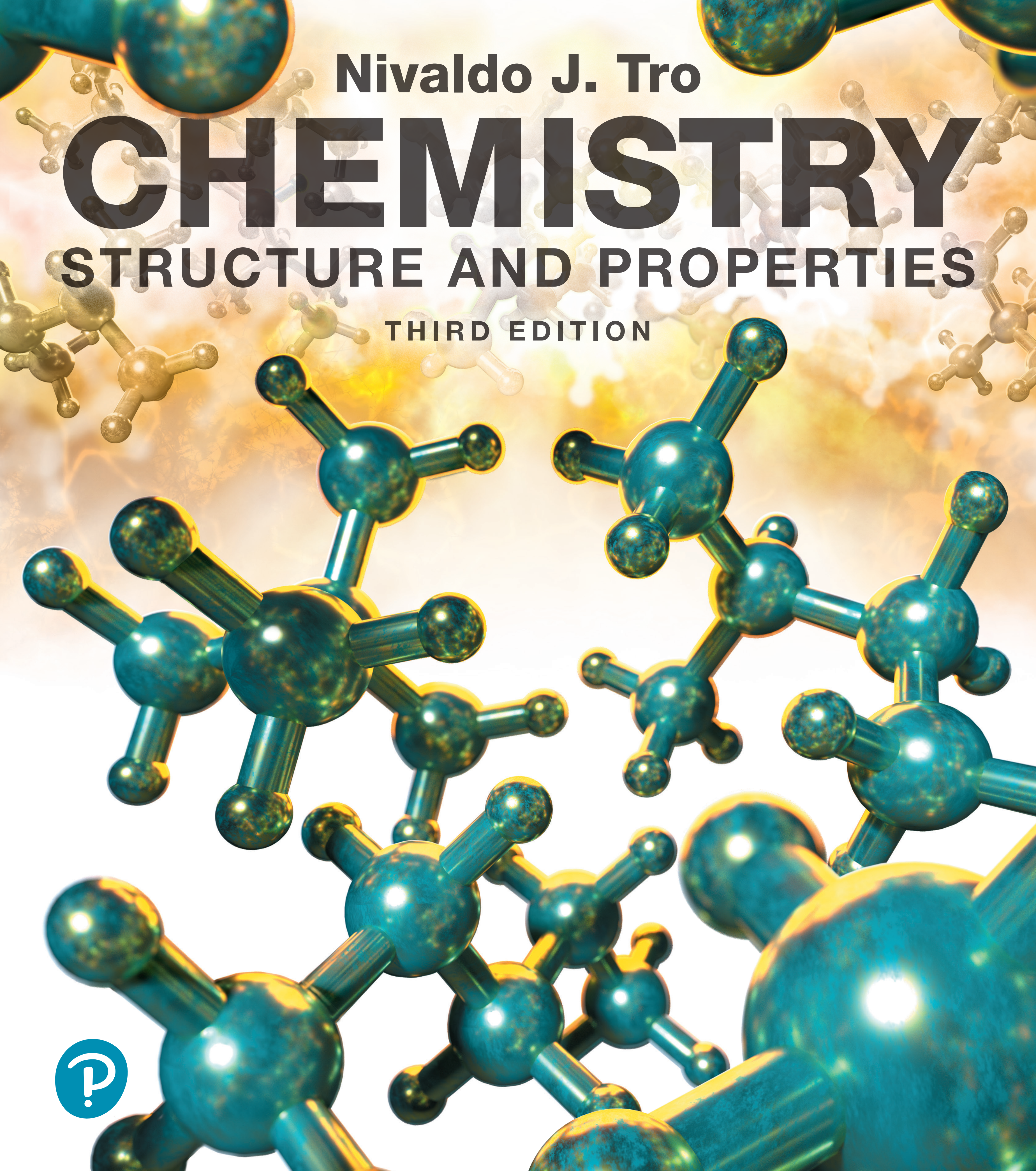
Nivaldo J. Tro

CHEMISTRY

STRUCTURE AND PROPERTIES

THIRD EDITION



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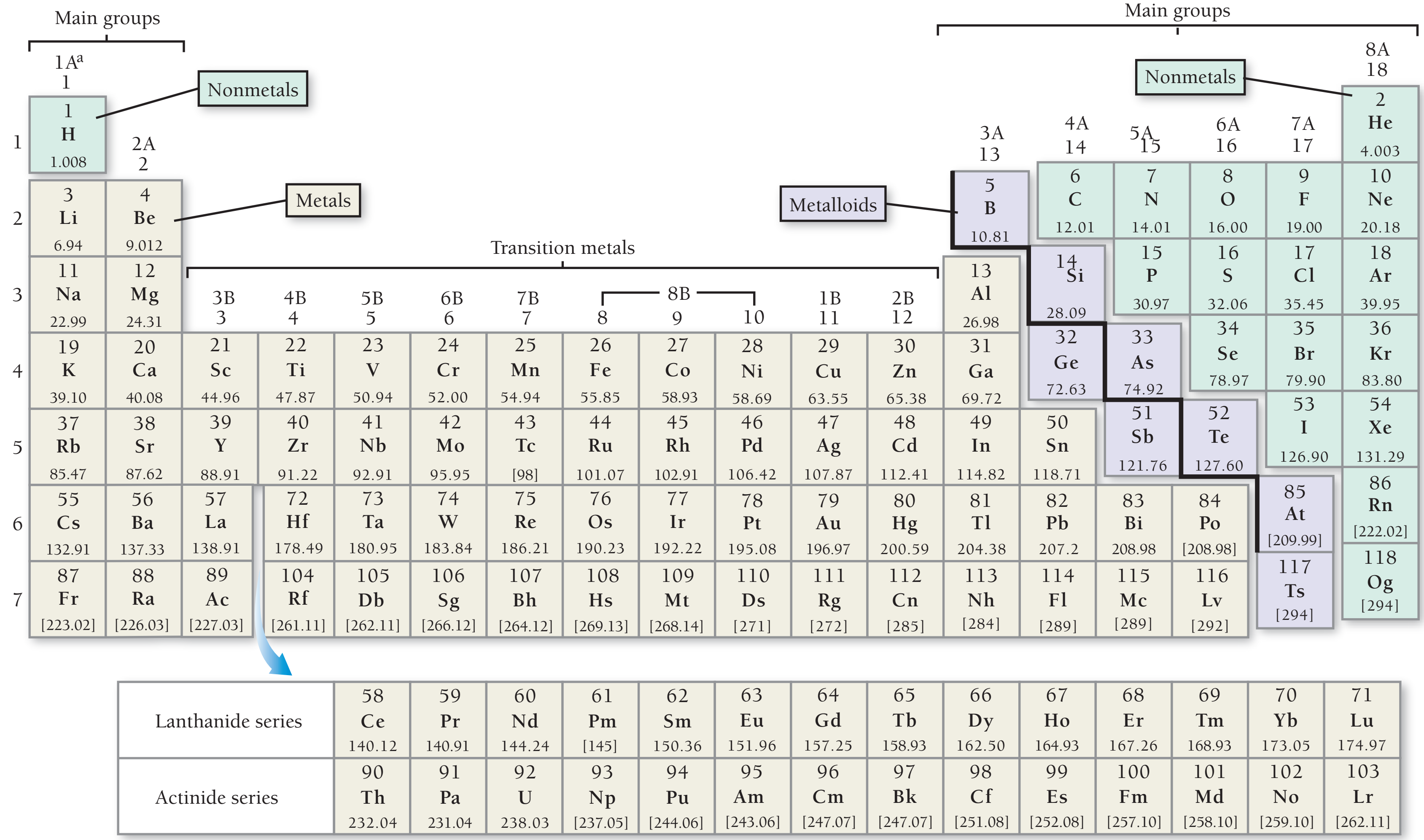

Main groups

Transition metals

Nonmetals

Metals

Metalloids

	1A[a] 1	2A 2	3B 3	4B 4	5B 5	6B 6	7B 7	8B 8	9	10	1B 11	2B 12	3A 13	4A 14	5A 15	6A 16	7A 17	8A 18
1	1 **H** 1.008																	2 **He** 4.003
2	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
