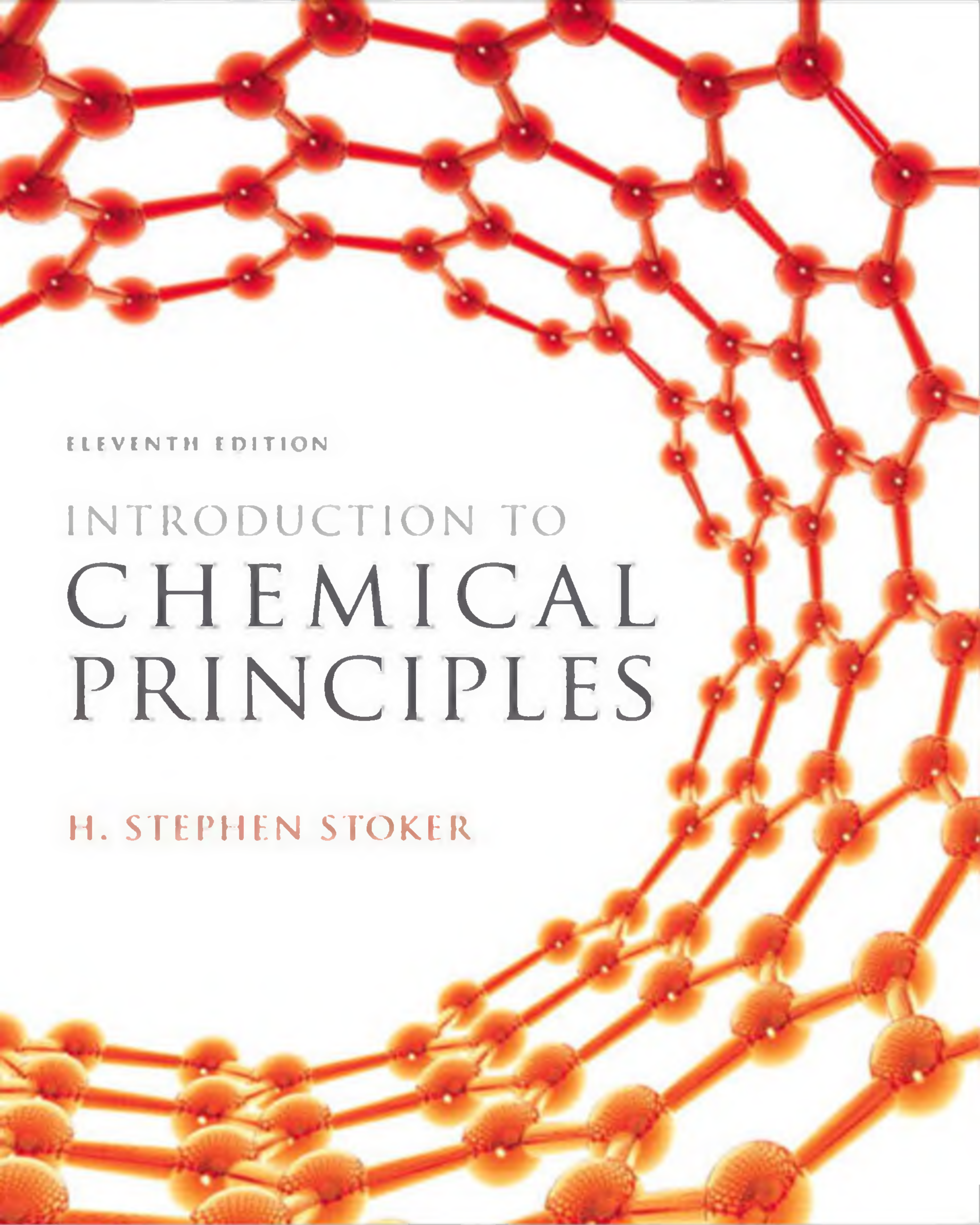
ELEVENTH EDITION

INTRODUCTION TO CHEMICAL PRINCIPLES

H. STEPHEN STOKER



Periodic Table of the Elements

1 Group IA	2 Group IIA	3 Group IIIB	4 Group IVB	5 Group VB	6 Group VIB	7 Group VIIB	8 Group ←	9 Group VIIIB	10 Group →	11 Group IB	12 Group IIB	13 Group IIIA	14 Group IVA	15 Group VA	16 Group VIA	17 Group VIIA	18 Group VIIIA
1 **H** 1.01																	2 **He** 4.00
3 **Li** 6.94	4 **Be** 9.01											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											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** 78.96	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** 95.96	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** (209)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** (226)	89 **Ac** (227)	104 **Rf** (267)	105 **Db** (268)	106 **Sg** (271)	107 **Bh** (272)	108 **Hs** (270)	109 **Mt** (276)	110 **Ds** (281)	111 **Rg** (280)	112 **Cn** (285)	113 **–** (284)	114 **Fl** (289)	115 **–** (288)	116 **Lv** (293)	117 **–** (293)	118 **–** (294)

Metals ← → Non-metals

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
90 **Th** 232.04	91 **Pa** 231.04	92 **U** 238.03	93 **Np** (237)	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (262)

