CHEMISTRY

STRUCTURE AND PROPERTIES

NIVALDO J. TRO

SECOND EDITION

Pearson

Main groups

1A 1	2A 2											3A 13	4A 14	5A 15	6A 16	7A 17	8A 18
1 **H** 1.008																	2 **He** 4.003
3 **Li** 6.94	4 **Be** 9.012											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
11 **Na** 22.99	12 **Mg** 24.31	3B 3	4B 4	5B 5	6B 6	7B 7	8B 8	8B 9	8B 10	1B 11	2B 12	13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.06	17 **Cl** 35.45	18 **Ar** 39.95
19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.87	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.85	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.38	31 **Ga** 69.72	32 **Ge** 72.63	33 **As** 74.92	34 **Se** 78.97	35 **Br** 79.90	36 **Kr** 83.80
37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.95	43 **Tc** [98]	44 **Ru** 101.07	45 **Rh** 102.91	46 **Pd** 106.42	47 **Ag** 107.87	48 **Cd** 112.41	49 **In** 114.82	50 **Sn** 118.71	51 **Sb** 121.76	52 **Te** 127.60	53 **I** 126.90	54 **Xe** 131.29
55 **Cs** 132.91	56 **Ba** 137.33	57 **La** 138.91	72 **Hf** 178.49	73 **Ta** 180.95	74 **W** 183.84	75 **Re** 186.21	76 **Os** 190.23	77 **Ir** 192.22	78 **Pt** 195.08	79 **Au** 196.97	80 **Hg** 200.59	81 **Tl** 204.38	82 **Pb** 207.2	83 **Bi** 208.98	84 **Po** [208.98]	85 **At** [209.99]	86 **Rn** [222.02]
87 **Fr** [223.02]	88 **Ra** [226.03]	89 **Ac** [227.03]	104 **Rf** [261.11]	105 **Db** [262.11]	106 **Sg** [266.12]	107 **Bh** [264.12]	108 **Hs** [269.13]	109 **Mt** [268.14]	110 **Ds** [271]	111 **Rg** [272]	112 **Cn** [285]	113 **Nh** [284]	114 **Fl** [289]	115 **Mc** [289]	116 **Lv** [292]	117 **Ts** [294]	118 **Og** [294]

Transition metals

Metals   Metalloids   Nonmetals

Lanthanide series

58 **Ce** 140.12	59 **Pr** 140.91	60 **Nd** 144.24	61 **Pm** [145]	62 **Sm** 150.36	63 **Eu** 151.96	64 **Gd** 157.25	65 **Tb** 158.93	66 **Dy** 162.50	67 **Ho** 164.93	68 **Er** 167.26	69 **Tm** 168.93	70 **Yb** 173.05	71 **Lu** 174.97

Actinide series

90 **Th** 232.04	91 **Pa** 231.04	92 **U** 238.03	93 **Np** [237.05]	94 **Pu** [244.06]	95 **Am** [243.06]	96 **Cm** [247.07]	97 **Bk** [247.07]	98 **Cf** [251.08]	99 **Es** [252.08]	100 **Fm** [257.10]	101 **Md** [258.10]	102 **No** [259.10]	103 **Lr** [262.11]

[a] The labels on top (1A, 2A, etc.) are common American usage. The labels below these (1, 2, etc.) are those recommended by the International Union of Pure and Applied Chemistry.

Atomic masses in brackets are the masses of the longest-lived or most important isotope of radioactive elements.

List of Elements with Their Symbols and Atomic Masses

Element	Symbol	Atomic Number	Atomic Mass
Actinium	Ac	89	227.03[a]
Aluminum	Al	13	26.98
Americium	Am	95	243.06[a]
Antimony	Sb	51	121.76
Argon	Ar	18	39.95
Arsenic	As	33	74.92
Astatine	At	85	209.99[a]
Barium	Ba	56	137.33
Berkelium	Bk	97	247.07[a]
Beryllium	Be	4	9.012
Bismuth	Bi	83	208.98
Bohrium	Bh	107	264.12[a]
Boron	B	5	10.81
Bromine	Br	35	79.90
Cadmium	Cd	48	112.41
Calcium	Ca	20	40.08
Californium	Cf	98	251.08[a]
Carbon	C	6	12.01
Cerium	Ce	58	140.12
Cesium	Cs	55	132.91
Chlorine	Cl	17	35.45
Chromium	Cr	24	52.00
Cobalt	Co	27	58.93
Copernicium	Cn	112	285[a]
Copper	Cu	29	63.55
Curium	Cm	96	247.07[a]
Darmstadtium	Ds	110	271[a]
Dubnium	Db	105	262.11[a]
Dysprosium	Dy	66	162.50
Einsteinium	Es	99	252.08[a]
Erbium	Er	68	167.26
Europium	Eu	63	151.96
Fermium	Fm	100	257.10[a]
Flerovium	Fl	114	289[a]
Fluorine	F	9	19.00
Francium	Fr	87	223.02[a]
Gadolinium	Gd	64	157.25
Gallium	Ga	31	69.72
Germanium	Ge	32	72.63
Gold	Au	79	196.97
Hafnium	Hf	72	178.49
Hassium	Hs	108	269.13[a]
Helium	He	2	4.003
Holmium	Ho	67	164.93
Hydrogen	H	1	1.008
Indium	In	49	114.82
Iodine	I	53	126.90
Iridium	Ir	77	192.22
Iron	Fe	26	55.85
Krypton	Kr	36	83.80
Lanthanum	La	57	138.91
Lawrencium	Lr	103	262.11[a]
Lead	Pb	82	207.2
Lithium	Li	3	6.94
Livermorium	Lv	116	292[a]
Lutetium	Lu	71	174.97
Magnesium	Mg	12	24.31
Manganese	Mn	25	54.94
Meitnerium	Mt	109	268.14[a]
Mendelevium	Md	101	258.10[a]
Mercury	Hg	80	200.59
Molybdenum	Mo	42	95.95
Moscovium	Mc	115	289[a]
Neodymium	Nd	60	144.24
Neon	Ne	10	20.18
Neptunium	Np	93	237.05[a]
Nickel	Ni	28	58.69
Nihonium	Nh	113	284[a]
Niobium	Nb	41	92.91
Nitrogen	N	7	14.01
Nobelium	No	102	259.10[a]
Oganesson	Og	118	294[a]
Osmium	Os	76	190.23
Oxygen	O	8	16.00
Palladium	Pd	46	106.42
Phosphorus	P	15	30.97
Platinum	Pt	78	195.08
Plutonium	Pu	94	244.06[a]
Polonium	Po	84	208.98[a]
Potassium	K	19	39.10
Praseodymium	Pr	59	140.91
Promethium	Pm	61	145[a]
Protactinium	Pa	91	231.04
Radium	Ra	88	226.03[a]
Radon	Rn	86	222.02[a]
Rhenium	Re	75	186.21
Rhodium	Rh	45	102.91
Roentgenium	Rg	111	272[a]
Rubidium	Rb	37	85.47
Ruthenium	Ru	44	101.07
Rutherfordium	Rf	104	261.11[a]
Samarium	Sm	62	150.36
Scandium	Sc	21	44.96
Seaborgium	Sg	106	266.12[a]
Selenium	Se	34	78.97
Silicon	Si	14	28.09
Silver	Ag	47	107.87
Sodium	Na	11	22.99
Strontium	Sr	38	87.62
Sulfur	S	16	32.06
Tantalum	Ta	73	180.95
Technetium	Tc	43	98[a]
Tellurium	Te	52	127.60
Tennessine	Ts	117	294[a]
Terbium	Tb	65	158.93
Thallium	Tl	81	204.38
Thorium	Th	90	232.04
Thulium	Tm	69	168.93
Tin	Sn	50	118.71
Titanium	Ti	22	47.87
Tungsten	W	74	183.84
Uranium	U	92	238.03
Vanadium	V	23	50.94
Xenon	Xe	54	131.293
Ytterbium	Yb	70	173.05
Yttrium	Y	39	88.91
Zinc	Zn	30	65.38
Zirconium	Zr	40	91.22

[a]Mass of longest-lived or most important isotope.

CHEMISTRY

STRUCTURE AND PROPERTIES

Second Edition

Nivaldo J. Tro

WESTMONT COLLEGE

P Pearson

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About the Author

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

To Ann, Michael, Ali, Kyle, and Kaden

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Interactive Media Contents

Interactive Worked Examples (IWEs)

Key Concept Videos (KCVs)

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The d_{z^2} orbital

The one in the highest orbital

Preface

To the Student

In this book, I tell the story of chemistry, a field of science that has not only revolutionized how we live (think of drugs designed to cure diseases or fertilizers that help feed the world), but also helps us to understand virtually everything that happens all around us all the time. The core of the story is simple: Matter is composed of particles, and the structure of those particles determines the properties of matter. Although these two ideas may seem familiar to you as a twenty-first-century student, they were not so obvious as recently as 200 years ago. Yet, they are among the most powerful ideas in all of science. You need not look any further than the advances in biology over the last half-century to see how the particulate view of matter drives understanding. In the last 50 years, we have learned how all living things derive much of what they are from the particles (especially proteins and DNA) that compose them. I invite you to join the story as you read this book. Your part in its unfolding is yet to be determined, and I wish you the best as you start your journey.

