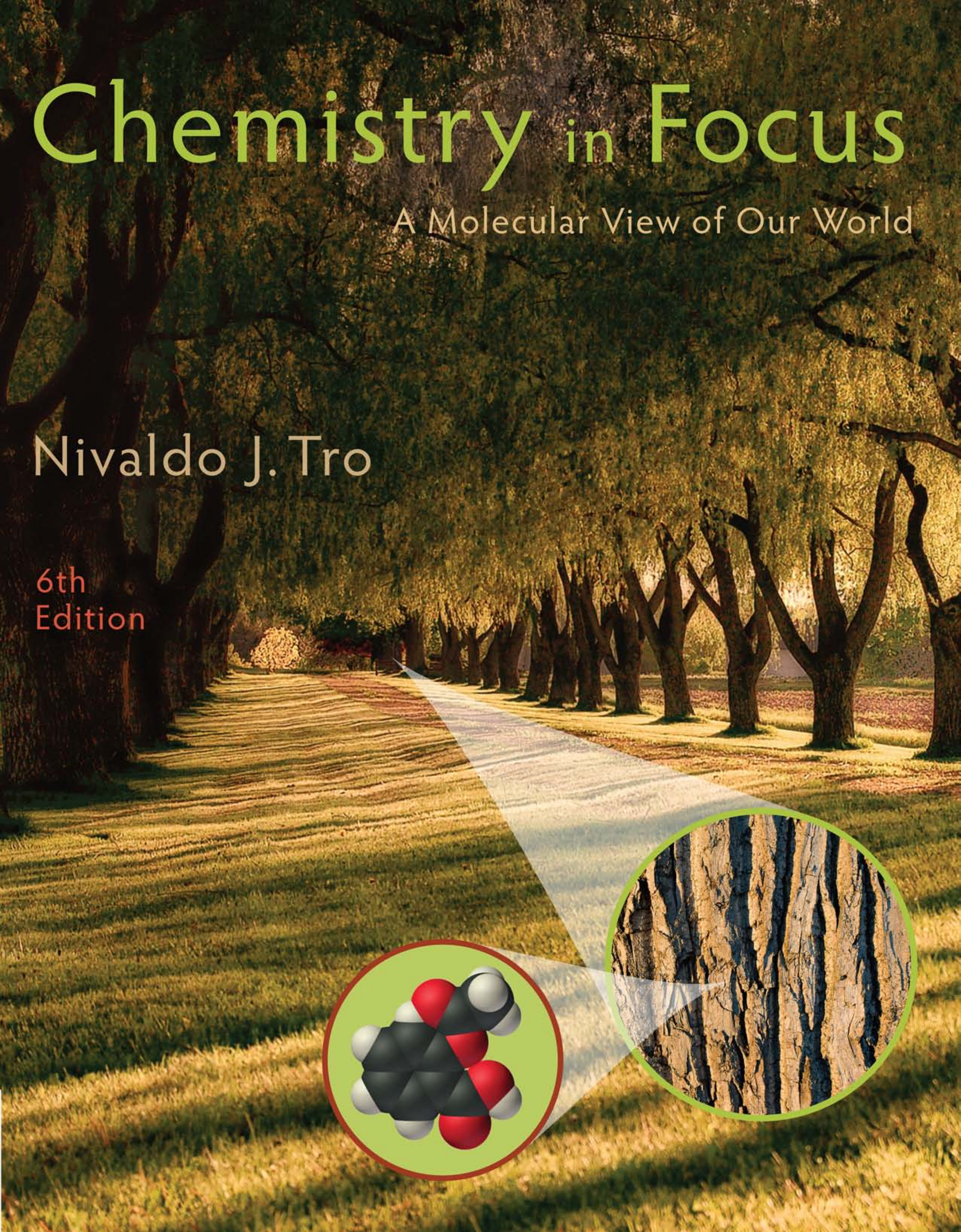
Chemistry in Focus

A Molecular View of Our World

Nivaldo J. Tro

6th
Edition



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CHEMISTRY
IN FOCUS

A Molecular View of Our World

Nivaldo J. Tro
Westmont College

With special contributions by

Don Neu
St. Cloud State University

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To Annie

About the Author

Nivaldo J. Tro received his BA degree from Westmont College and his PhD degree from Stanford University. He went on to a postdoctoral research position at the University of California at Berkeley. In 1990, he joined the chemistry faculty at Westmont College in Santa Barbara, California. Professor Tro has been honored as Westmont's outstanding teacher of the year three times (1994, 2001, and 2008). He was named Westmont's outstanding researcher of the year in 1996. Professor Tro lives in the foothills of Santa Barbara with his wife, Ann, and their four children, Michael, Alicia, Kyle, and Kaden. In his leisure time, Professor Tro likes to spend time with his family in the outdoors. He enjoys running, biking, surfing, and snowboarding.

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Preface

To the Instructor

Chemistry in Focus is a text designed for a one-semester college chemistry course for students not majoring in the sciences. This book has two main goals: the first is to develop in students an appreciation for the molecular world and the fundamental role it plays in daily life; the second is to develop in students an understanding of the major scientific and technological issues affecting our society.

The two main goals of this book are for students to understand the molecular world and to understand the scientific issues that face society.

A MOLECULAR FOCUS

The first goal is essential. Students should leave this course understanding that the world is composed of atoms and molecules and that everyday processes—water boiling, pencils writing, soap cleaning—are caused by atoms and molecules. After taking this course, a student should look at water droplets, salt crystals, and even the paper and ink of