LIST OF ELEMENTS WITH THEIR SYMBOLS AND ATOMIC MASSES

Element	Symbol	Atomic Number	Atomic Mass	Element	Symbol	Atomic Number	Atomic Mass
Actinium	Ac	89	(227)	Mendelevium	Md	101	(258)
Aluminum	Al	13	26.98	Mercury	Hg	80	200.59
Americium	Am	95	(243)	Molybdenum	Mo	42	95.94
Antimony	Sb	51	121.76	Neodymium	Nd	60	144.24
Argon	Ar	18	39.95	Neon	Ne	10	20.18
Arsenic	As	33	74.92	Neptunium	Np	93	(237)
Astatine	At	85	(210)	Nickel	Ni	28	58.69
Barium	Ba	56	137.33	Niobium	Nb	41	92.91
Berkelium	Bk	97	(247)	Nitrogen	N	7	14.01
Beryllium	Be	4	9.012	Nobelium	No	102	(259)
Bismuth	Bi	83	208.98	Osmium	Os	76	190.23
Bohrium	Bh	107	(272)	Oxygen	O	8	16.00
Boron	B	5	10.81	Palladium	Pd	46	106.42
Bromine	Br	35	79.90	Phosphorus	P	15	30.97
Cadmium	Cd	48	112.41	Platinum	Pt	78	195.08
Calcium	Ca	20	40.08	Plutonium	Pu	94	(244)
Californium	Cf	98	(251)	Polonium	Po	84	(209)
Carbon	C	6	12.01	Potassium	K	19	39.10
Cerium	Ce	58	140.12	Praseodymium	Pr	59	140.91
Cesium	Cs	55	132.91	Promethium	Pm	61	(145)
Chlorine	Cl	17	35.45	Protactinium	Pa	91	231.04
Chromium	Cr	24	52.00	Radium	Ra	88	(226)
Cobalt	Co	27	58.93	Radon	Rn	86	(222)
Copernicium	Cn	112	(285)	Rhenium	Re	75	186.21
Copper	Cu	29	63.55	Rhodium	Rh	45	102.91
Curium	Cm	96	(247)	Roentgenium	Rg	111	(280)
Darmstadtium	Ds	110	(281)	Rubidium	Rb	37	85.47
Dubnium	Db	105	(268)	Ruthenium	Ru	44	101.07
Dysprosium	Dy	66	162.50	Rutherfordium	Rf	104	(267)
Einsteinium	Es	99	(252)	Samarium	Sm	62	150.36
Erbium	Er	68	167.26	Scandium	Sc	21	44.96
Europium	Eu	63	151.96	Seaborgium	Sg	106	(271)
Fermium	Fm	100	(257)	Selenium	Se	34	78.96
Flerovium	Fl	114	(289)	Silicon	Si	14	28.09
Fluorine	F	9	19.00	Silver	Ag	47	107.87
Francium	Fr	87	(223)	Sodium	Na	11	22.99
Gadolinium	Gd	64	157.25	Strontium	Sr	38	87.62
Gallium	Ga	31	69.72	Sulfur	S	16	32.06
Germanium	Ge	32	72.63	Tantalum	Ta	73	180.95
Gold	Au	79	196.97	Technetium	Tc	43	(98)
Hafnium	Hf	72	178.49	Tellurium	Te	52	127.60
Hassium	Hs	108	(270)	Terbium	Tb	65	158.93
Helium	He	2	4.003	Thallium	Tl	81	204.38
Holmium	Ho	67	164.93	Thorium	Th	90	232.04
Hydrogen	H	1	1.008	Thulium	Tm	69	168.93
Indium	In	49	114.82	Tin	Sn	50	118.71
Iodine	I	53	126.90	Titanium	Ti	22	47.87
Iridium	Ir	77	192.22	Tungsten	W	74	183.84
Iron	Fe	26	55.85	Uranium	U	92	238.03
Krypton	Kr	36	83.80	Vanadium	V	23	50.94
Lanthanum	La	57	138.91	Xenon	Xe	54	131.293
Lawrencium	Lr	103	(262)	Ytterbium	Yb	70	173.04
Lead	Pb	82	207.2	Yttrium	Y	39	88.91
Lithium	Li	3	6.941	Zinc	Zn	30	65.41
Lutetium	Lu	71	174.97	Zirconium	Zr	40	91.22
Livermorium	Lv	116	(293)	Element 113	—	113	(284)
Magnesium	Mg	12	24.31	Element 115	—	115	(288)
Manganese	Mn	25	54.94	Element 117	—	117	(293)
Meitnerium	Mt	109	(276)	Element 118	—	118	(294)

A mass value which is enclosed in parentheses is the mass number for the most stable isotope of an element that is laboratory produced rather than naturally occurring.

Eleventh Edition

Introduction to Chemical Principles

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Eleventh Edition

Introduction to Chemical Principles

H. Stephen Stoker

Weber State University

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CONTENTS

PREFACE

Introduction to Chemical Principles is a text for students who have had little or no previous instruction in chemistry or whose instruction was so long ago that a thorough review is needed. The text's purpose is to give students the background (and confidence) needed for a subsequent successful encounter with a main sequence, college-level, general chemistry course.

Many texts written for preparatory chemistry courses are simply watered-down versions of general chemistry texts: They treat almost all topics found in the general chemistry course, but at a superficial level. *Introduction to Chemical Principles* does not fit this mold. My philosophy is that it is better to treat fewer topics extensively and have the student understand those topics in greater depth. I resisted the very real temptation to include lots of additional concepts in this new edition. Instead, my focus for this edition was on rewriting selected portions to improve the clarity of presentation.

NEW FEATURES OF THE ELEVENTH EDITION

- **"Chemical Insights" are used to bridge the gap between mathematics and chemistry.** This new "insight" feature, which is appended to many of the worked-out example problems in the text that involve calculations, focuses on the element or compound that is the *subject* of the calculation. These insights give information on the subject element's/compound's occurrence, its properties and uses, its relationship to the environment, its relationship to living systems (biochemistry), and so on. It is easy for students to become so involved in the mathematics of problem solving that they completely forget about the "realness" of the type of matter that is the subject of the calculation. There are 85 total insights which address this "realness" issue.
- **A "Student Learning Focus" feature is used as a mini study guide for students.** These learning objectives, found at the start of all sections of all chapters, "pinpoint" for the student what it is hoped they will gain by study of the given section.
- **New Worked-Out Example Problems.** Nineteen of the 236 worked-out example problems in the text are new. *Worked-out-in-detail* example problems with their extensive commentary constitute one of the greatest strengths of the text.
- **Extensive revision of "End-of-Chapter Problem Sets."** Although the total number of end-of-chapter problems, which already exceeds that of most other similar texts, has not increased significantly, almost 500 of the previous edition's 2200 problems have been replaced with new problems. A special effort was made to create new problems that address specifically the "core concepts" associated with a given chapter section's subject matter. In most chapters several of the newly added problems involve presentation of data in a "visual form" rather than in a "sentence form." Many of the "visual problems" involve situations where reasoning, with little or no calculation, is needed to test a student's grasp of a key concept.

Content changes to individual chapters. After ten successful editions of *Introduction to Chemical Principles*, the need for drastic alterations in chapter ordering and chapter content does not exist. Changes that have been made relate to "fine tuning" of the presentation of the subject matter. Among the most important changes to this edition are the following:

- *Chapters 4 and 5:* The last four sections of chapter 4 of the previous edition (atoms, molecules, and chemical formulas) has been moved to the start of Chapter 5. Material concerning unstable nuclei previously found in chapter 5 has been deleted
- *Chapter 13:* Material dealing with the use of the molarity concentration unit in chemical calculations now immediately follows the introduction of the concept of molarity. Previously this material was found at the end of the chapter.