Nivaldo J. Tro
tro@westmont.edu

To the Professor

First and foremost, thanks to all of you who adopted this book in its first edition. You made this book the market-leading atoms-first book. I am grateful beyond words. Second, know that I have listened carefully to your feedback about the first edition. The changes you see in this edition are the direct result of your input, as well as my own experience using the book in my general chemistry courses. If you are a reviewer or have contacted me directly, you will likely see your suggestions reflected in the changes I have made. Thank you.

In spite of the changes in this edition, the goal of the text remains the same: *to tell the story of chemistry in the most compelling way possible.* This book grew out of the *atoms-first* movement in General Chemistry. In a practical sense, the main thrust of this movement is a reordering of topics so that atomic theory and bonding models come much earlier than in the traditional approach. A primary rationale for this approach is for students to understand the theory and framework behind the chemical "facts" they are learning. For example, in the traditional approach students learn early that magnesium atoms tend to form ions with a charge of 2+. They don't understand *why* until much later (when they get to quantum theory). In contrast, in an atoms-first approach, students learn quantum theory first and understand immediately why magnesium atoms form ions with a charge of 2+. In this way, students see chemistry as a coherent picture and not just a jumble of disjointed facts.

From my perspective, the atoms-first approach is better understood—not in terms of topic order—but in terms of emphasis. Professors who teach with an atoms-first approach generally emphasize: (1) the particulate

nature of matter and (2) the connection between the *structure* of atoms and molecules and their *properties* (or their function). The result of this emphasis is that the topic order is rearranged to make these connections earlier, stronger, and more often than the traditional approach. Consequently, I chose to name this book *Chemistry*: *Structure and Properties*, and have not included the phrase *atoms-first* in the title. From my perspective, the topic order grows out of the particulate emphasis, not the other way around.

In addition, by making the relationship between structure and properties the emphasis of the book, I extend that emphasis beyond just the topic order in the first half of the book. For example, in the chapter on acids and bases, a more traditional approach puts the relationship between the structure of an acid and its acidity toward the end of the chapter, and many professors even skip this material. In this book, I cover this relationship early in the chapter, and I emphasize its importance in the continuing story of structure and properties. Similarly, in the chapter on free energy and thermodynamics, a traditional approach does not emphasize the relationship between molecular structure and entropy. In this book, however, I emphasize this relationship and use it to tell the overall story of entropy and its ultimate importance in determining the direction of chemical reactions. In this edition, I have also changed the topic order in the gases chapter, so that the particulate view inherent in kinetic molecular theory comes at the beginning of the chapter, followed by the gas laws and the rest of the chapter content. In this way, students can understand the gas laws and all that follows in terms of the particulate model.

Throughout the course of writing this book and in conversations with many of my colleagues, I have also come to realize that the atoms-first approach has some unique challenges. For example, how do you teach quantum theory and bonding (with topics like bond energies) when you have not covered thermochemistry? Or how do you find laboratory activities for the first few weeks if you have not covered chemical quantities and stoichiometry? I have sought to develop solutions to these challenges in this book. For example, I include a section on energy and its units in Chapter E, "Essentials: Units, Measurement, and Problem Solving." This section introduces changes in energy and the concepts of exothermicity and endothermicity. These topics are therefore in place when you need them to discuss the energies of orbitals and spectroscopy in Chapter 2, "Periodic Properties of the Elements," and bond energies in Chapter 5, "Chemical Bonding I: Drawing Lewis Structures and Determining Molecular Shapes." Similarly, I introduce the mole concept in Chapter 1; this placement allows not only for a more even distribution of quantitative homework problems, but also for laboratory exercises that require use of the mole concept.

In addition, because I strongly support the efforts of my colleagues at the Examinations Institute of the American Chemical Society, and because I have sat on several committees that write the ACS General Chemistry exam, I have ordered the chapters in this book so that they can be used with those exams in their present form. The end result is a table of contents

that emphasizes structure and properties, while still maintaining the overall traditional division of first- and second-semester topics.

Some of the most exciting changes and additions to this edition are in the media associated with the book. To enhance student engagement in your chemistry course, I have added approximately 37 new Key Concept Videos and 50 new Interactive Worked Examples to the media package, which now contains over 150 interactive videos. There is a more detailed description of these videos in the following section entitled "New to This Edition." In my courses, I employ readings from the book and these videos to implement a *before, during, after* strategy for my students. My goal is to *engage students in active learning before class, during class, and after class.* Recent research has conclusively demonstrated that students learn better when they are active as opposed to passively listening and simply taking in content.

To that end, in addition to a reading assignment from the text, I assign a key concept video *before* each class session. Reading sections from the text in conjunction with viewing the video introduces students to a key concept for that day and gets them thinking about it before they come to class. Since the videos and the book are so closely linked, students get a seamless presentation of the content. *During* class, I expand on the concept and use *Learning Catalytics*™ in MasteringChemistry™ to question my students. Instead of passively listening to a lecture, they interact with the concepts through questions that I pose. Sometimes I ask my students to answer individually, other times in pairs or even groups. This approach has changed my classroom. Students engage in the material in new ways. They have to think, process, and interact. *After* class, I give them another assignment, often an Interactive Worked Example with a follow-up question. They put their new skills to work in solving this assignment. Finally, I assign a weekly problem set in which they have to apply all that they have learned to solve a variety of end-of-chapter problems.

The results have been fantastic. Instead of just starting to learn the material the night before a problem set is due, my students are engaged in chemistry before, during, and after class. I have seen evidence of their improved learning through increases in their scores on the American Chemical Society Standard General Chemistry Exam, which I always administer as the final exam for my course.

For those of you who have used my other general chemistry book (*Chemistry: A Molecular Approach*), you will find that this book is a bit shorter and more focused and streamlined than that one. I have shortened some chapters, divided others in half, and completely eliminated three chapters ("Biochemistry," "Chemistry of the Nonmetals," and "Metals and Metallurgy"). These topics are simply not being taught much in many general chemistry courses. *Chemistry: Structures and Properties* is a leaner and more efficient book that fits well with current trends that emphasize depth over breadth. Nonetheless, the main features that have made *Chemistry: A Molecular Approach* a success continue in this book. For example, strong problem-solving pedagogy, clear and concise writing, mathematical and chemical rigor, and dynamic art are all vital components of this book.

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

Nivaldo J. Tro

tro@westmont.edu

New to This Edition

- Conceptual Connections and Self-Assessment Quizzes at the end of each chapter in the book are now embedded and interactive in eText 2.0. The interactive quizzes help students to study and test their understanding in real time. Quizzes are algorithmically coded into MasteringChemistry™ to allow students to practice the types of questions they will encounter on the ACS or other exams.

- I added a new chapter, Chapter E, "Essentials: Units, Measurement, and Problem Solving." This material, located in Appendices I and II and Chapter 2 in the first edition, was moved to the front of the book to provide a foundation for students who need some review in these areas.

- I revised Chapter 1, "Atoms," to include a more personal introduction that documents my own introduction into the world of atoms. I also moved the mole concept for atoms, covered in Chapter 2 in the first edition, into Chapter 1 in the second edition.

- I moved phase diagrams into Chapter 11, "Liquids, Solids, Intermolecular Forces, and Phase Diagrams," to immediately follow the coverage of liquids, solids, and intermolecular forces.

- The chemistry of modern materials is now covered in Chapter 12, "Crystalline Solids and Materials," which includes new topics as well as the materials content found in other parts of the book in the first edition.

- With the help of my colleagues, Thomas Greenbowe (University of Oregon), Kristin Ziebert (Oregon State University), and Michael Everest (Westmont College), I added two new categories of end-of-chapter questions designed to help students build "twenty-first-century skills." The first new category of questions, Data Interpretation and Analysis, presents real data in real-life situations and asks students to analyze that data. These in-depth exercises give students much needed practice in reading graphs, digesting tables, and making data-driven decisions. The second new category of questions, Questions for Group Work, encourages students to work with their peers in small groups. The questions can be assigned in or out of the classroom to foster collaborative learning and to allow students to work together in teams to solve problems.