3	11 **Na** 22.99	12 **Mg** 24.31											13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.06	17 **Cl** 35.45	18 **Ar** 39.95
4	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
5	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
6	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]
7	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]

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

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Nivaldo J. Tro

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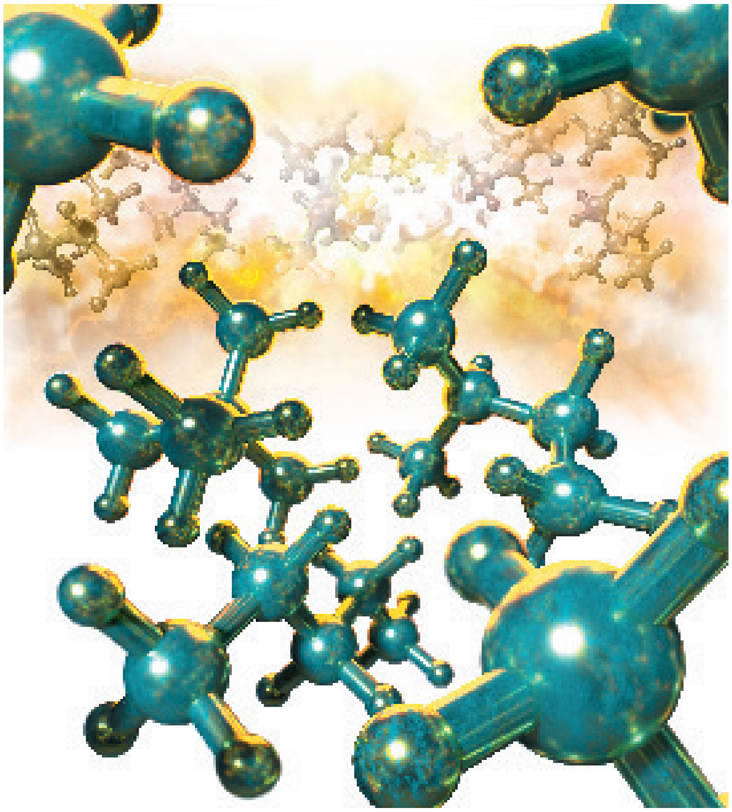
About the Author