IMPORTANT CONTINUING FEATURES IN THE ELEVENTH EDITION

1. **Development of each topic starts out at ground level.** Because of the varied degrees of understanding of chemical principles possessed by students taking a preparatory chemistry course, each topic is developed step by step from ground level until the level of sophistication required for a further chemistry course is attained.
2. **Problem-solving pedagogy is based on dimensional analysis.** Over forty years of teaching experience suggest to me that student "troubles" in general chemistry courses are almost always centered on the inability to set up and solve problems. Whenever possible, I use dimensional analysis in problem solving. This method, which requires no mathematics beyond arithmetic and elementary algebra, is a powerful and widely applicable problem-solving tool. Most important, it is a method that an average student can master with an average amount of diligence. Mastering dimensional analysis also helps build the confidence that is so valuable for future chemistry courses.
3. **Detailed commentary accompanies all worked-out example problems.** In all chapters, one or more worked-out example problems follow the presentation of key concepts. These examples walk students through the thought processes involved in solving the particular type of problem. Detailed commentary accompanies all of the steps involved in solving a problem.
4. **"Answer Double Check" feature.** Over half (60%) of the text's worked-out examples are enhanced by the feature called "answer double check." The purpose of this feature, which is appended to the end of the worked-out example discussion, is to encourage students to consider whether the answer they obtain in working a problem is a reasonable answer in terms of items such as numerical magnitude, number of significant figures present, sign convention (plus or minus), and direction of change (increase or descrease). An unreasonable answer is often a sign that a calculator error has been made.
5. **Significant-figure concepts are emphasized in all problem-solving situations.** Routinely, electronic calculators display answers that contain more digits than are needed or acceptable. In all worked-out examples, students are reminded about these unneeded digits by the appearance of two answers to the example: the calculator answer (which does not take into account significant figures) and, in color, the correct answer (which is the calculator answer adjusted to the correct number of significant figures).
6. **Operation rules for standardizing uncertainty in numbers are used.** Students often experience a relatively high degree of frustration when they correctly solve a problem and yet obtain an answer that differs *slightly* from the one given in the answer section at the back of the book. They want to get the exact number shown in the answer section. Most often the discrepancy is due to differing degrees of uncertainty in the input numbers used for the calculation, for example, in molecular mass values. To minimize such frustration, operational rules have been introduced for standardizing uncertainty in input numbers. The standard mode of operation is always (1) to round all atomic masses to hundredths before using them in molecular mass calculations, and (2) to specify frequently used numbers, such as Avogadro's number, molar volume, and the ideal gas constant to four significant figures. Using these operational rules for input numbers, student answers will match the back-of-the-book answers *to the last significant digit*.
7. **Defined terms always appear in self-standing complete sentences.** All definitions are highlighted in the text when they are first presented, using boldface and italic type. Each defined term appears as a complete sentence; students are never required to deduce a definition from context. In addition, the definitions of all terms appear in a separate glossary found at the end of the text. All defined terms have been reexamined to see if they could be stated with greater clarity. The result is a rewording of many defined terms. In addition, the number of defined terms has been increased. There are 29 new or modified definitions in this new edition of the text.
8. **All end-of-chapter exercises occur in matched pairs.** In essence, each chapter has two independent, but similar, problem sets. Counting subparts to problems, there are over 5000 questions and problems available for students to use in their journey to proficient problem solving. Answers to all of the odd-numbered problems are found at the end of the text. Thus, two problem sets exist, one with answers and one without.

9. **"Multiple-Choice Practice Test" feature.** The emphasis in this text has always been and still is on working problems from scratch. Some, but certainly not all instructors, use this same approach when giving class examinations. A multiple-choice question examination is another common type of examination given. To aid students whose examinations involve multiple-choice examinations, a 20-question "multiple-choice practice test" in included as the last feature in each chapter. It is intended that students use this feature as an aid in reviewing subject matter for an upcoming multiple-choice examination.
10. **Historical vignettes are used to address some of the "people aspects" of chemistry.** These vignettes, entitled "The Human Side of Chemistry," are brief biographies of scientists who helped develop the foundations of modern chemistry. In courses such as the one for which this text is written, it is very easy for students to completely lose any feeling for the people involved in the development of the subject matter they are considering. If it were not for the contributions of these people, many of whom worked under adverse conditions, chemistry would not be the central science that it is today.
11. **Marginal notes are used extensively.** The two main functions of the marginal notes are (1) to summarize key concepts and often give help for remembering concepts or distinguishing between similar concepts, and (2) to provide additional details, links between concepts, or historical information about the concepts under discussion.

SUPPLEMENTS

For the Instructor

Instructor Solutions Manual (download only): (ISBN: 0321815130) by Nancy J. Gardner, California State University–Long Beach. Contains full solutions to all of the end-of-chapter problems in the text.

TestGen Computerized Test Bank: (ISBN: 0321815319) by Pamela Kerrigan, Mount Saint Vincent. Contains approximately 1000 multiple-choice and short-answer questions, all referenced to the text.

CourseSmart: (ISBN: 0321815149) Access your college textbook in online format at www.coursesmart.com.

For the Student

Student Solutions Manual: (ISBN: 0321815122) by Nancy J. Gardner, California State University–Long Beach. Includes full solutions to all odd-numbered end-of-chapter problems and answers to all multiple choice practice test questions in the text.

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I'd like to gratefully acknowledge the valuable contributions of my accuracy reviewer Andreas Lippert of Weber State University.

Every effort has been made to rid this text of any typographical errors. I encourage my readers who notice anything suspicious, or who have other questions or comments, to e-mail me at the address below.

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CHAPTER

1

The Science of Chemistry

1.1 CHEMISTRY—A SCIENTIFIC DISCIPLINE

Student Learning Focus: Understand the relationship of the scientific discipline called chemistry to other scientific disciplines and be familiar with the sub-structuring that occurs with the discipline of chemistry.

Chemistry is part of a larger body of knowledge called *science*. **Science** *is the study in which humans attempt to organize and explain, in a systematic and logical manner, knowledge about themselves and their surroundings*.

Because of the enormous scope of science, the sheer amount of accumulated knowledge, and the limitations of human mental capacity to master such a large and diverse body of knowledge, science is divided into smaller subdivisions called *scientific disciplines*. A **scientific discipline** *is a branch of science limited in size and scope to make it more manageable*. Examples of scientific disciplines are *chemistry*, astronomy, botany, geology, physics, and zoology.

Figure 1.1 shows an organizational chart, with emphasis on chemistry, for the various scientific disciplines. These disciplines can be grouped into *physical sciences* (the study of matter and energy) and *biological sciences* (the study of living organisms). Chemistry is a physical science.

Rigid boundaries between scientific disciplines *do not exist*. All scientific disciplines borrow information and methods from each other. No scientific discipline is totally independent. Environmental problems that scientists have encountered in the last two decades