- I added 37 new Key Concept Videos and 50 new Interactive Worked Examples to the media package that accompanies the book. This book now has a video library of over 150 interactive videos designed to help professors engage their students in active learning. These videos are also embedded in the eText 2.0 version of the book.
  - The Key Concept Videos are brief (3 to 5 minutes), and each one introduces a key concept from a chapter. The student does not just passively listen to the video; the video stops in the middle and poses a question to the student. The student must answer the question before the video continues. Each video also includes a follow-up question that is assignable in MasteringChemistry™.
  - The Interactive Worked Examples are similar in concept, but instead of explaining a key concept, each video walks the student through one of the in-chapter worked examples from the book. Like the Key Concept Videos, Interactive Worked Examples stop in the middle and force the student to interact by completing a step in the example. Each example also has a follow-up question that is assignable in MasteringChemistry™. The power of interactivity

to make connections in problem solving is immense. I did not quite realize this power until we started making the Interactive Worked Examples, and I saw how I could use the animations to make connections that are just not possible on the static page.

- In order to share best practices for using all of the rich print and media resources that are specific to this title with your students most effectively, professors across the country teaching with my materials curated NEW Ready-To-Go Teaching Modules for this edition. These modules provide instructors with a roadmap for teaching the toughest topics in chemistry.

- There are 13 new Conceptual Connection questions in the book. These questions make reading an active experience by asking students short questions designed to help them determine if they have understood what they are reading. All the Conceptual Connections in the book are embedded and interactive in eText 2.0 with answer-specific feedback.

- All the data in the book has been updated to reflect the most recent measurements available. Examples include Figure 7.2, "Carbon Dioxide in the Atmosphere," Figure 7.3, "Global Temperatures," and Figure 14.19, "Ozone Depletion in the Antarctic Spring."

- I revised the art program throughout to move key points out of the caption and into the art itself. Changes have been made in figures in every chapter in the book. For example, see Figure 5.6, "Hybridization," Figure 8.2, "Concentrated and Dilute Solutions," and Figure 8.3, "Preparing a 1.00 M NaCl Solution."

- I have revised several chapter-opening sections and (or) the corresponding art, including Sections E.1, 1.1, 9.1, 11.1, 12.1, and 18.1.

- In Section 7.5, "Stoichiometric Relationships: Limiting Reactant, Theoretical Yield, Percent Yield, and Reactant in Excess," you will find a new subsection ("Reactant in Excess") and a new in-chapter worked example (Example 7.8, "Reactant in Excess") that address the amount of excess reagent left over after a reaction.

- In Section 8.7, "Acid–Base Reactions," I added new content on acid–base reactions involving a weak acid and a new worked example (Example 8.12, "Writing Equations for Acid–Base Reactions Involving a Weak Acid").

- In Section 8.9, "Oxidation–Reduction Reactions," I added new content on the activity series for metals, including a new worked example (Example 8.18, "Predicting Spontaneous Redox Reactions").

- I reorganized Chapter 10, "Gases," so that kinetic molecular theory is covered earlier in order to emphasize the particulate nature of gases.

- There is a new worked example in Section 12.3, "Crystalline Solids: Unit Cells and Basic Structures" (Example 12.2, "Calculating the Packing Efficiency of a Unit Cell").

- I added a new section (Section 18.4, "Entropy Changes Associated with State Changes") to Chapter 18, "Free Energy and Thermodynamics," that includes a subsection on calculating the entropy changes associated with state changes. The section includes a new worked example (Example 18.2, "Calculating ΔS for a State Change") and new content on reversible and irreversible processes.

- Several sections and tables in Chapter 20, "Radioactivity and Nuclear Chemistry," have been modified and updated including Sections 20.3 and 20.5 and Tables 20.1 and 20.4.

- The MasteringChemistry™ data indicating which problems give students the most trouble and where they need the most assistance for all end-of-chapter problems were reviewed and taken into account in revising the problems. Over 75% of the section problems have wrong answer-specific feedback.

Acknowledgments

and Carrie Hill, who have supported me in my department while I worked on this book. I am also grateful to Mark Sargent, the provost of Westmont College, who has allowed me the time and space to work on my books. Thank you, Mark, for allowing me to pursue my gifts and my vision. You are an outstanding leader and a true friend.

I am also grateful to those who have supported me personally. First on that list is my wife, Ann. Her patience and love for me are beyond description, and without her, this book would never have been written. I am also indebted to my children, Michael, Ali, Kyle, and Kaden, whose smiling faces and love of life always inspire me. I come from a large Cuban family whose closeness and support most people would envy. Thanks to my parents, Nivaldo and Sara; my siblings, Sarita, Mary, and Jorge; my siblings-in-law, Nachy, Karen, and John; my nephews and nieces, Germain, Danny, Lisette, Sara, and Kenny. These are the people with whom I celebrate life.

I would like to thank all of the general chemistry students who have been in my classes throughout my 26 years as a professor at Westmont College. You have taught me much about teaching that is now in this book. I am especially grateful to Michael Tro who put in many hours proofreading my manuscript, working problems and quiz questions, and organizing art codes and appendices. Michael, you are an amazing kid—it is my privilege to have you work with me on this project. I am very grateful to Thomas Greenbowe, Michael Everest, and Ali Sezer who played particularly important roles in many of the new features of this edition. I am also grateful to the accuracy reviewers Christiane Barnes, Rachel Campbell, Alton Hassell, Deborah Herrington, Clifford LeMaster, and Charles McLaughlin who tirelessly checked page proofs for correctness.

Lastly, I am indebted to the many reviewers, listed on the following pages, whose ideas are imbedded throughout this book. They have corrected me, inspired me, and sharpened my thinking on how best to emphasize structure and properties while teaching chemistry. I deeply appreciate their commitment to this project.

Reviewers of the Second Edition

Jim Bann, *Wichita State University*
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Rebekah Brosky, *Florida Gulf Coast University*
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Melanie Veige, *University of Florida*
John Vincent, *University of Alabama*
Lin Zhu, *Indiana University-Purdue University Indianapolis*
Kristin Ziebart, *Oregon State University*

Focus Group Participants:

Ericka Barnes, *Southern Connecticut State University*
James Beil, *Lorain County Community College*
David Boatright, *University of West Georgia*
Jeff Bryan, *University of Wisconsin, La Crosse*
Allen Easton, *Georgia Highlands College*
Maria Korolev, *University of Florida*
Greg Peters, *University of Findlay*
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Ali Sezer, *California University of Pennsylvania*
Cathrine Southern, *DePaul University*
John Vincent, *University of Alabama*

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Keith Baessler, *Suffolk County Community College*
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Richard Bell, *Pennsylvania State University, Altoona*
Shannon Biros, *Grand Valley State University*
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Why Structure and Properties?

Dear Colleague,

In recent years, many chemistry professors, myself among them, have begun teaching their General Chemistry courses with an atoms-first approach. On the surface, this approach may seem like a mere reordering of topics, so that atomic theory and bonding theories come earlier than they do in the traditional approach. A rationale for this reordering is that students should understand the theory and framework behind the chemical "facts" they are learning. For example, in the traditional approach, students learn early that magnesium atoms tend to form ions with a charge of 2+. However, they don't understand *why* until much later (when they get to quantum theory). In an atoms-first approach, students learn quantum theory first and are therefore able to understand why magnesium atoms form ions with a charge of 2+ when they learn this fact. In this way, students see chemistry as a more coherent picture and not just a jumble of disjointed facts.

From my perspective, as an author and a teacher who teaches an atoms-first class, however, the atoms-first movement is more than just a reordering or topics. To me, the atoms-first movement is a result of the growing emphasis in chemistry courses on the two main ideas of chemistry, which are: 1) that matter is particulate, and 2) that the structure of the particles that compose matter determines its properties. In other words, the atoms-first movement is—at its core—an attempt to tell the story of chemistry in a more unified and thematic way. As a result, an atoms-first textbook must be more than a rearrangement of topics: it must tell the story of chemistry through the lens of the particulate model of matter. That is the goal I attempted to accomplish with *Chemistry: Structure and Properties*. Thanks to all of you who made the first edition the best-selling atoms-first book on the market. With this, the second edition, I continue to refine and improve on the approach taken in the first edition. My continuing hope is that students will recognize the power and beauty of the simple ideas that lie at the core of chemistry, and that they learn to apply them to see and understand the world around them in new ways.

> "To me, the atoms-first movement is a result of the growing emphasis in chemistry courses on the two main ideas of chemistry: 1) that matter is particulate, and 2) that the structure of the particles that compose matter determines its properties."

N. J. Tro

Structure and properties: A unified theme through the entire book

Section 1.1 – Introduction to the theme

1.1 A Particulate View of the World: Structure Determines Properties

As I sat in the "omnimover" and listened to the narrator's voice telling me that I was shrinking down to the size of an atom, I grew apprehensive but curious. Just minutes before, while waiting in line, I witnessed what appeared to be full-sized humans entering a microscope and emerging from the other end many times smaller. I was 7 years old and I was about to ride *Adventure Through Inner Space*, a Disneyland ride

Section 3.1 – How the structure of Al atoms determines the density of aluminum metal

The densities of elements and the radii of their atoms are examples of *periodic properties*. A **periodic property** is one that is generally predictable based on an element's position within the periodic table. In this chapter, we examine several periodic properties of elements, including atomic radius, ionization energy, and electron affinity. As we do, we will see that these properties—as well as the overall arrangement of the periodic table—are explained by quantum-mechanical theory, which we first examined in Chapter 2. *Quantum-mechanical theory explains the electronic structure of atoms—this in turn determines the properties of those atoms*.