Nivaldo Tro has been teaching college chemistry since 1990 and is currently teaching at Santa Barbara City College. He received his PhD in chemistry from Stanford University for work on developing and using optical techniques to study the adsorption and desorption of molecules to and from surfaces in ultrahigh vacuum. He then went on to the University of California at Berkeley, where he did postdoctoral research on ultrafast reaction dynamics in solution. Professor Tro has been awarded grants from the American Chemical Society Petroleum Research Fund, 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. Professor Tro lives in Santa Barbara with his wife, Ann. In his leisure time, Professor Tro enjoys cycling, surfing, and being outdoors.

To Ann, Michael, Ali, Kyle, and Kaden

About the Cover



The front cover of this book displays the structures of three different substances: *n*-pentane (bottom left), isopentane (middle right), and neopentane (middle left). The three substances are isomers—all three molecules are composed of exactly the same 17 atoms (5 carbon atoms and 12 hydrogen atoms), yet their properties are different. For example, neopentane boils at 9.5 °C (making it a gas at room temperature). Isopentane and *n*-pentane boil at 27.8 °C and 36.1 °C, respectively, making them both liquids at room temperature. Why do the same 17 atoms form molecules with different properties? The ways the atoms are bonded together—the molecules' *structures*—are different, and *structure determines properties.* The relationship between the structure of matter at the atomic and molecular scale and the properties of matter, which we can see and measure at the macroscopic level, is the central theme of this book. As the properties of these three isomers demonstrate, differences in structure nearly always result in differences in properties.

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Schrodinger's Cat
$\Delta x \times m\Delta v \geq \frac{h}{4\pi}$

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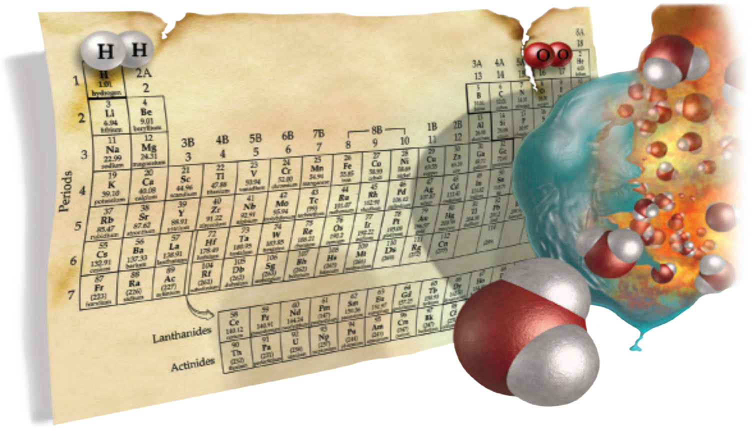

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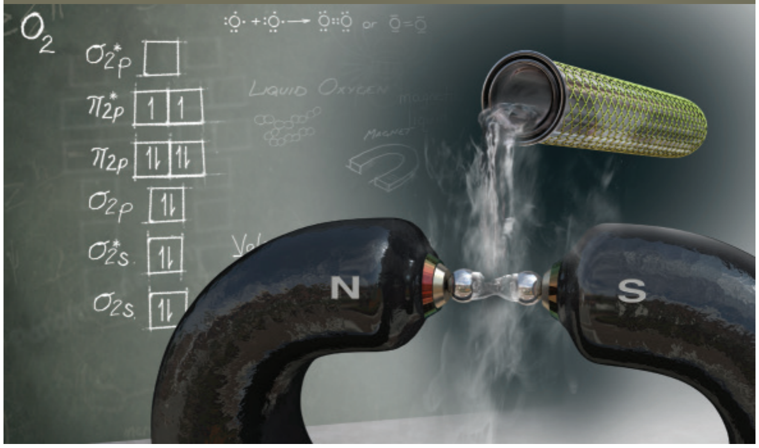

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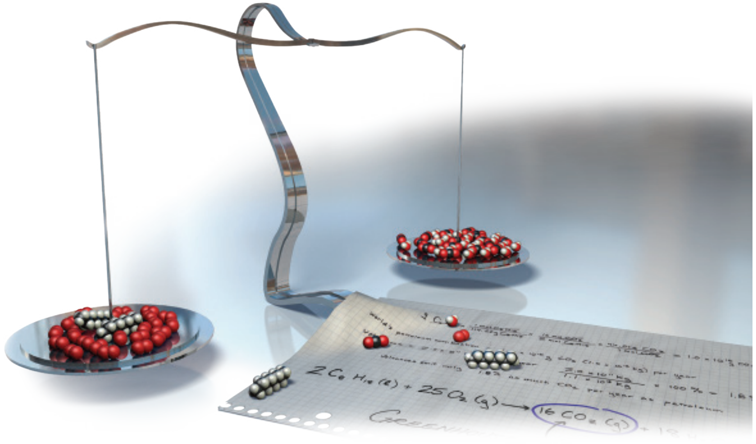