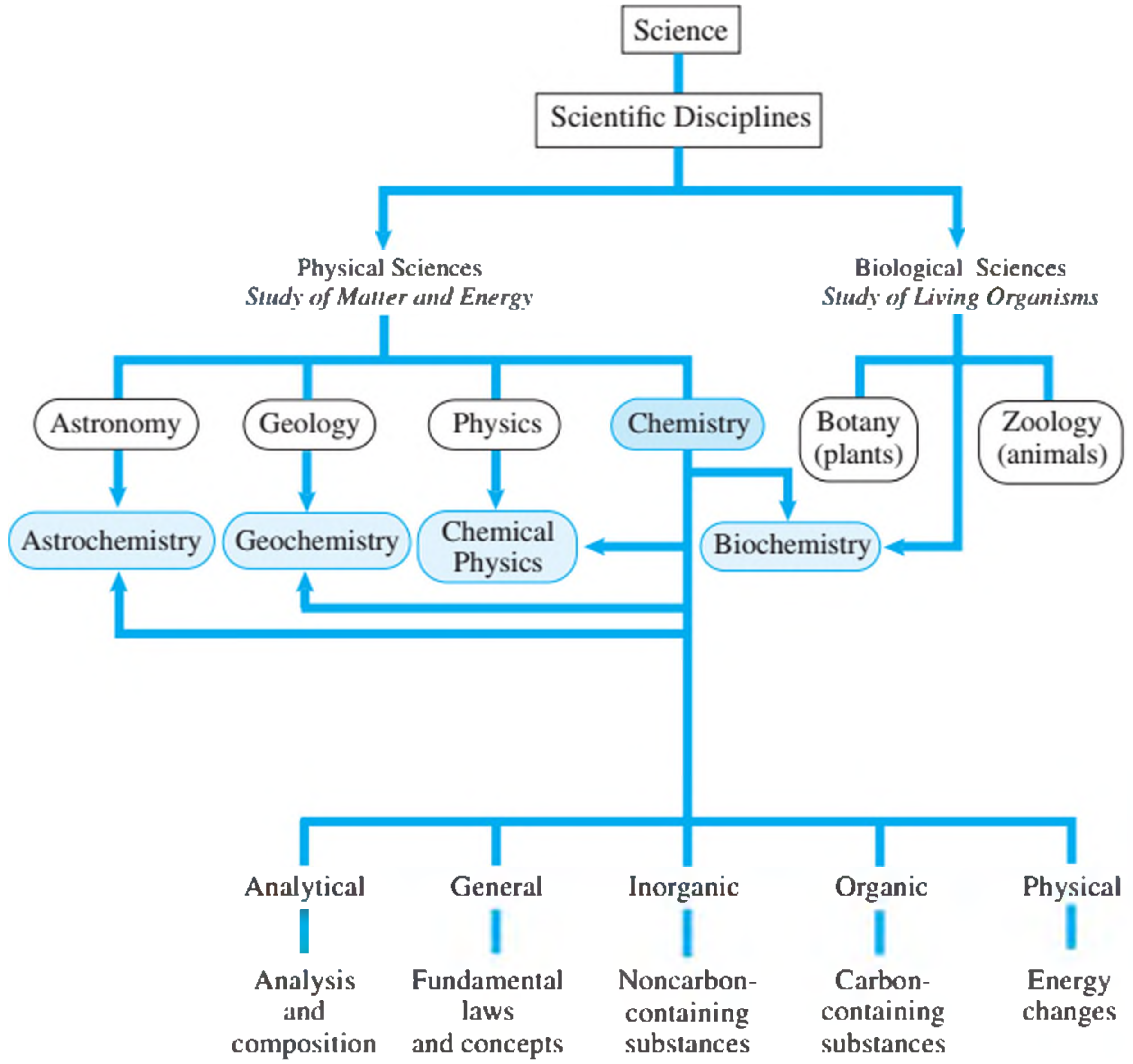

FIGURE 1.1 An organizational chart showing the relationship of the scientific discipline called chemistry to other scientific disciplines and also the sub-structuring that occurs within the discipline of chemistry.

particularly show the interdependence of the various scientific disciplines. For example, chemists attempting to solve the problems of chemical contamination of the environment find that they need some knowledge of geology, zoology, and botany. It is now common to talk not only of chemists, but also of geochemists, biochemists, chemical physicists, and so on. The middle portion of Figure 1.1 shows the overlap of the other scientific disciplines with chemistry.

Discipline overlap requires that scientists, in addition to having in-depth knowledge of a selected discipline, also have limited knowledge of other disciplines. Discipline overlap also explains why a great many college students are required to study chemistry. One or more chemistry courses are required because of their applicability to the disciplines in which the student has more specific interest.

The body of knowledge found within the scientific discipline of chemistry is itself vast. No one can hope to master completely all aspects of chemical knowledge. However, the fundamental concepts of chemistry can be learned in a relatively short period of time.

The vastness of chemistry is sufficiently large that it, like most scientific disciplines, is partitioned into *subdisciplines*. The lower portion of Figure 1.1 shows the five fundamental branches of chemistry: analytical, general, inorganic, organic, and physical. Most of the subject matter of this textbook falls within the realm of *general chemistry*, the fundamental laws and concepts of chemistry.

The American Chemical Society (ACS) is the largest scientific organization in the world. Examination of the names of the 33 subdivisions of ACS (see Table 1.1) further

TABLE 1.1 Names of the Divisions of the American Chemical Society

Agricultural and Food Chemistry	Fluorine Chemistry
Agrochemicals	Fuel Chemistry
Analytical Chemistry	Geochemistry
Biochemical Technology	History of Chemistry
Biological Chemistry	Industrial and Engineering Chemistry
Business Development and Management	Inorganic Chemistry
Carbohydrate Chemistry	Medicinal Chemistry
Catalysis Science and Technology	Nuclear Chemistry and Technology
Cellulose and Renewable Materials	Organic Chemistry
Chemical Education	Petroleum Chemistry
Chemical Health and Safety	Physical Chemistry
Chemical Information	Polymer Chemistry
Chemical Toxicology	Polymeric Materials: Science and Engineering
Chemistry and the Law	Professional Relations
Colloid and Surface Science	Rubber
Computers in Chemistry	Small Chemical Businesses
Environmental Chemistry	

illustrates the wide diversity of subject matter and activities encompassed within the discipline of chemistry.

1.2 SCIENTIFIC RESEARCH AND TECHNOLOGY

Student Learning Focus: Understand how the fields of basic scientific research and applied scientific research differ from each other and how the concepts of applied chemical research and technology are related.

The basic activity through which new knowledge is added to the various scientific disciplines, including chemistry, is that of *scientific research*. **Scientific research** *is the process of methodical investigation into a subject in order to discover new information about the subject*. There are two general types of scientific research—*basic* and *applied*. **Basic scientific research** *is research whose major focus is the discovery of new fundamental information about humans and other living organisms and the universe in which they live*. The number of scientists involved in basic scientific research is small compared to those involved in applied scientific research. Most scientists function in the area of applied scientific research. **Applied chemical research** *is research whose major focus is the discovery of products and processes that can be used to benefit humankind*.

In many ways, basic scientific research is the precursor to applied scientific research. The former is the lifeline that supplies the latter with new ideas on which to work. No change in quality of life results from basic scientific research endeavors unless something is done with the body of information that accumulates. Use of this information for the betterment of humankind is the role of applied chemical research and the ensuing technology that results from it. **Technology** *is the application of applied chemical research to the production of new products to improve human survival, comfort, and quality of life*.

Whether or not a given piece of scientific knowledge is technologically used for beneficial or detrimental purposes depends on the motives of those men and women, whether in industry or government, who have the decision-making authority. In democratic societies, citizens (the voters) can influence many technological decisions. It is important for citizens to become informed about scientific and technological issues.