Section 3.5 – How atomic structure determines the properties of the elements

3.5 Electron Configurations and Elemental Properties

As we discussed in Section 3.4, *the chemical properties of elements are largely determined by the number of valence electrons the elements contain*. The properties of elements are periodic because the number of valence electrons is periodic. Mendeleev grouped elements into families (or columns) based on observations about their properties. We now know that elements in a family have the same number of valence electrons. In other words, elements in a family have similar properties because they have the same number of valence electrons.

Section 14.2 – How reaction rates depend of the structure of the reacting particles

14.2 Rates of Reaction and the Particulate Nature of Matter

We have seen throughout this book that matter is composed of particles (atoms, ions, and molecules). The simplest way to begin to understand the factors that influence a reaction rate is to think of a chemical reaction as the result of a collision between these particles. This is the basis of *the collision model*, which we cover in more detail in Section 14.6. For example, consider the following simple generic reaction occurring in the gaseous state:

$$A\!-\!A + B \longrightarrow A\!-\!B + A$$

According to the collision model, the reaction occurs as a result of a collision between A-A particles and B particles.

CHAPTER

3 Periodic Properties of the Elements

GREAT ADVANCES IN SCIENCE occur not only when a scientist sees something new, but also when a scientist sees something everyone else has seen in a new way. That is what happened in 1869 when Dmitri Mendeleev, a Russian chemistry professor, saw a pattern in the properties of elements. Mendeleev's insight led to the development of the periodic table. Recall from Chapter 1 that theories explain the underlying reasons for observations. If we think of Mendeleev's periodic table as a compact way to summarize a large number of observations, then quantum mechanics is the theory that explains the underlying reasons. Quantum mechanics explains how electrons are arranged in an element's atoms, which in turn determines the element's properties. Because the periodic table is organized according to those properties, quantum mechanics elegantly accounts for Mendeleev's periodic table. In this chapter, we see a continuation of this book's theme—the properties of matter (in this case, the elements in the periodic table) are explained by the properties of the particles that compose them (in this case, atoms and their electrons).

> "It is the function of science to discover the existence of a general reign of order in nature and to find the causes governing this order."
>
> —Dmitri Mendeleev (1834–1907)

3.1 Aluminum: Low-Density Atoms Result in Low-Density Metal

Look out the window of almost any airplane and you will see the large sheets of aluminum that compose the aircraft's wing. In fact, the majority of the plane is most likely made out of aluminum. Aluminum has several properties that make it suitable for airplane construction, but among the most important is its low density. Aluminum has a density of only 2.70 g/cm^3. For comparison, iron's density is 7.86 g/cm^3, and platinum's density is 21.4 g/cm^3. Why is the density of aluminum metal so low?

The density of aluminum metal is low because the density of an aluminum atom is low. Few metal atoms have a lower mass-to-volume ratio than aluminum, and those that do can't be used in airplanes for other reasons (such as their high chemical reactivity). Although the *arrangements* of atoms in a solid must also be considered when evaluating the density of the solid, the mass-to-volume ratio of the composite atoms

Section 16.4 – How the structure of an acid determines its strength

16.4 Acid Strength and Molecular Structure

We have learned that a Brønsted–Lowry acid is a proton [H$^+$] donor. Now we explore why some hydrogen-containing molecules act as proton donors while others do not. In other words, we explore *how the structure of a molecule affects its acidity*. Why is H$_2$S acidic while CH$_4$ is not? Or why is HF a weak acid while HCl is a strong acid? We divide our discussion about these issues into two categories: binary acids (those containing hydrogen and only one other element) and oxyacids (those containing hydrogen bonded to an oxygen atom that is bonded to another element).

Section 18.4 – How the structure of a molecule determines its entropy

18.7 Entropy Changes in Chemical Reactions: Calculating ΔS°_{rxn}

We now turn our attention to predicting and quantifying entropy and entropy changes in a sample of matter. As we examine this topic, we again encounter the theme of this text: *Structure determines properties*. In this case, the property we are interested in is entropy. In this section we see how the structure of the particles that compose a particular sample of matter determines the entropy that the sample possesses at a given temperature and pressure.

Build students' 21st-century skills to set them up for success.

Data Interpretation and Analysis Questions at the end of each chapter allow students to use real data to develop 21st-century problem-solving skills. These in-depth exercises give students practice reading graphs, digesting tables, and making data-driven decisions. Find these questions at the end of every chapter as well as in the item library of MasteringChemistry™.

Questions for Group Work allow students to collaborate and apply problem-solving skills on questions covering multiple concepts. The questions can be used in or out of the classroom, and the goal is to foster collaborative learning and encourage students to work together as a team to solve problems. All questions for group work are pre-loaded into Learning Catalytics™ for ease of assignment.

DATA INTERPRETATION AND ANALYSIS

108. In April 2014, in an effort to save money, officials in Flint, Michigan, changed their water source from Lake Huron to the Flint River. In subsequent months, residents began complaining about the quality of the water, and General Motors (which has an engine plant in Flint) stopped using the water in manufacturing because of its corrosiveness. That corrosiveness was causing problems that would soon fuel a national outrage. The water flowed through pipes to taps in homes, and as it flowed through the pipes, many of which contained lead, the corrosive water became contaminated with lead. Routine monitoring of the tap water in select homes did not reveal the magnitude of the problem because samples were collected only after preflushing the tap (allowing the water to run for a time).

A Virginia Tech professor and his students began an independent test of the water coming from Flint's taps and got much different results by analyzing the water that initially came from the taps (first draw). Their results—which showed elevated lead levels in the tap water—ultimately forced officials to switch back to the Lake Huron water source.

The following table shows a set of data collected by the Virginia Tech team. The lead levels in water are expressed in units of parts per billion (ppb). 1 ppb = 1 g Pb/10^9 parts solution. Examine the data and answer the questions that follow.

a. Determine the average value of lead for first draw, 45-second flush, and 2-minute flush (round to three significant figures).
b. Do the data support the idea that running the tap water before taking a sample made the lead levels in the water appear lower? Why might this occur?
c. The EPA requires water providers to monitor drinking water at customer taps. If lead concentrations exceed 15 ppm in 10% or more of the taps sampled, the water provider must notify the customer and take steps to control the corrosiveness of the water. If the water provider in Flint had used first-draw samples to monitor lead levels, would they have been required to take action by EPA requirements? If the Flint water provider used 2-min flush samples, would they have had to take action? Which drawing technique do you think more closely mimics the way residents actually use their water?
d. Using the highest value of lead from the first-draw data set, and assuming a resident drinks 2 L of water per day, calculate the mass of lead that the resident would consume over the course of one year. (Assume the water has a density of 1.0 g/mL.)

Lead Levels in Samples of Flint Tap Water

Sample #	Lead Level 1st draw (ppb)	Lead Level 45 sec flush (ppb)	Lead Level 2 min flush (ppb)
1	0.344	0.226	0.145
2	8.133	10.77	2.761
3	1.111	0.11	0.123
4	8.007	7.446	3.384
5	1.951	0.048	0.035
6	7.2	1.4	0.2
7	40.63	9.726	6.132
8	1.1	2.5	0.1
9	10.6	1.038	1.294
10	6.2	4.2	2.3
11	4.358	0.822	0.147
12	24.37	8.796	4.347
13	6.609	5.752	1.433
14	4.062	1.099	1.085
15	29.59	3.258	1.843

Source: FlintWaterStudy.org (2015) "Lead Results from Tap Water Sampling in Flint, Michigan, during the Flint Water Crisis"

QUESTIONS FOR GROUP WORK   *Active Classroom Learning*

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

136. In a complete sentence, describe the relationship between shielding and penetration.

137. Play a game to memorize the order in which orbitals fill. Have each group member in turn state the name of the next orbital to fill and the maximum number of electrons it can hold (for example, "1s two," "2s two," "2p six"). If a member gets stuck, other group members can help, consulting Figure 3.8 and the accompanying text summary if necessary. However, when a member gets stuck, the next player starts back at "1s two." Keep going until each group member can list all the orbitals in order up to "6s two."

138. Sketch a periodic table (without element symbols). Include the correct number of rows and columns in the s, p, d, and f blocks. Shade in the squares for elements that have irregular electron configurations.

139. In complete sentences, explain: a) why Se^{2-} and Br^- are about the same size; b) why Br^- is slightly smaller than Se^{2-}; and c) which singly charged cation you would expect to be approximately the same size as Se^{2-} and Br^- and why.