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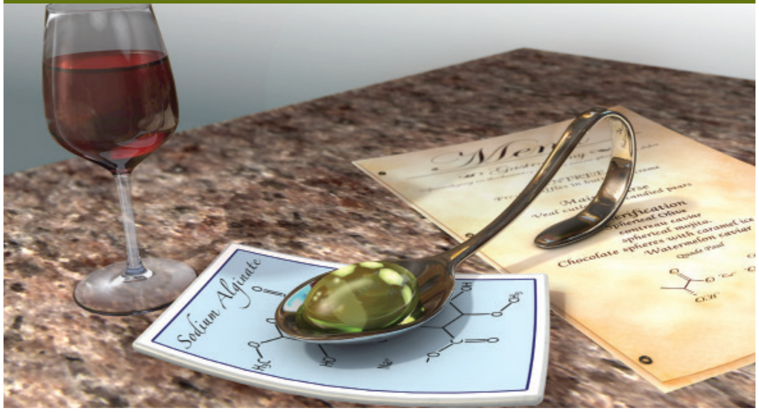

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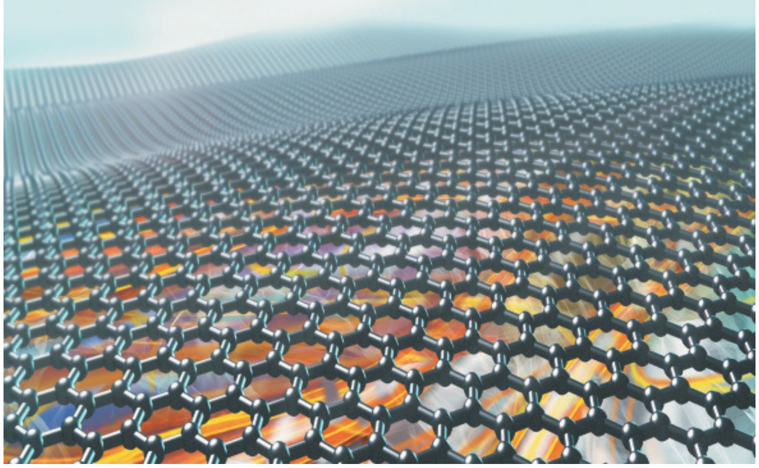

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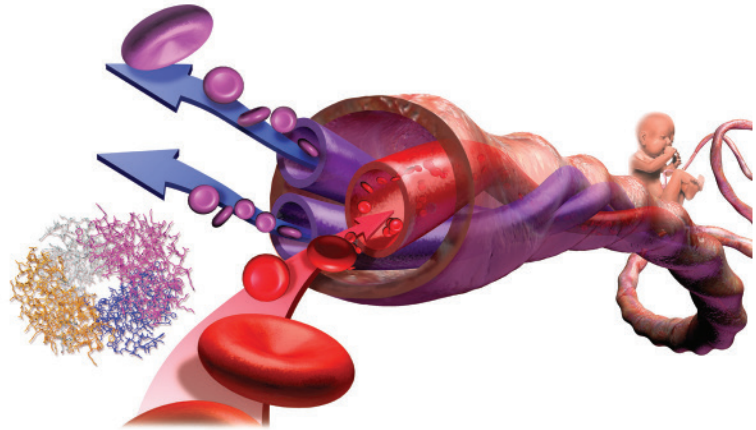

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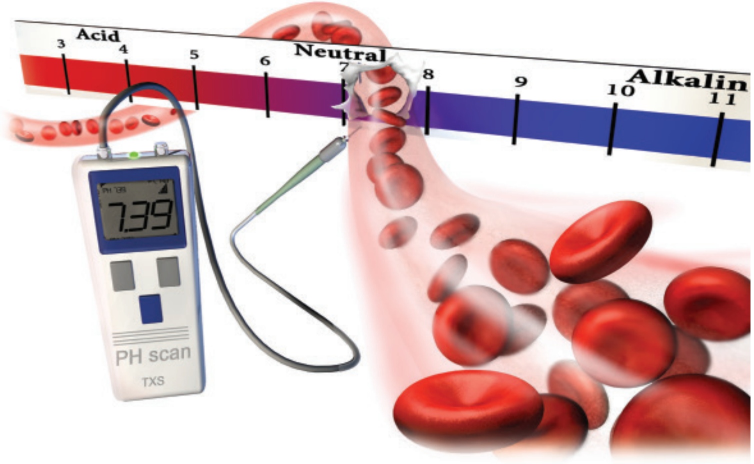

