within a group). The size and volume of larger atoms are used to justify the stability in negative charge as we proceed down a column. Although other explanations for that trend exist (such as less effective orbital overlap and lower bond energy), the stability of the anion as size increases will serve well in other contexts. Specifically, students can use that idea when evaluating the stability of leaving groups in substitution reactions, which becomes important in Chapter 9.

Hybridization is touched on briefly next. Effective electronegativity is used here to explain the difference between the acidity of alkanes, alkenes, and alkynes. In Solved Problem 6.16, it also is used to explain the difference in acidity of protonated oxygens with different hybridization.

Resonance stabilization is explained through charge delocalization, using the example of the stability of conjugate bases (acetate anion vs. ethoxide anion in Equations 6-21a and 6-21b) and the stability of acids (protonated acetic acid vs. protonated acetone in Solved Problem 6.18). That is an area in which students often need encouragement to draw all resonance contributors to be able to fully see what is going on. Your Turn 6.15 asks students to draw a resonance hybrid, and Solved Problem 6.20 asks students to evaluate pentane-2,4-dione and choose the more acidic site. Solving that problem is easy if students draw the possible conjugate bases and then look for resonance stabilization, but is quite difficult if they simply look at the structure and hope for inspiration.