140. Have each member of your group sketch a periodic table indicating a periodic trend (atomic size, first ionization energy, metallic character, etc.). Have each member present his or her table to the rest of the group and explain the trend based on concepts such as orbital size or effective nuclear charge.

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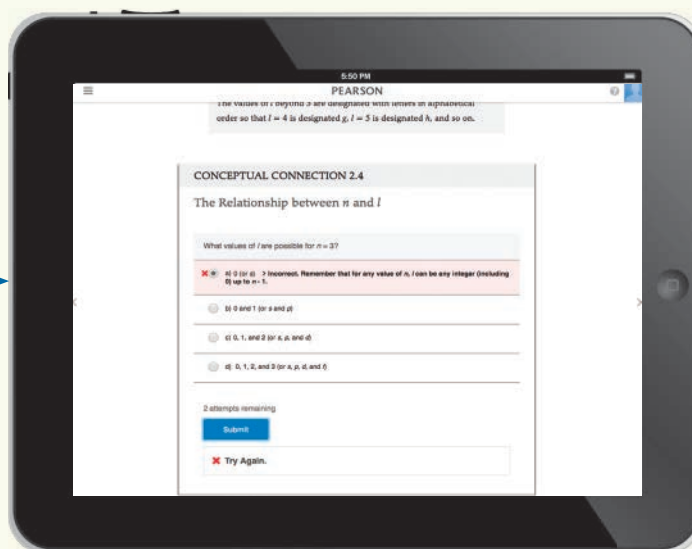
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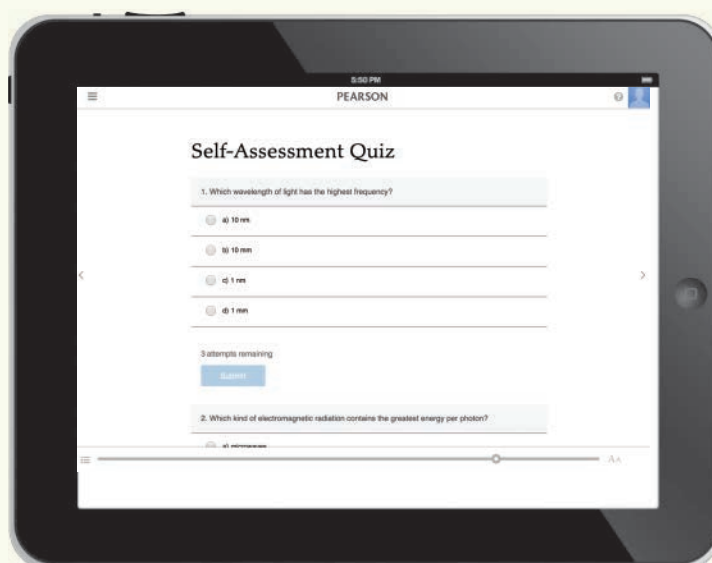
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Unit Cells: Simple Cubic, Body-Centered Cubic, and Face-Centered Cubic

Simple Cubic Unit Cell

$\frac{1}{8}$ atom at each of 8 corners
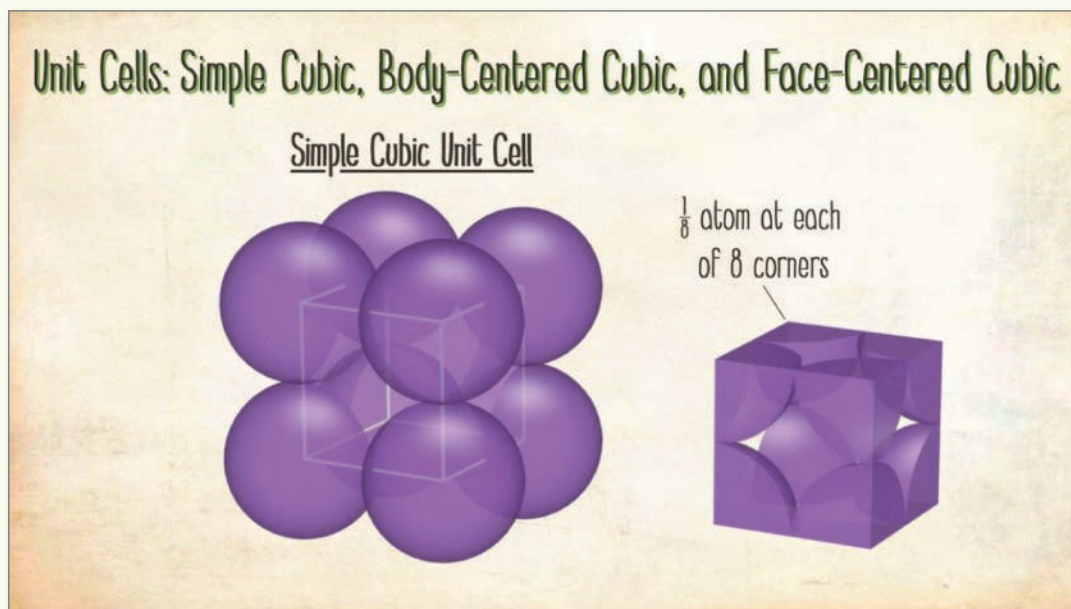
Key Concept Videos combine artwork from the textbook with 2D and 3D animations to create a dynamic on-screen viewing and learning experience. These short videos include narration and brief live-action clips of author Nivaldo Tro explaining the key concepts of each chapter of *Chemistry: Structure and Properties*. All Key Concept Videos are embedded and interactive in eText and are assignable activities MasteringChemistry™.

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Density

Given: $T(°C) = 125\ °C$
$P = 755$ mmHg

Find: d

Conceptual Plan

$P, T, \mathcal{M} \rightarrow d$

$d = \dfrac{P\mathcal{M}}{RT}$

molar mass $N_2 = 28.02$ g/mol

$T(K) = 125 + 273 = 398$ K

$P = 755\ \text{mmHg} \times \dfrac{1\ \text{atm}}{760\ \text{mmHg}} = 0.99342$ atm

$d = \dfrac{P\mathcal{M}}{RT}$ $\qquad R = 0.08206\ \dfrac{\text{L} \cdot \text{atm}}{\text{mol} \cdot \text{K}}$

What is the density of the gas?