their texts in a different way. They should know, for example, that beneath the surface of a water droplet or a grain of salt lie profound reasons for each of their properties. From the opening example to the closing chapter, this text maintains this theme through a consistent focus on explaining the macroscopic world in terms of the molecular world.

The art program, a unique component of this text, emphasizes the connection between what we see—the macroscopic world—and what we cannot see—the molecular world. Throughout the text, photographs of everyday objects or processes are magnified to show the molecules and atoms responsible for them. The molecules within these magnifications are depicted using space-filling models to help students develop the most accurate picture of the molecular world. Similarly, many molecular formulas are portrayed not only with structural formulas but with space-filling drawings as well. Students are not meant to understand every detail of these formulas—because they are not scientists, they do not need to. Rather, they should begin to appreciate the beauty and form of the molecular world. Such an appreciation will enrich their lives as it has enriched the lives of those of us who have chosen science and science education as our career paths.

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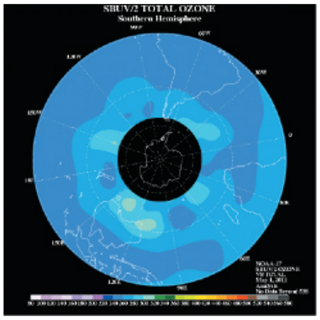
CHEMISTRY IN A SOCIETAL AND ENVIRONMENTAL CONTEXT

The other primary goal of this text is to develop in students an understanding of the scientific, technological, and environmental issues facing them as citizens and consumers. They should leave this course with an understanding of the impact of chemistry on society and on humankind's view of itself. Topics such as global warming, ozone depletion, acid rain, drugs, medical technology, and consumer products are covered in detail. In the early chapters, which focus primarily

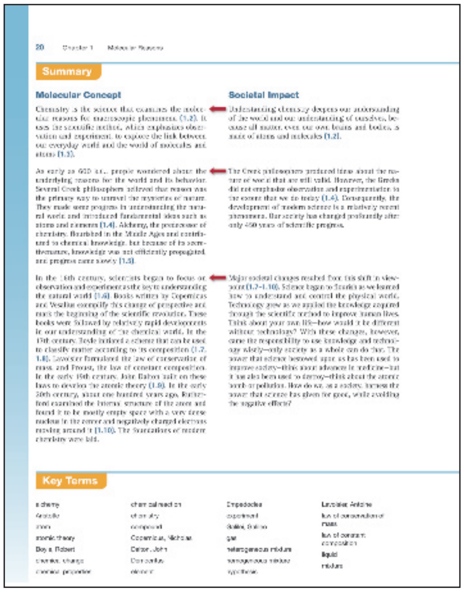


NOAA

on chemical and molecular concepts, many of the box features introduce these applications and environmental concerns. The later chapters focus on these topics directly and in more detail.