Technological advances began affecting our society more than 200 years ago, and new advances still continue, at an accelerating pace, to have a major impact on human society.

Both benefits and detriments can be obtained from the same piece of scientific knowledge, depending on the technology used to put it to work. For example, knowledge concerning the closely related structures of the naturally-occurring substances morphine and codeine, obtained through basic research, has led to the development of several important codeine-derivatives currently used in modern medicine as prescription painkillers (hydrocodone and oxycodone) as well as the synthesis of the illegal drug heroin, whose structure parallels closely that of morphine.

1.3 THE SCOPE OF CHEMISTRY

Student Learning Focus: Be able to list several areas in which chemistry applications are important to human beings.

Although chemistry is concerned with only a part of the scientific knowledge that has been accumulated, it is in itself an enormous and broad field. Chemistry touches all parts of our lives.

Many of the clothes we wear are made from synthetic fibers produced by chemical processes. Even natural fibers, such as cotton or wool, are the products of naturally occurring chemical reactions within living systems. Our transportation usually involves vehicles powered with energy obtained by burning chemical mixtures such as gasoline or diesel and jet fuels. The drugs used to cure many of our illnesses are the result of chemical research. The paper on which this textbook is printed was produced through a chemical process, and the ink used in printing the words and illustrations is a mixture of many chemicals. Almost all of our recreational pursuits involve objects made of materials produced by chemical industries. Skis, boats, basketballs, bowling balls, musical instruments, and television sets all contain materials that do not occur naturally, but are products of human technological expertise.

Our bodies are a complex mixture of chemicals. The principles of chemistry are fundamental to an understanding of all processes of the living state. Chemical secretions (hormones) produced within our bodies help determine our outward physical characteristics such as height, weight, and appearance. Digestion of food involves a complex series of chemical reactions. Food itself is an extremely complicated array of chemical substances. Chemical reactions govern our thought processes and how knowledge is stored in and retrieved from our brains. In short, chemistry runs our lives.

A formal course in chemistry can be a fascinating experience because it helps us understand ourselves and our surroundings. We cannot truly understand or even know very much about the world we live in or about our own bodies without being conversant with the fundamental ideas of chemistry.

1.4 HOW CHEMISTS DISCOVER THINGS—THE SCIENTIFIC METHOD

Student Learning Focus: List procedural steps associated with the problem-solving approach called the scientific method and distinguish among the terms *experiment, scientific fact, scientific law, scientific hypothesis,* and *scientific theory.*

There is no one single correct way to do scientific research, be it *basic* or *applied* (Sec. 1.2). Different scientists often have different approaches to solving the same problem. However, the various approaches used always have embodied within them a number of common characteristics that constitute the problem-solving approach known as the *scientific method*.

The **scientific method** *is a set of general procedures based on experimentation and observation used to acquire scientific knowledge and explain natural phenomena*. The procedural steps in the scientific method are as follows:

1. Identify the problem, break it into small parts, and carefully plan procedures to obtain information about all aspects of this problem.
2. Collect data concerning the problem through observation and experimentation (see Figure 1.2).
3. Analyze and organize the data in terms of general statements (generalizations) that summarize the experimental observations.
4. Suggest probable explanations for the generalizations.
5. Experiment further to prove or disprove the proposed explanations.

Although two different scientists rarely approach the same problem in exactly the same way, there are always similarities in their approaches. These similarities are the procedures associated with the scientific method.

On occasion, a great discovery is made by accident, but the majority of scientific discoveries are the result of the application of these five steps over long periods of time. There are no instantaneous steps in the scientific method; applying them requires considerable amounts of time. Even in those situations where luck is involved, it must be remembered that chance favors the prepared mind. To take full advantage of an accidental discovery, a person must be well trained in the procedures of the scientific method.

The imagination, creativity, and mental attitude of a scientist using the scientific method are always major factors in scientific success. The procedures of the scientific method must always be enhanced with the abilities of a thinking scientist.

There are special vocabulary terms associated with the scientific method and its use. This vocabulary includes the terms *experiment*, *scientific fact*, *scientific law*, *scientific hypothesis*, and *scientific theory*. An understanding of the relationships among these terms is the key to a real understanding of how to obtain chemical knowledge.

Experiments, Observations, and Data

The beginning step in the search for chemical knowledge is the identification of an aspect of a chemical system that needs study. After determining what other chemists have already learned about the selected situation, a chemist sets up *experiments* for obtaining

FIGURE 1.2 Chemistry is an experimental science. Most discoveries in chemistry are made through analysis of data obtained from experiments carried out in laboratories. *(iStockphoto)*

more information. An **experiment** *is a well-defined, controlled procedure for obtaining information about a system under study*.

Performing an experiment involves making careful observations about a system under study. An **observation** *is a statement that describes something we see, hear, smell, taste, or feel*. Instrumentation is most often used as an aid in making observations. Observations obtained while performing an experiment are called *data*. Such data may be *qualitative* or *quantitative*, with the latter being preferred. **Qualitative data** *is non-numerical data consisting of general observations about a system under study*. The observation that ice is less dense than liquid water is an example of qualitative information about a system. **Quantitative data** *is numerical data obtained by various measurements on a system under study*. The information that ice has a density of 0.9170 grams per cubic centimeter at 0°C whereas liquid water has a density of 0.9999 grams per cubic centimeter at the same temperature represents quantitative data. Quantitative observations are more useful than qualitative ones because they can be compared with each other and trends or patterns in information can be seen.

An experiment typically involves study of at least two quantities, that is, variables that have changing values. Usually, the effect of change in one variable on another variable, with all other variables held constant, is measured. For example, the effect that temperature change has on the density of a fixed quantity of a gas, with pressure held constant, can be measured.

A well-designed experiment is always performed under controlled conditions, that is, the values of all variables are always noted, not just those that are changing. When such is the case, the experimental data can be reproduced, if needed, by repeating the experiment.

EXAMPLE 1.1 Distinguishing between Qualitative and Quantitative Data

Classify each of the following pieces of information as *qualitative data* or *quantitative data*.

a. The patient's high fever has reached 105.3°F.
b. The cricket is chirping more loudly tonight than last night.
c. The package of candy contains about 200 gummi bears.

SOLUTION

a. Quantitative data—the temperature was measured with a thermometer.
b. Qualitative data—no measurement was made.
c. Qualitative data—even though a number is specified, it is an estimated number rather than a measured number.

Scientific Facts

The individual pieces of new information (data) about a system under study, obtained by carrying out experimental procedures, are called *scientific facts*. A **scientific fact** *is a reproducible piece of data about some natural phenomenon that is obtained from experimentation*. Note the word *reproducible* in this definition. If a given experiment is repeated under exactly the same conditions, the same results (scientific facts) should be obtained. To be acceptable, all scientific facts must be verifiable by anyone who has the time, means, and knowledge needed to repeat the experiments that led to their discovery.