a) 0.852 g/L   b) 648 g/L   c) 2.71 g/L

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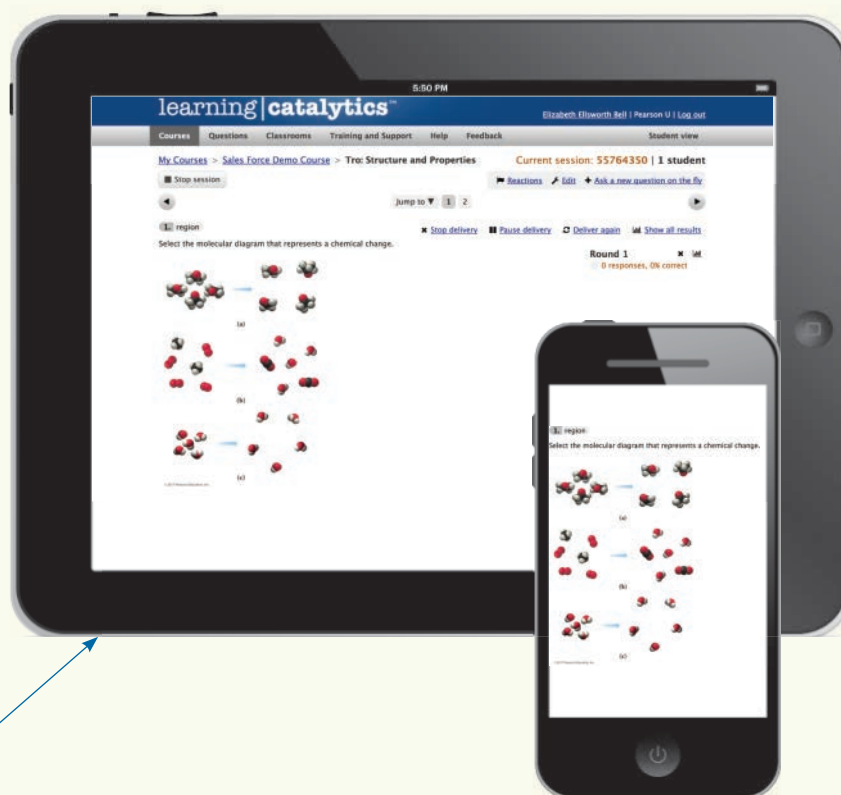
The Chemistry Primer and Dynamic Study modules encourage students to come to class prepared.
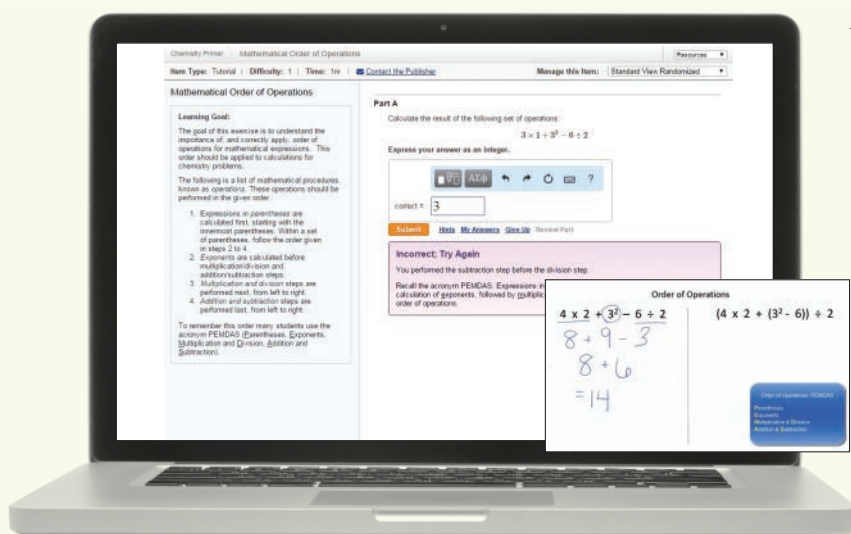
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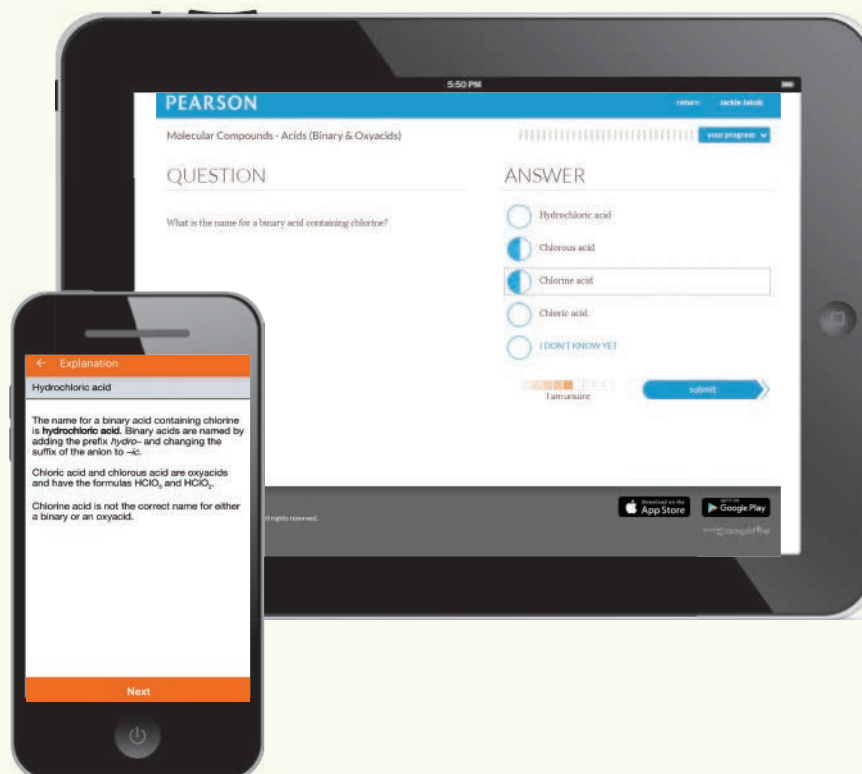
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Tro | **Chemistry: Structure and Properties**

The $125 million Mars Climate Orbiter *was lost in the Martian atmosphere in 1999 because of a unit mix-up.*

E

Essentials: Units, Measurement, and Problem Solving

Q UANTIFICATION IS THE ASSIGNMENT of a number to some property of a substance or thing. For example, when we say that a pencil is 16 cm long, we assign a number to its length—we *quantify* how long it is. Quantification is among the most powerful tools in science. It requires the use of units, agreed-upon quantities by which properties are quantified. We used the unit *centimeter* in quantifying the length of the pencil. People all over the world agree about the length of a centimeter; therefore, we can use that standard to specify the length of any object. In this chapter, we look closely at quantification and problem solving. Science would be much less powerful without these tools.

> **"The eternal mystery of the world is its comprehensibility."**
>
> **—Albert Einstein (1879–1955)**

E.1 The Metric Mix-up: A $125 Million Unit Error

On December 11, 1998, NASA launched the Mars Climate Orbiter, which was to become the first weather satellite for a planet other than Earth. The Orbiter's mission was to monitor the Martian atmosphere and to serve as a communications relay for the Mars Polar Lander, a probe that was to follow the Orbiter and land on the planet's surface three weeks later. Unfortunately, the mission ended in disaster. A unit mix-up caused the Orbiter to enter the Martian atmosphere at an altitude that was too low. Instead of settling into a stable orbit, the Orbiter likely disintegrated. The cost of the failed mission was estimated at $125 million.

There were hints of trouble several times during the Orbiter's nine-month cruise from Earth to Mars. Several adjustments made to its trajectory seemed to alter the course of the Orbiter less than expected. As the Orbiter neared the planet on September 8, 1999, discrepancies emerged about its trajectory. Some of the data indicated that the satellite was approaching Mars on a path that would place it too low in the Martian atmosphere. On September 15, engineers made the final adjustments that were supposed to put the Orbiter 226 km above the planet's surface. About a week later, as the Orbiter entered the atmosphere, communications were lost. The Orbiter had disappeared.

Later investigations showed that the Orbiter had come within 57 km of the planet surface (**Figure E.1 ▶** on the next page), an altitude that was too low. If a spacecraft enters a planet's atmosphere too close to the planet's surface, friction can cause the spacecraft to burn up. The on-board computers that
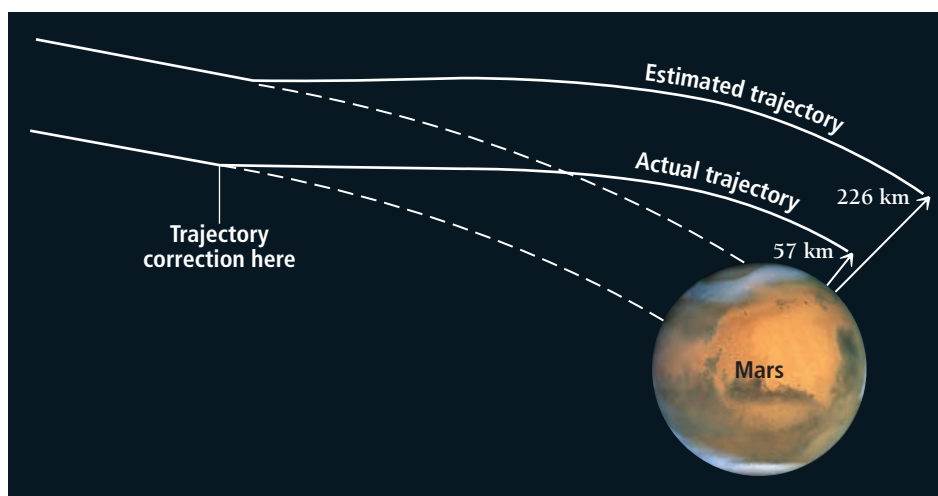
controlled the trajectory corrections were programmed in metric units (newton · second), but the ground engineers entered the trajectory corrections in English units (pound · second). The English and the metric units are not equivalent (1 pound · second = 4.45 newton · second). The corrections that the ground engineers entered were 4.45 times too small and did not alter the trajectory enough to keep the Orbiter at a sufficiently high altitude. In chemistry as in space exploration, **units** are critical. If we get them wrong, the consequences can be disastrous.

E.2   The Units of Measurement

The abbreviation *SI* comes from the French, *Système International d'Unités.*

The two most common unit systems are the **metric system**, used in most of the world, and the **English system**, used in the United States. Scientists use the **International System of Units (SI)**, which is based on the metric system.

The Standard Units

Table E.1 shows the standard SI base units. For now, we focus on the first four of these units: the *meter*, the standard unit of length; the *kilogram*, the standard unit of mass; the *second*, the standard unit of time; and the *kelvin*, the standard unit of temperature.

TABLE E.1   SI Base Units

Quantity	Unit	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Temperature	Kelvin	K
Amount of substance	Mole	mol
Electric current	Ampere	A
Luminous intensity	Candela	cd

The Meter: A Measure of Length

The velocity of light in a vacuum is 3.00×10^8 m/s.

Scientific notation is reviewed in Appendix IA.