MAKING CONNECTIONS

Throughout the text, I have made extensive efforts to help students make connections, both between the molecular and macroscopic world and between principles and applications. The chapter summaries are designed to reinforce those connections, particularly between chemical concepts and societal impact. The chapter summaries consist of two columns, one summarizing the major molecular concepts of the chapter and the other, the impacts of those concepts on society. By putting these summaries side by side, the student can clearly see the connections.



Summary

Molecular Concept

Societal Impact

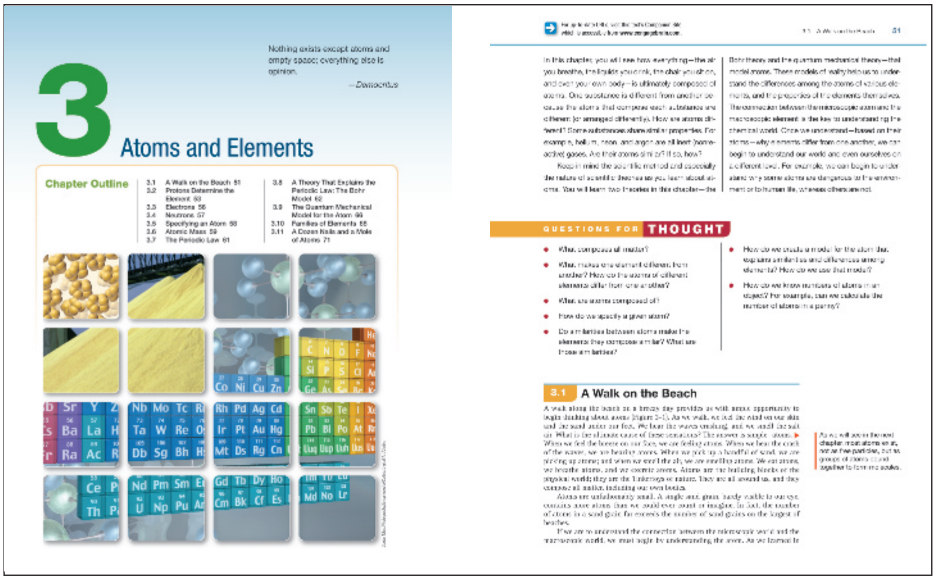
Key Terms

A Tour of the Text

GENERAL CHAPTER STRUCTURE

Each chapter introduces the material with *Questions for Thought.*

Each chapter opens with a brief paragraph introducing the chapter's main topics and explaining to students why these topics are relevant to their lives. These openers pose questions to help students understand the importance of the topics. For example, the opening paragraphs to Chapter 1 state, "As you read these pages, think about the scientific method—its inception just a few hundred years ago has changed



Nothing exists except atoms and empty space; everything else is opinion.

—*Democritus*

3 Atoms and Elements

Chapter Outline

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QUESTIONS FOR THOUGHT

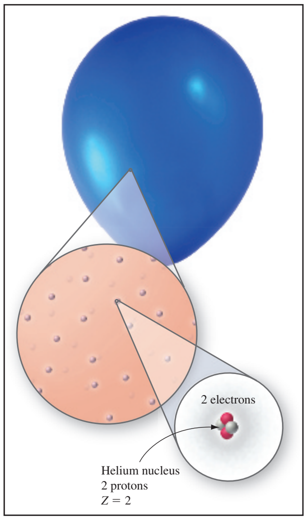
3.1 A Walk on the Beach

human civilization. What are some of those changes? How has the scientific method directly impacted the way you and I live?"

The opening paragraphs of each chapter are followed by *Questions for Thought* directly related to chapter content. These questions are answered in the main body of each chapter; presenting them early provides a context for the chapter material.

Most chapters, as appropriate, follow with a description or thought experiment about an everyday experience. The observations of the thought experiment are then explained in molecular terms. For example, a familiar experience may be washing a greasy dish with soapy water. Why does plain water not dissolve the grease? The molecular reason is then given, enhanced by artwork that shows a picture of a soapy dish and a magnification showing what happens with the molecules.