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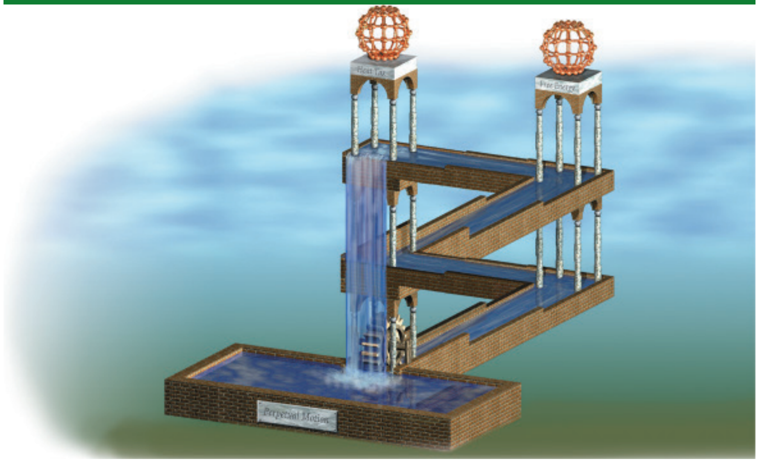

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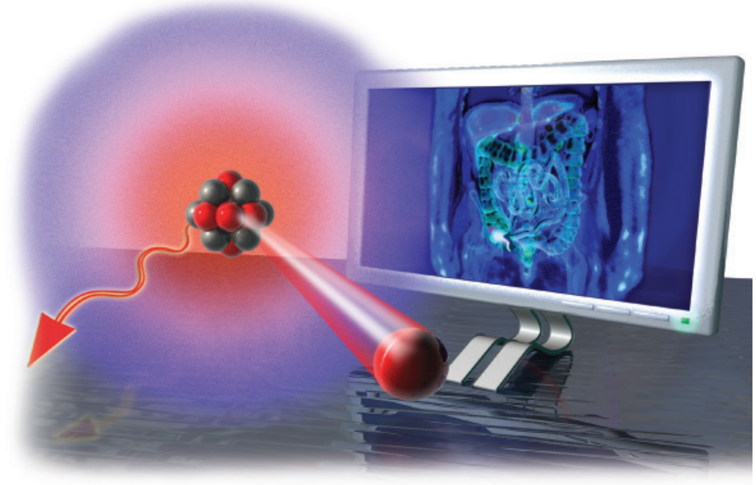

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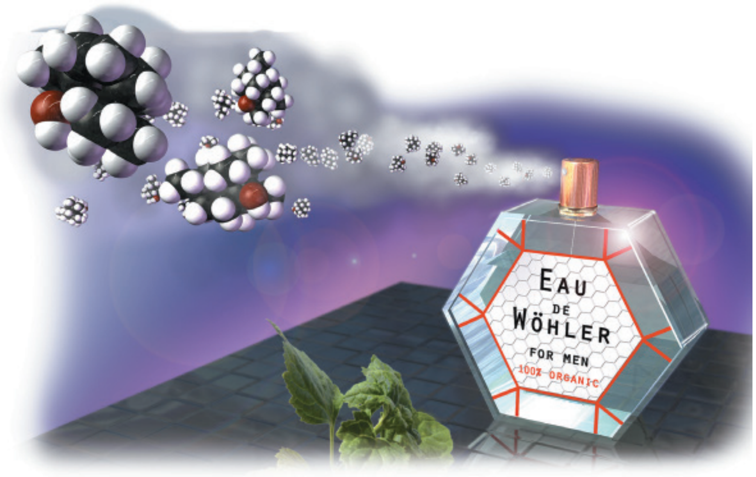

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Preface

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
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To the Professor

First and foremost, thanks to all of you who adopted this book in its previous editions. 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 previous editions. 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 the gases chapter, 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 35 new Key Concept Videos and 48 new Interactive Worked Examples to the media package, which now contains over 240 interactive videos. In addition, I have created new digital content called Key Concept Interactives. The following section, entitled "What's New in This Edition," contains a more detailed description of the digital content. In my courses, I employ readings from the book and this digital content 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 or a Key Concept Interactive *before* each class session. Reading sections from the text in conjunction with engaging with the digital content introduces students to the key concepts for that day and gets them ready for class. Since the digital content 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 and completely eliminated three chapters ("Biochemistry," "Chemistry of the Nonmetals," and "Metals and Metallurgy"). These topics are simply not being taught 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.

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Acknowledgments

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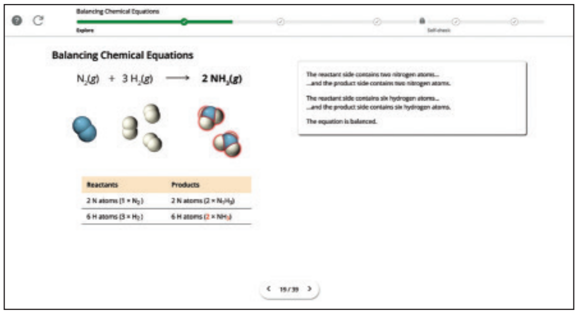
What's New in This Edition?