A **meter (m)** is slightly longer than a yard (1 yard is 36 inches while 1 meter is 39.37 inches). Thus, a 100-yard football field measures only 91.4 meters. The meter was originally defined as 1/10,000,000 of the distance from the equator to the North Pole (through Paris). The International Bureau of Weights and Measures now defines it more precisely as the distance light travels through a vacuum in a designated period of time, 1/299,792,458 second. Scientists commonly deal with a wide range of lengths and distances. The separation between the sun and the closest star (Proxima Centauri) is about 3.8×10^{16} m, while many chemical bonds measure about 1.5×10^{-10} m.

The Kilogram: A Measure of Mass

The **kilogram (kg)**, defined as the mass of a metal cylinder kept at the International Bureau of Weights and Measures at Sèvres, France, is a measure of *mass*, a quantity different from *weight*. The **mass** of an object is a measure of the quantity of matter within it, while the weight of an object is a measure of the *gravitational pull* on its matter. If you could weigh yourself on the moon, for example, its weaker gravity would pull on you with less force than does Earth's gravity, resulting in a lower weight. A 130-pound (lb) person on Earth would weigh only 21.5 lb on the moon. However, the person's mass—the quantity of matter in his or her body—remains the same on every planet. One kilogram of mass is the equivalent of 2.205 lb of weight on Earth, so if we express mass in kilograms, a 130-lb person has a mass of approximately 59 kg and this book has a mass of about 2.5 kg. Another common unit of mass is the gram (g). One gram is 1/1000 kg. A nickel (5¢) has a mass of about 5 g.

The Second: A Measure of Time

If you live in the United States, the **second (s)** is perhaps the most familiar SI unit. The International Bureau of Weights and Measures originally defined the second in terms of the day and the year, but a second is now defined more precisely as the duration of 9,192,631,770 periods of the radiation emitted from a certain transition in a cesium-133 atom. (We discuss transitions and the emission of radiation by atoms in Chapter 2.) Scientists measure time on a large range of scales. The human heart beats about once every second; the age of the universe is estimated to be about 4.32×10^{17} s (13.7 billion years); and some molecular bonds break or form in time periods as short as 1×10^{-15} s.

▲ A nickel (5 cents) weighs about 5 grams.

The Kelvin: A Measure of Temperature

The **kelvin (K)** is the SI unit of **temperature**. The temperature of a sample of matter is a measure of the amount of average kinetic energy—the energy due to motion—of the atoms or molecules that compose the matter. The molecules in a *hot* glass of water are, on average, moving faster than the molecules in a *cold* glass of water. Temperature is a measure of this molecular motion.

Temperature also determines the direction of thermal energy transfer, or what we commonly call *heat*. Thermal energy transfers from hot objects to cold ones. For example, when you touch another person's warm hand (and yours is cold), thermal energy flows *from that person's hand to yours*, making your hand feel warmer. However, if you touch an ice cube, thermal energy flows *out of your hand* to the ice, cooling your hand (and possibly melting some of the ice cube).

Figure E.2 ▶ shows the three temperature scales. The most common in the United States is the **Fahrenheit scale (°F)**, shown on the left. On the Fahrenheit scale, water freezes at 32 °F and boils at 212 °F at sea level. Room temperature is approximately 72 °F. The Fahrenheit scale was originally determined by assigning 0 °F to the freezing point of a concentrated saltwater solution and 96 °F to normal body temperature. Normal body temperature was later measured more accurately to be 98.6 °F.

Scientists and citizens of most countries other than the United States typically use the **Celsius (°C) scale**, shown in the middle of Figure E.2. On this scale, pure water freezes at 0 °C and boils at 100 °C (at sea level). Room temperature is approximately 22 °C. The Fahrenheit scale and the Celsius scale differ both in the size of their respective degrees and the temperature each designates as "zero." Both the Fahrenheit and Celsius scales allow for negative temperatures.

The SI unit for temperature, as we have seen, is the kelvin, shown on the right in Figure E.2. The **Kelvin scale** (sometimes also called the *absolute scale)* avoids negative temperatures by assigning 0 K to the coldest temperature possible, absolute zero. Absolute zero (−273 °C or −459 °F) is the temperature at which molecular motion virtually stops. Lower temperatures do not exist. The size of the kelvin is

Temperature Scales

212 °F	100 °C	373 K	**Water boils**
180 Fahrenheit degrees	100 Celsius degrees	100 kelvins	
32 °F	0.00 °C	273 K	**Water freezes**
−459 °F	−273 °C	0.00 K	**Absolute zero**
Fahrenheit	Celsius	Kelvin	

▶ **FIGURE E.2 Comparison of the Fahrenheit, Celsius, and Kelvin Temperature Scales** The Fahrenheit degree is five-ninths the size of the Celsius degree and the kelvin. The zero point of the Kelvin scale is absolute zero (the lowest possible temperature), whereas the zero point of the Celsius scale is the freezing point of water.
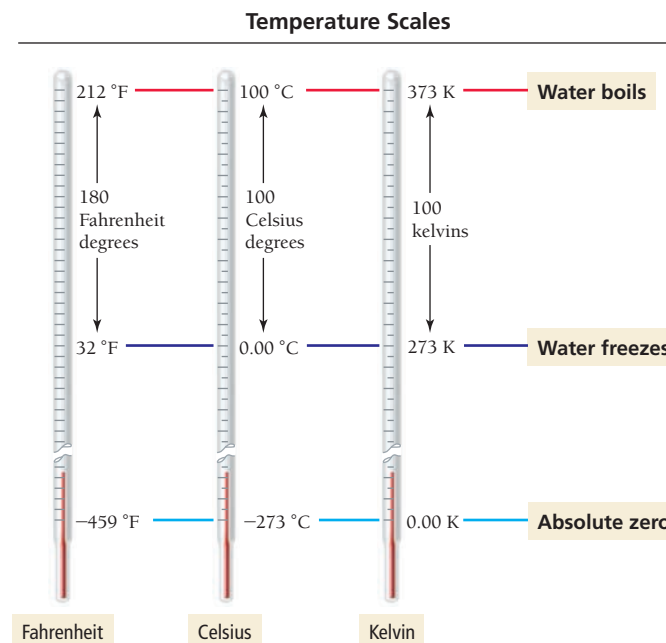
The Celsius Temperature Scale

0 °C – Water freezes

10 °C – Brisk fall day

22 °C – Room temperature

45 °C – Summer day in Death Valley

Note that we refer to Kelvin temperatures in kelvins (*not* "degrees Kelvin") or K (*not* °K).

identical to that of the Celsius degree—the only difference is the temperature that each designates as zero. You can convert between the temperature scales with these formulas:

$$°C = \frac{(°F - 32)}{1.8}$$

$$K = °C + 273.15$$

EXAMPLE **E.1**

Converting between Temperature Scales

A sick child has a temperature of 40.00 °C. What is the child's temperature in **(a)** K and **(b)** °F?

SOLUTION

(a) Begin by finding the equation that relates the quantity that is given (°C) and the quantity you are trying to find (K).	$K = °C + 273.15$
Since this equation gives the temperature in K directly, substitute in the correct value for the temperature in °C and calculate the answer.	$K = °C + 273.15$ $K = 40.00 + 273.15 = 313.15 \text{ K}$
(b) To convert from °C to °F, find the equation that relates these two quantities.	$°C = \frac{(°F - 32)}{1.8}$
Since this equation expresses °C in terms of °F, solve the equation for °F.	$°C = \frac{(°F - 32)}{1.8}$ $1.8(°C) = (°F - 32)$ $°F = 1.8\,(°C) + 32$
Now substitute °C into the equation and calculate the answer. *Note: The number of digits reported in this answer follows significant figure conventions, covered later in this section.*	$°F = 1.8\,(°C) + 32$ $°F = 1.8\,(40.00\,°C) + 32 = 104.00\,°F$

FOR PRACTICE E.1

Gallium is a solid metal at room temperature but will melt to a liquid in your hand. The melting point of gallium is 85.6 °F. What is this temperature on (a) the Celsius scale and (b) the Kelvin scale?

Answers to For Practice and For More Practice problems are in Appendix IV.

Prefix Multipliers

Scientific notation (see Appendix IA) allows us to express very large or very small quantities in a compact manner by using exponents. For example, we write the diameter of a hydrogen atom as 1.06×10^{-10} m. The International System of Units uses the **prefix multipliers** shown in Table E.2 with the standard units.