Continuing this theme, the main body of each chapter introduces chemical principles in the context of discovering the molecular causes behind everyday observations. What is it about helium *atoms* that makes it possible to breathe small amounts of helium *gas*—as in a helium balloon—without adverse side effects? What is it about chlorine *atoms* that makes breathing chlorine *gas* dangerous? What happens to water *molecules* when water boils? These questions have molecular answers that teach and illustrate chemical principles. The text develops the chemical principles and concepts involved in a molecular understanding of the macroscopic observations.

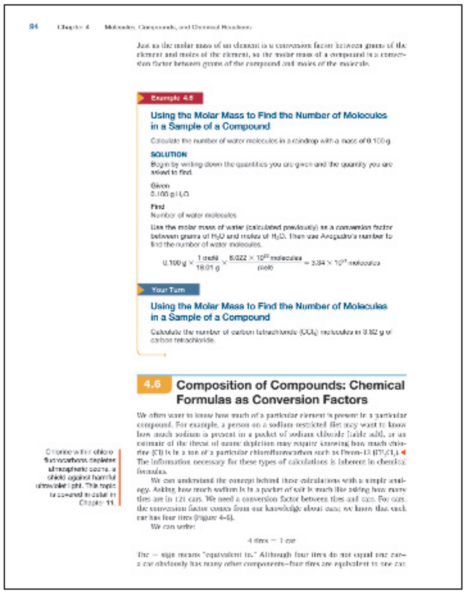


Progressive Information Technologies

Once the student is introduced to basic concepts, consumer applications and environmental problems follow. The text, however, does not separate principles and applications. Early chapters involving basic principles also contain applications, and later chapters with more emphasis on applications build on and expand basic principles.

EXAMPLES AND YOUR TURN EXERCISES

Example problems are included throughout the text, followed by related *Your Turn* exercises for student practice. In designing the text, I made allowances for different instructor preferences on quantitative material. Although a course for nonmajors is not usually highly quantitative, some instructors prefer more quantitative material than others. To accommodate individual preferences, many quantitative sections, including some *Examples* and *Your Turn* exercises, can be easily omitted. These are often placed toward the end of chapters for easy omission. Similarly, exercises in the back of each chapter that rely on quantitative material can also be easily omitted. Instructors desiring a more quantitative course should include these sections, whereas those wanting a more qualitative course can skip them. The answers to the *Your Turn* exercises can be found in Appendix 3.



Example 4.6

Using the Molar Mass to Find the Number of Molecules in a Sample of a Compound

Calculate the number of water molecules in a raindrop with a mass of 0.100 g.

SOLUTION

Begin by writing down the quantities you are given and the quantity you are asked to find.

Given
0.100 g H_2O

Find
Number of water molecules

Use the molar mass of water (calculated previously) as a conversion factor between grams of H_2O and moles of H_2O. Then use Avogadro's number to find the number of water molecules.

$$0.100\ \text{g} \times \frac{1\ \text{mol}}{18.01\ \text{g}} \times \frac{6.022 \times 10^{23}\ \text{molecules}}{\text{mol}} = 3.34 \times 10^{21}\ \text{molecules}$$

Your Turn

Using the Molar Mass to Find the Number of Molecules in a Sample of a Compound

Calculate the number of carbon tetrachloride (CCl_4) molecules in 3.82 g of carbon tetrachloride.

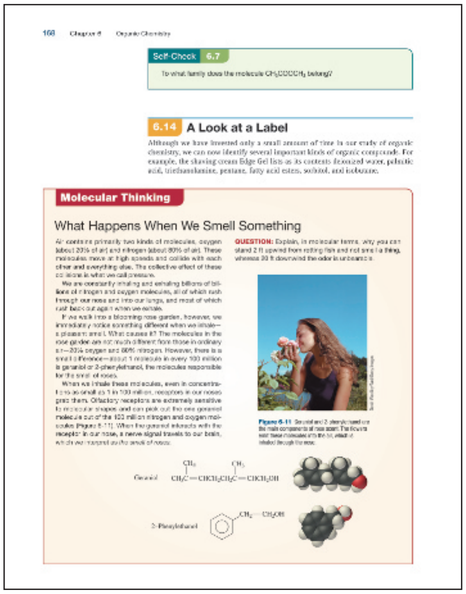
4.6 Composition of Compounds: Chemical Formulas as Conversion Factors

BOXED FEATURES

Molecular Thinking

Boxed features show relevance and ask students to interact with the material.