The book has been extensively revised and contains more small changes than can be detailed here. The most significant changes to the book and its supplements are listed below:

New Key Concept Interactives

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



Balancing Chemical Equations

$N_2(g) + 3\,H_2(g) \longrightarrow 2\,NH_3(g)$

The reactant side contains two nitrogen atoms...
...and the product side contains two nitrogen atoms.

The reactant side contains six hydrogen atoms...
...and the product side contains six hydrogen atoms.

The equation is balanced.

Reactants	Products
2 N atoms (1 × N_2)	2 N atoms (2 × NH_3)
6 H atoms (3 × H_2)	6 H atoms (2 × NH_3)

New Online Problem Sets

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

New Predict

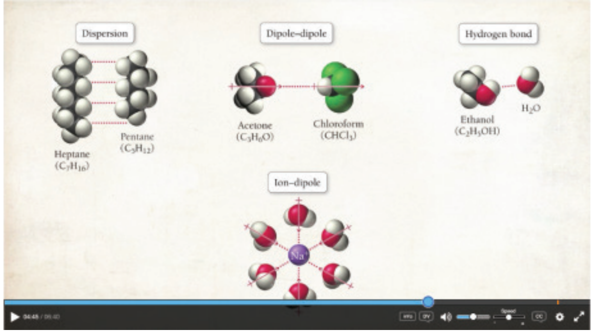
Asks students to predict the outcome of the topic they are about to read. After the student reads the section, **Predict** confirms whether the student predicted correctly or incorrectly and why. Education research has demonstrated that students learn a topic better if they make a prediction about the topic before learning it (even if the prediction is wrong).

Diversity, Equity, and Inclusion Review

The entire book has gone through a detailed review to ensure the content reflects the rich diversity of our learners and is inclusive of their lived experiences.

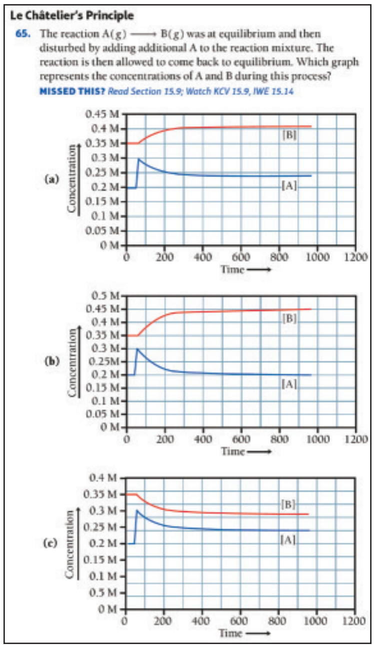
New Interactive Videos

Thirty-five new **Key Concept Videos (KCVs)** and 48 new **Interactive Worked Examples (IWEs)** have been added to the media package that accompanies the book. All videos are available within the eTextbook and are assignable in Mastering Chemistry. *The video library now contains over 240 interactive videos*. These tools are designed to help professors engage their students in active learning.



New and Revised End-of-Chapter Problems

130 New End-of-Chapter questions have been added throughout the book, and **314 have been revised**. Many new End-of-Chapter questions involve the interpretation of graphs and data. All new End-of-Chapter questions are assignable in Mastering Chemistry.



Le Châtelier's Principle

65. The reaction $A(g) \longrightarrow B(g)$ was at equilibrium and then disturbed by adding additional A to the reaction mixture. The reaction is then allowed to come back to equilibrium. Which graph represents the concentrations of A and B during this process?
MISSED THIS? *Read Section 15.9; Watch KCV 15.9, IWE 15.14*

Why Structure and Properties?

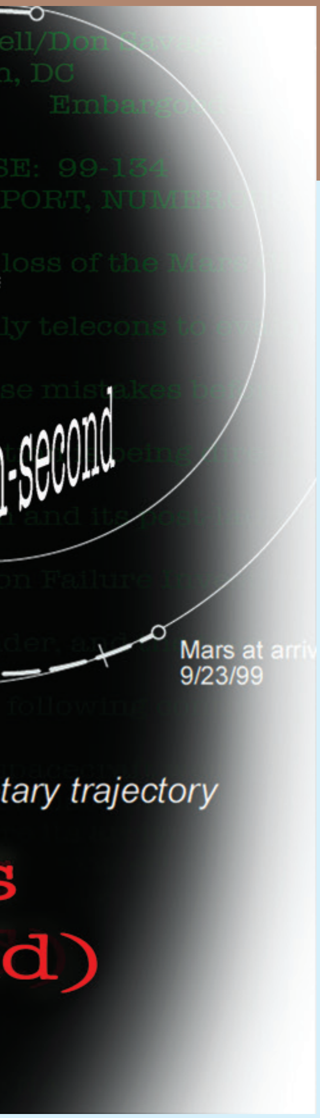
Dear Colleague,

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 of topics. 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. 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 third 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 will learn to apply them to see and understand the world around them in new ways.

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

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



CHAPTER

E Essentials: Units, Measurement, and Problem Solving

QUANTIFICATION 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.

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.