These multipliers change the value of the unit by powers of 10 (just like an exponent does in scientific notation). For example, the kilometer has the prefix "kilo" meaning 1000 or 10^3. Therefore,

$$1 \text{ kilometer} = 1000 \text{ meters} = 10^3 \text{ meters}$$

TABLE E.2 SI Prefix Multipliers

Prefix	Symbol	Multiplier	
exa	E	1,000,000,000,000,000,000	(10^{18})
peta	P	1,000,000,000,000,000	(10^{15})
tera	T	1,000,000,000,000	(10^{12})
giga	G	1,000,000,000	(10^{9})
mega	M	1,000,000	(10^{6})
kilo	k	1000	(10^{3})
deci	d	0.1	(10^{-1})
centi	c	0.01	(10^{-2})
milli	m	0.001	(10^{-3})
micro	μ	0.000001	(10^{-6})
nano	n	0.000000001	(10^{-9})
pico	p	0.000000000001	(10^{-12})
femto	f	0.000000000000001	(10^{-15})
atto	a	0.000000000000000001	(10^{-18})

Similarly, the millimeter has the prefix "milli," meaning 0.001 or 10^{-3}.

$$1 \text{ millimeter} = 0.001 \text{ meters} = 10^{-3} \text{ meters}$$

When we report a measurement, we choose a prefix multiplier close to the size of the quantity we are measuring. For example, to state the diameter of a hydrogen atom, which is 1.06×10^{-10} m, we use picometers (106 pm) or nanometers (0.106 nm) rather than micrometers or millimeters. We choose the prefix multiplier that is most convenient for a particular number.

The eText 2.0 icon indicates that this feature is embedded and interactive in the eText.

E.1

Cc

Conceptual Connection

PEARSON
eText 2.0

Prefix Multipliers

What prefix multiplier is appropriate for reporting a measurement of 5.57×10^{-5} m?
Note: Answers to Conceptual Connections can be found at the end of each chapter.

Units of Volume

Many scientific measurements require combinations of units. For example, velocities are often reported in units such as km/s, and densities are often reported in units of g/cm^3. Both of these units are **derived units**, combinations of other units. An important SI-derived unit for chemistry is the m^3, used to report measurements of volume.

Volume is a measure of space. Any unit of length, when cubed (raised to the third power), becomes a unit of volume. The cubic meter (m^3), cubic centimeter (cm^3), and cubic millimeter (mm^3) are all

Relationship between Length and Volume

10 cm

1 cm

A 10-cm cube contains 1000 1-cm cubes.
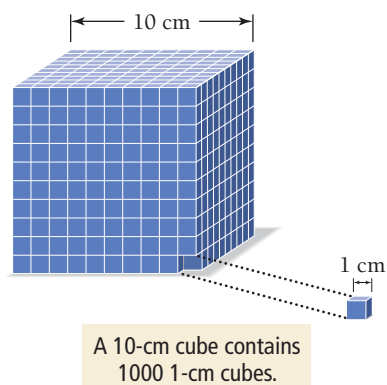
▲ **FIGURE E.3 The Relationship between Length and Volume**

TABLE E.3 Common Units for Volume and Their Equivalents

1 liter (L) = 1000 mL = 1000 cm³
1 liter (L) = 1.057 quarts (qt)
1 U.S. gallon (gal) = 3.785 liters (L)

units of volume. The cubic nature of volume is not always intuitive, and studies have shown that our brains are not naturally wired to think abstractly, which we need to do in order to think about volume. For example, consider this question: How many small cubes measuring 1 cm on each side are required to construct a large cube measuring 10 cm (or 1 dm) on a side?

The answer to this question, as we can see by carefully examining the unit cube in **Figure E.3** ◀, is 1000 small cubes. When we go from a linear, one-dimensional distance to a three-dimensional volume, we must raise both the linear dimension *and* its unit to the third power (not just multiply by 3). The volume of a cube is equal to the length of its edge cubed:

$$\text{volume of cube} = (\text{edge length})^3$$

A cube with a 10-cm edge length has a volume of $(10 \text{ cm})^3$ or 1000 cm^3, and a cube with a 100-cm edge length has a volume of $(100 \text{ cm})^3 = 1{,}000{,}000 \text{ cm}^3$. Other common units of volume in chemistry are the **liter (L)** and the **milliliter (mL)**. One milliliter (10^{-3} L) is equal to 1 cm^3. A gallon of gasoline contains 3.785 L. Table E.3 lists some common units for volume and their equivalents.

E.3 ## The Reliability of a Measurement

The reliability of a measurement depends on the instrument used to make the measurement. For example, a bathroom scale can reliably differentiate between 65 lb and 75 lb but probably can't differentiate between 1.65 and 1.75 lb. A more precise scale, such as the one a butcher uses to weigh meat, can differentiate between 1.65 and 1.75 lb. The butcher shop scale is more precise than the bathroom scale. We must consider the reliability of measurements when reporting and manipulating them.

Reporting Measurements to Reflect Certainty

Scientists normally report measured quantities so that the number of reported digits reflects the certainty in the measurement: more digits, more certainty; fewer digits, less certainty.

For example, cosmologists report the age of the universe as 13.7 billion years. Measured values like this are usually written so that the uncertainty is in the last reported digit. (We assume the uncertainty to be ± 1 in the last digit unless otherwise indicated.) By reporting the age of the universe as 13.7 billion years, cosmologists mean that the uncertainty in the measurement is ± 0.1 billion years (or ± 100 million years). If the measurement was less certain, then the age would be reported differently. For example, reporting the age as 14 billion years would indicate that the uncertainty is ± 1 billion years. In general,

> **Scientific measurements are reported so that every digit is certain except the last, which is estimated.**

Consider the following reported number:

$$5.213$$

certain   estimated

The first three digits are certain; the last digit is estimated.

The number of digits reported in a measurement depends on the measuring device. Consider weighing a sample on two different balances (**Figure E.4** ▶). These two balances have different levels of precision. The balance shown on top is accurate to the tenths place, so the uncertainty is ± 0.1 and the measurement should be reported as 10.5. The bottom balance is more precise, measuring to the ten-thousandths place, so the uncertainty is ± 0.0001 and the measurement should be reported as 10.4977 g. Many measuring instruments—such as laboratory glassware—are not digital. The measurement on these kinds of instruments must also be reported to reflect the instrument's precision. The usual procedure is to divide the space between the finest markings into ten and make that estimation the last digit reported. Example E.2 demonstrates this procedure.

Estimation in Weighing

EXAMPLE **E.2**

Reporting the Correct Number of Digits

The graduated cylinder shown here has markings every 0.1 mL. Report the volume (which is read at the bottom of the meniscus) to the correct number of digits. (*Note*: The meniscus is the crescent-shaped surface at the top of a column of liquid.)
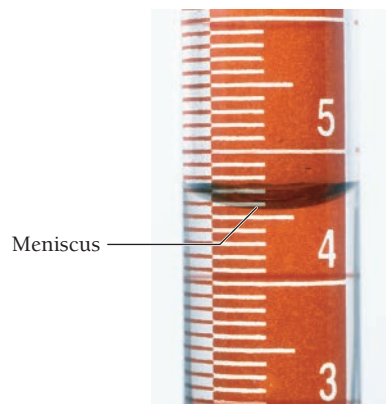
Meniscus

SOLUTION

Since the bottom of the meniscus is between the 4.5 and 4.6 mL markings, mentally divide the space between the markings into 10 equal spaces and estimate the next digit. In this case, the result is 4.57 mL.

What if you estimated a little differently and wrote 4.56 mL? In general, a one-unit difference in the last digit is acceptable because the last digit is estimated and different people might estimate it slightly differently. However, if you wrote 4.63 mL, you would have misreported the measurement.
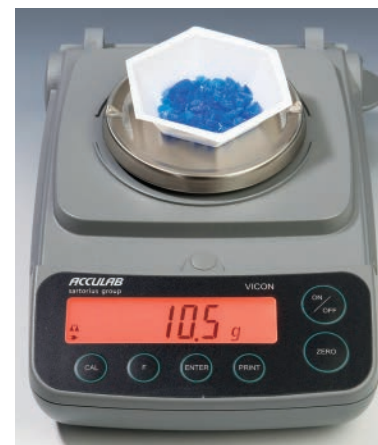
FOR PRACTICE E.2

Record the temperature on this thermometer to the correct number of digits.

(a)

Report as 10.5 g

(b)

Report as 10.4977 g

▲ **FIGURE E.4 Precision in Weighing.** **(a)** This balance is precise to the tenths place. **(b)** This balance is precise to the ten-thousandths place.

Precision and Accuracy

Scientists often repeat measurements several times to increase their confidence in the result. We can distinguish between two different kinds of certainty—called accuracy and precision—associated with such measurements. **Accuracy** refers to how close the measured value is to the actual value. **Precision** refers to how close a series of measurements are to one another or how reproducible they are. A series of measurements can be precise (close to one another in value and reproducible) but not accurate (not close to the true value). Consider the results of three students who repeatedly weighed a lead block known to have a true mass of 10.00 g tabulated below and displayed in **Figure E.5** ▶ on the next page.

	Student A	Student B	Student C
Trial 1	10.49 g	9.78 g	10.03 g
Trial 2	9.79 g	9.82 g	9.99 g
Trial 3	9.92 g	9.75 g	10.03 g
Trial 4	10.31 g	9.80 g	9.98 g
Average	**10.13 g**	**9.79 g**	**10.01 g**