It is important that scientific data be published so that other scientists have the opportunity to critique and double-check both the data and experimental design. The most common publication avenue is that of articles in scientific journals. Other communication avenues include papers presented at scientific meetings and specialized textbooks. Communication of research results to other scientists is as important as the actual obtaining of the results in the laboratory.

Scientific Laws

After obtaining scientific facts through experimentation, a scientist then makes an effort to determine ways in which the scientific facts about a given system relate both to each other and to scientific facts known about similar systems. Repeating patterns often emerge among the collected scientific facts. These patterns that describe the behavior of chemical systems under specific conditions are called *scientific laws*. A **scientific law** *is a generalization that summarizes scientific facts about a natural phenomenon*.

A major goal of basic scientific research is to organize scientific facts so that relationships can be established among them. Such relationships are called scientific laws.

Do not assume that scientific laws are easy to discover. Often, many years of work and thousands of facts are needed before the true relationships among variables in the area under study emerge.

A scientific law is a description of what happens in a given type of experiment. No new understanding of nature results from simply stating a scientific law. A scientific law merely summarizes already known observations (scientific facts).

A scientific law can be expressed either as a verbal statement or as a mathematical equation. An example of a verbally stated scientific law is "If hot and cold pieces of metal are placed in contact with each other, the temperature of the hot piece always decreases and the temperature of the cold piece always increases."

It is important to distinguish between the use of the word *law* in science and its use in a societal context. Scientific laws are *discovered* by research (see Fig. 1.2), and researchers have *no control* over what the laws turn out to be. Societal laws, which are designed to control aspects of human behavior, are *arbitrary conventions* agreed upon (in a democracy) by the majority of those to whom the laws apply. These laws *can be* and *are changed* when necessary. For example, the speed limit for a particular highway (a societal law) can be decreased or increased for various safety or political reasons.

A contrast exists between the ways in which scientific facts and the results of technology (Sec. 1.2) are shared. Scientists publish their observations (scientific facts) as widely, openly, and quickly as possible. Technological breakthroughs, on the other hand, are usually kept secret by an individual or company until patent rights for the new process or product are obtained. Even then, only limited information is released.

Scientific Hypotheses

There is no mention in a scientific law about why the occurrence described happens. The scientific law simply summarizes experimental observations without attempting to clarify the reasons for the occurrence. Chemists and other scientists are not content with such a situation. They want to know *why* a certain type of observation is always made. Thus, after a scientific law is discovered, scientists work out *plausible, tentative* explanations of the behavior encompassed by the scientific law. These explanations are called *scientific hypotheses*. A **scientific hypothesis** *is a model or statement that can be tested by experiment, which offers an explanation for a scientific law*. Note the inclusion of the concept of *testability* in this definition. A scientific hypothesis is different from other kinds of hypotheses because of the testability requirement. In other academic disciplines, such as philosophy, hypotheses concerning the meaning of life are often considered. Such hypotheses are not *scientific* hypotheses because they cannot be tested by experiment.

Once a scientific hypothesis has been proposed, experimentation begins again. Scientists run more experiments under varied, but controlled, conditions to test the reliability of the proposed explanation. The scientific hypothesis must be able to predict the outcome of as-yet-untried experiments. The validity of the scientific hypothesis depends upon its predictions being true.

In practice, scientists usually start with a number of alternative scientific hypotheses for a given scientific law. Evaluation proceeds by demonstrating that certain proposals are *not* valid. A successful experiment is one in which one or more of the alternative scientific hypotheses are demonstrated to be inconsistent with experimental observation and are thus rejected. Scientific progress is made in the same way a marble statue is: Unwanted bits of marble are chipped away. Example 1.2 contains a simple illustration of this "chipping away" principle in a scientific context.

EXAMPLE 1.2 Relating Scientific Hypotheses to Experimental Information

As a problem-solving approach, the scientific method is used by many people who do not call themselves scientists. An automobile mechanic uses the scientific approach when working on a car. First, based on tests (experimental observations), the automobile mechanic deduces a probable cause of the problem (a hypothesis). Then parts are adjusted or replaced, and the car is checked (more experimental observations) to see if the problem has been corrected (testing of the hypothesis). An experienced automobile mechanic learns that certain observations almost always indicate a specific problem (a validated hypothesis).

Suppose you encounter a situation involving two unopened books with no identification on their covers and four alternative scientific hypotheses about these books, which are (1) the thinner book is a chemistry textbook, (2) the thicker book is a chemistry textbook, (3) both books are chemistry textbooks, and (4) neither book is a chemistry textbook. What information about the validity of these scientific hypotheses can be obtained by opening the thicker book and determining that it is a chemistry textbook?

SOLUTION

This experiment (opening the thicker book) proves scientific hypothesis 2 and disproves scientific hypothesis 4; it does not, however, prove that *only one* of the scientific hypotheses is true. The fact that the thicker book is a chemistry textbook does not rule out the possibility that the thinner book is also a chemistry textbook.

EXAMPLE 1.3 Differentiating among Terminologies Associated with the Scientific Method

Classify each of the following as a *scientific fact*, *scientific law*, or *scientific hypothesis*.

a. The burning candle generated both heat and light.
b. As a candle burns, its wax gradually disappears.
c. All burning candles generate heat and light.
d. Burning candles generate heat as the result of the decomposition of melted wax.

SOLUTION

a. This is a single observation, that is, a *scientific fact*.
b. This is a single observation, that is, a *scientific fact*.
c. This is a generalization based on many observations, that is, a *scientific law*.
d. This is a tentative testable explanation for observations, that is, a *scientific hypothesis*.

Scientific Theories

As further experimentation continues to validate a particular scientific hypothesis, its acceptance in scientific circles increases. If after extensive testing, the reliability of a scientific hypothesis is still very high, confidence in it increases to the extent that it is accepted by the scientific community at large. After more time has elapsed and more positive support has accumulated, the scientific hypothesis assumes the status of a *scientific theory*. A **scientific theory** *is a scientific hypothesis that has been tested and validated over a long period of time*. The dividing line between a scientific hypothesis and a scientific theory is arbitrary and cannot be precisely defined. There is no set number of supporting experiments that must be performed to give scientific theory status to a scientific hypothesis.

Scientific theories serve two important purposes: (1) they allow scientists to predict what will happen in experiments that have not yet been run, and (2) they simplify the very real problem of being able to remember all the scientific facts that have already been discovered. Figure 1.3 shows the interplay that must occur between scientific hypotheses and experimentation before an acceptable scientific theory is obtained.

Scientific theories must often undergo modification. As scientific tools, particularly instrumentation, become more accurate, there is an increasing probability that some experimental observations will not be consistent with all aspects of a given scientific theory. A scientific theory inconsistent with new observations must either be modified to accommodate the new results or be restated in such a way that scientists know where it is useful and where it is not. Most scientific theories in use have known limitations. These imperfect scientific theories are simply the best ideas anyone has found *so far* to describe, explain, and predict what happens in the world in which we live. Scientific theories with limitations are generally not abandoned until a better scientific theory is developed.