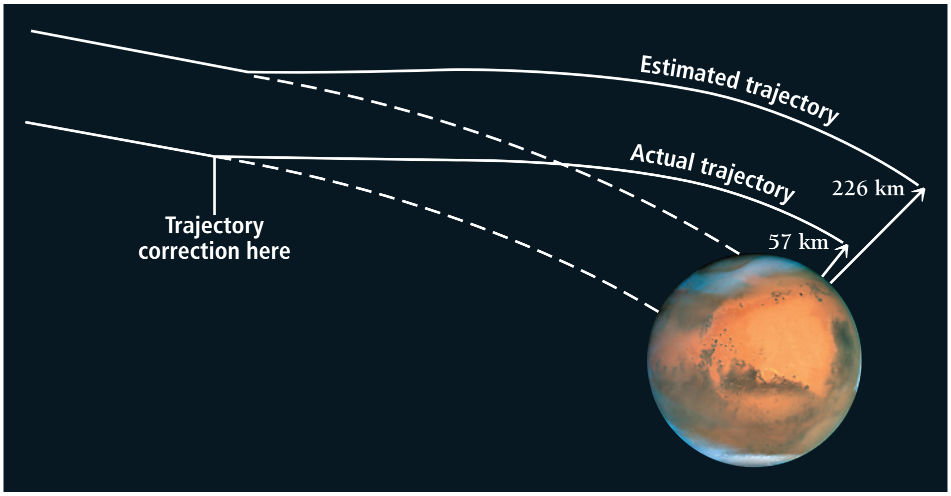


FIGURE E.1 The Metric Mix-up The top trajectory represents the expected Mars Climate Orbiter trajectory; the bottom trajectory represents the actual one.

The Pearson+ icon indicates that this feature is embedded and interactive in the eTextbook.

WATCH **NOW!**

KEY CONCEPT VIDEO E.2

Units and Significant Figures

E.2 The Units of Measurement

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

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

The Meter: A Measure of Length

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.

Scientific notation is reviewed in Appendix IA.

The Kilogram: A Measure of Mass

The **kilogram (kg)** was long defined as the mass of a metal cylinder kept at the International Bureau of Weights and Measures at Sèvres, France. However, its definition was recently changed to be based on a physical constant called Planck's constant, which is known to a high level of precision. The kilogram 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 their 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.

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

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.

The Kelvin: A Measure of Temperature

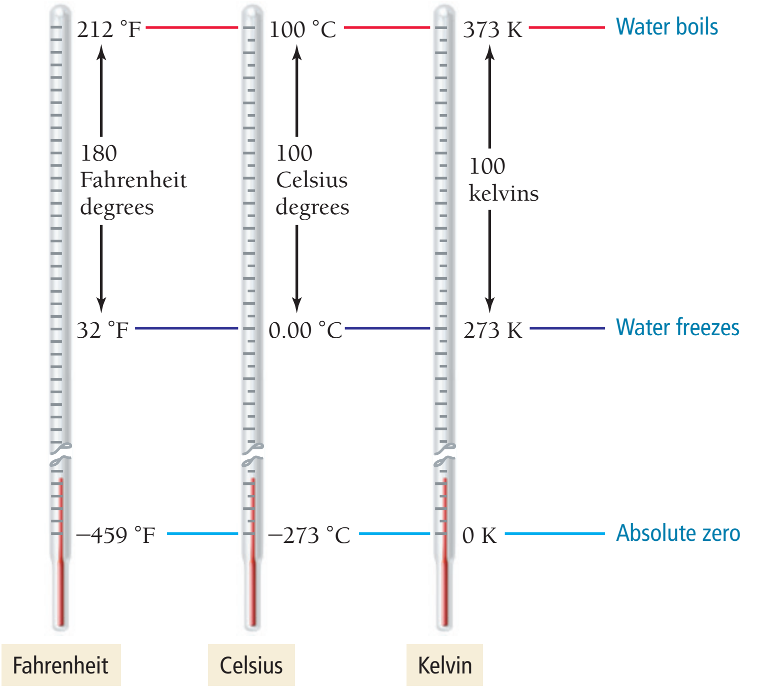
The **kelvin (K)** is the SI unit of **temperature**. The temperature of a sample of matter is a measure of the amount of average kinetic energy—the energy due to motion—of the atoms or molecules that compose the matter. The molecules in a *hot* glass of water are, on average, moving faster than the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

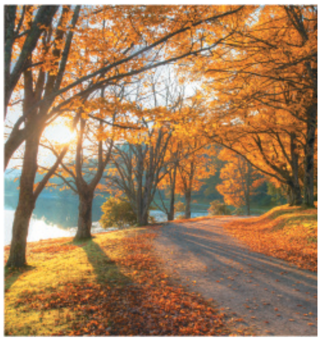
Temperature Scales



▶ **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).

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 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:

$$
\begin{aligned}
{}^{\circ}\mathrm{C} &= \frac{({}^{\circ}\mathrm{F} - 32)}{1.8} \\
\mathrm{K} &= {}^{\circ}\mathrm{C} + 273.15
\end{aligned}
$$

ANSWER **NOW!**

E.1

Cc

Conceptual Connection

Temperature Scales

Which temperature scale has no negative temperatures?