The term *theory* is often misused by nonscientists in everyday contexts. "I have a theory that such and such is the case" is a frequently heard comment. In this case, *theory* means a "speculative guess," which is not what a theory is. The terminology *unvalidated hypothesis* would be closer to what is meant.

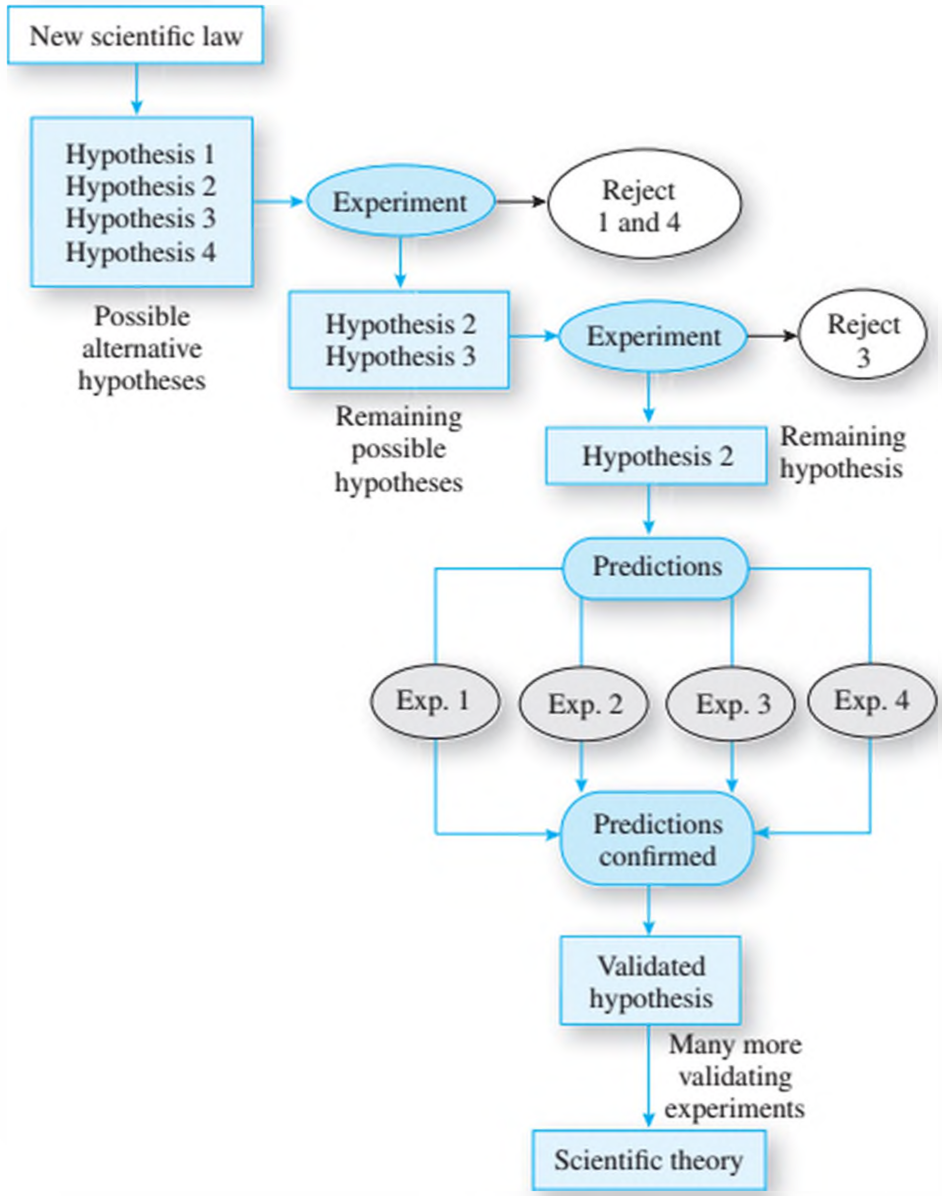

FIGURE 1.3 A possible sequence of events experienced by scientists doing experimental research based on a newly discovered scientific law. (1) A number of alternative scientific hypotheses are proposed to explain the new scientific law; (2) experiments are carried out to eliminate invalid scientific hypotheses; (3) predictions are made based on the surviving scientific hypothesis, and further experiments are carried out to test these predictions; (4) confirmed predictions produce a validated scientific hypothesis; and (5) many more validating experiments give the scientific hypothesis the status of a scientific theory.