(a) Kelvin (b) Celsius (c) Fahrenheit

Note: Answers to Conceptual Connections can be found at the end of each chapter.

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).

$$\mathrm{K} = {}^{\circ}\mathrm{C} + 273.15$$

Since this equation gives the temperature in K directly, substitute in the correct value for the temperature in °C and calculate the answer.

$$
\begin{aligned}
\mathrm{K} &= {}^{\circ}\mathrm{C} + 273.15 \\
\mathrm{K} &= 40.00 + 273.15 = 313.15\ \mathrm{K}
\end{aligned}
$$

(b) To convert from °C to °F, find the equation that relates these two quantities.

$${}^{\circ}\mathrm{C} = \frac{({}^{\circ}\mathrm{F} - 32)}{1.8}$$

Since this equation expresses °C in terms of °F, solve the equation for °F.

$$
\begin{aligned}
{}^{\circ}\mathrm{C} &= \frac{({}^{\circ}\mathrm{F} - 32)}{1.8} \\
1.8({}^{\circ}\mathrm{C}) &= ({}^{\circ}\mathrm{F} - 32) \\
{}^{\circ}\mathrm{F} &= 1.8({}^{\circ}\mathrm{C}) + 32
\end{aligned}
$$

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.

$$
\begin{aligned}
{}^{\circ}\mathrm{F} &= 1.8({}^{\circ}\mathrm{C}) + 32 \\
{}^{\circ}\mathrm{F} &= 1.8(40.00\ {}^{\circ}\mathrm{C}) + 32 = 104.00\ {}^{\circ}\mathrm{F}
\end{aligned}
$$

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.

E.2 Cc Conceptual Connection

ANSWER **NOW!**

Prefix Multipliers

What prefix multiplier is most appropriate for reporting a measurement of 5.57×10^{-5} m?

(a) mega (b) milli (c) micro (d) kilo

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.

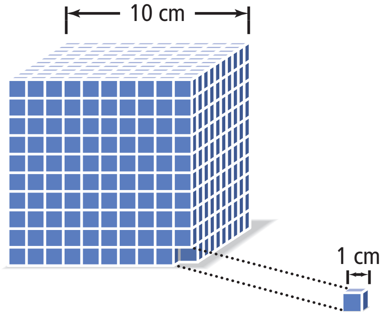
Volume is a measure of space. Any unit of length, when cubed (raised to the third power), becomes a unit of volume. The cubic meter (m^3), cubic centimeter (cm^3), and cubic millimeter (mm^3) are all units of volume. The cubic nature of volume is not always intuitive, and studies have shown that our 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 other quantities—and their equivalents.

Relationship between Length and Volume



A 10-cm cube contains 1000 1-cm cubes.

▲ **FIGURE E.3 The Relationship between Length and Volume**

TABLE E.3 Some Common Units and Their Equivalents

Length	Mass	Volume
1 kilometer (km) = 0.6214 mile (mi)	1 kilogram (kg) = 2.205 pounds (lb)	1 liter (L) = 1000 mL = 1000 cm^3
1 meter (m) = 39.37 inches (in) = 1.094 yards (yd)	1 pound (lb) = 453.59 grams (g)	1 liter (L) = 1.057 quarts (qt)
1 foot (ft) = 30.48 centimeters (cm) (exact)	1 ounce (oz) = 28.35 grams (g)	1 U.S. gallon (gal) = 3.785 liters (L)
1 inch (in) = 2.54 centimeters (cm)(exact)		

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.**

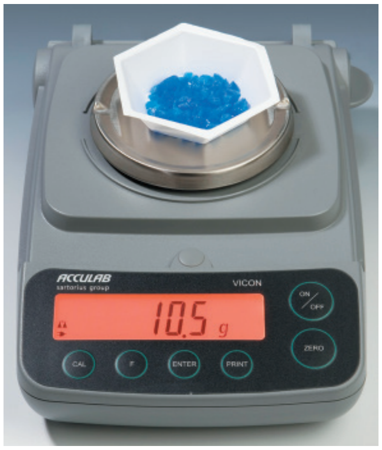
Consider the following reported number:

$$\underset{\text{certain}}{5.21}\underset{\text{estimated}}{3}$$

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 g. 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



Report as 10.5 g
(a)

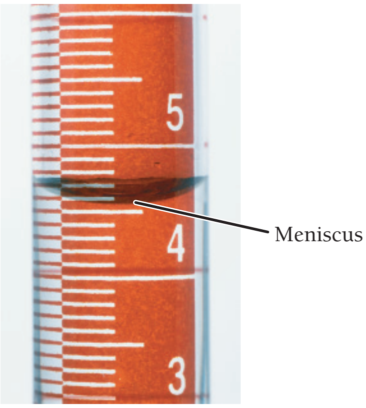
Report as 10.4977 g
(b)

▲ **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.

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.)

WATCH **NOW!**
INTERACTIVE WORKED EXAMPLE VIDEO E.2



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.