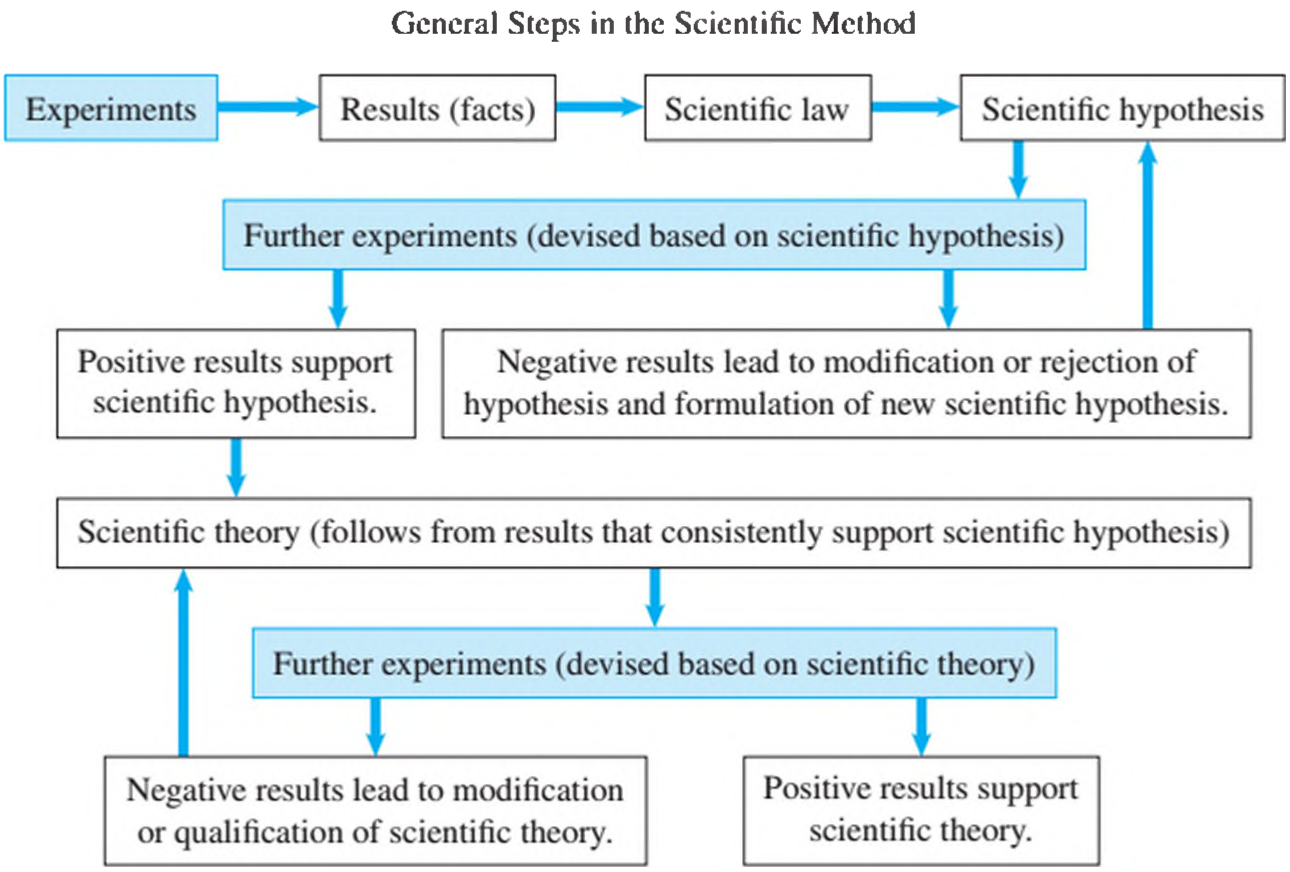

FIGURE 1.4 A diagram showing the central role that experimentation plays in the scientific method for obtaining new scientific information.

Scientific theories are tested conceptual models (mental pictures) that separate scientific thinking from speculative ideas. They represent simplified—but not exact—models that describe various aspects of nature.

Scientific facts that have been verified by repeated experiments will never be changed, but the scientific theories that were invented to explain these scientific facts are subject to change. In this sense, scientific facts are more important than the scientific theories devised to explain them. It is a mistake to believe that, by knowing all the scientific laws and scientific theories that are derived from experimental observations, the experimental facts are not needed. New scientific theories can be developed only by people who have a wide knowledge of the scientific facts relating to a particular field, especially those scientific facts that have not been satisfactorily accounted for by existing scientific theories.

Figure 1.4 highlights the central role that experimentation plays in the scientific method and also summarizes the general steps, procedures, and terminology associated with this most important pattern of action for acquiring scientific knowledge.

1.5 THE LIMITATIONS OF THE SCIENTIFIC METHOD

Student Learning Focus: Be familiar with the limitations inherent in the use of scientific-method procedures.

Scientists do not view scientific theories or their precursors—scientific hypotheses—as absolute truth. All scientific theories are considered provisional—subject to change in the light of new experimental observations. There is always the chance that some future, yet-unthought-of experiment using instrumentation that has not yet been invented will be devised that disproves or places limitations on a currently well-established scientific theory. If such were the case, the scientific theory would then be modified to take into account the new experimental developments. In many ways, science is like a living organism: It continues to grow and change.

Thus, inherent in the use of the scientific method is the not-often-stated concept that "no theory can ever be proved correct by experiment." Experiments can provide supporting data for a theory, but there is always a chance that new experiments will negate aspects of the theory. It is important that experimental design focus just as much on disproving a theory as on providing additional supporting evidence for the theory.

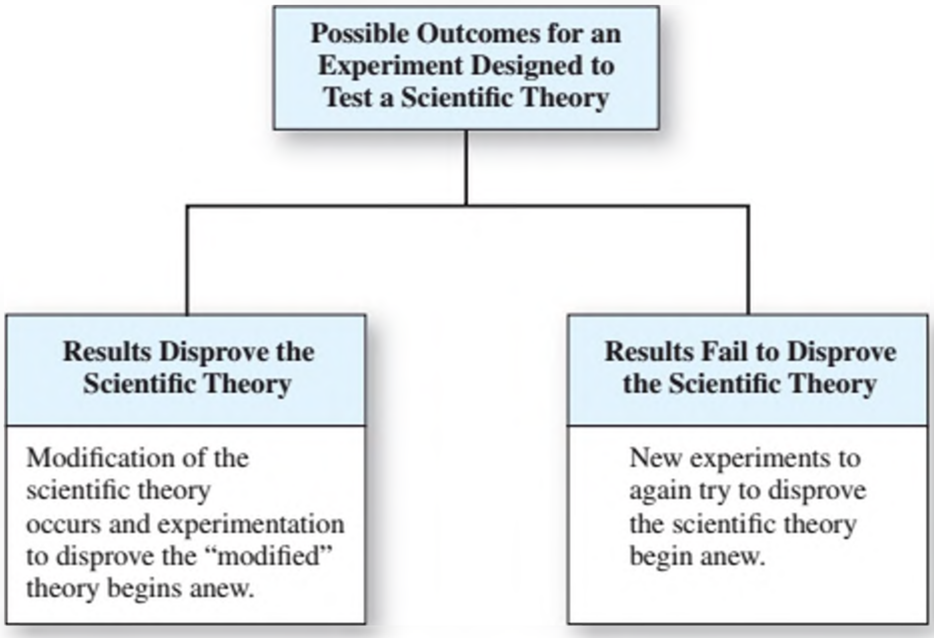

FIGURE 1.5 Possible results from attempting to disprove a scientific theory.

Theoretically, experimentation to "disprove" a theory is a never-to-be-completed process. However, in practice, after many, many failed attempts to disprove, experimentation attempts to become infrequent and the scientific theory becomes one of the foundations of the scientific discipline.

Figure 1.5 summarizes diagrammatically the preceding line of reasoning relative to disproving a scientific theory.

1.6 APPLICATION LIMITATIONS FOR METHODS OF SCIENCE

Student Learning Focus: Be able to explain the application limitations for the methods of science.

The testability requirement associated with scientific theories and scientific hypotheses also has the effect of limiting the application of these theories and hypotheses to the realm of the natural world. The methods of science are not applicable to supernatural phenomenon. The dictionary definition for *supernatural* is "not of the natural world," that is, something that cannot be explained using scientific laws. Thus, science is not equipped to deal with philosophical or religious questions such as "What is the purpose of life?" or "Does the human body contain a spirit that gives it life?" Questions such as these fall outside the realm of science because of their lack of testability using scientific methods. This does not mean that such questions are not valid questions nor that they are not important questions. It simply means that answers to such questions cannot be obtained using the methodology of science.

Concepts to Remember

The following concise summaries of chapter content by section restate the major ideas (concepts) considered in the chapter. They are a helpful study aid for students as they prepare for an upcoming examination or are reviewing for a final comprehensive examination.

1. **Science and Scientific Disciplines** Science is the study in which humans attempt to organize and explain, in a systematic manner, knowledge about themselves and their surroundings. Scientific disciplines, of which chemistry is one, are branches of science limited in size and scope to make them more manageable.