Molecular Thinking boxes describe an everyday observation related to the chapter material. The student is then asked to explain the observation based on what the molecules are doing. For example, in Chapter 4, when chemical equations and combustion are discussed, the *Molecular Thinking* box describes how a fire will burn hotter in the presence of wind. The student is then asked to give a molecular reason—based on what was just learned about chemical equations and combustion—to explain this observation.



Self-Check 6.7

To what family does the molecule CH_3COOCH_3 belong?

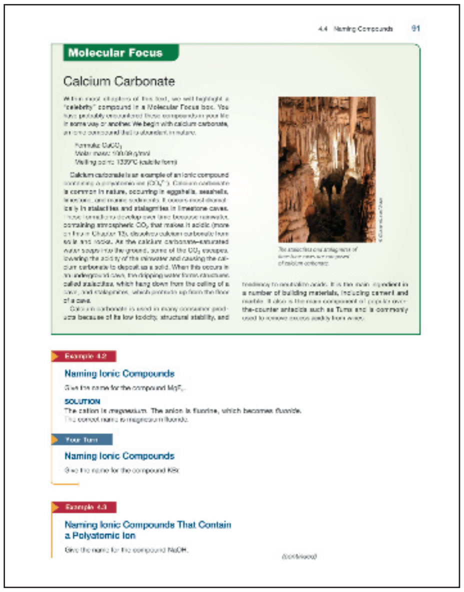
6.14 A Look at a Label

Although we have invested only a small amount of time in our study of organic chemistry, we can now identify several important kinds of organic compounds. For example, the shaving cream Edge Gel lists as its contents deionized water, palmitic acid, triethanolamine, pentane, fatty acid esters, sorbitol, and isobutane.

Molecular Thinking

What Happens When We Smell Something

QUESTION: Explain, in molecular terms, why you can stand 2 ft upwind from rotting fish and not smell a thing, whereas 20 ft downwind the odor is unbearable.



4.4 Naming Compounds 91

Molecular Focus

Calcium Carbonate

Example 4.2

Naming Ionic Compounds

Give the name for the compound MgF_2.

SOLUTION

The cation is magnesium. The anion is fluorine, which becomes fluoride. The correct name is magnesium fluoride.

Your Turn

Naming Ionic Compounds

Give the name for the compound KBr.

Example 4.3

Naming Ionic Compounds That Contain a Polyatomic Ion

Give the name for the compound NaOH.

(continued)

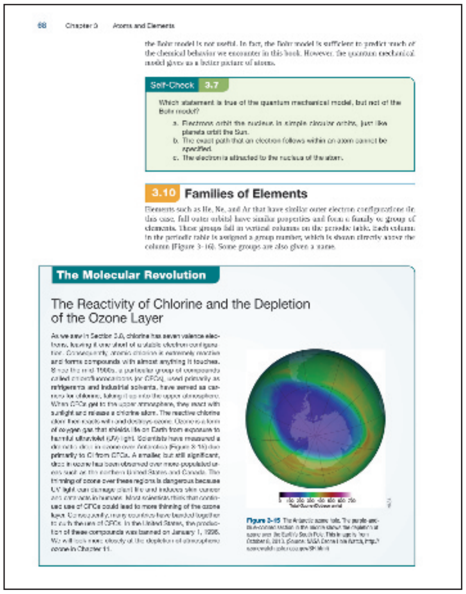
Molecular Focus

Celebrity compounds are highlighted.

Molecular Focus boxes highlight a "celebrity" compound related to the chapter's material. The physical properties and structure of the compound are given and its use(s) described. Featured compounds include calcium carbonate, hydrogen peroxide, ammonia, AZT, retinal, sulfur dioxide, ammonium nitrate, and others.

The Molecular Revolution

Molecular Revolution boxes highlight topics of modern research and recent technology related to the chapter's material. Examples include measuring global temperatures, imaging atoms with scanning tunneling microscopy, and the development of fuel cell and hybrid electric vehicles.



68 Chapter 3 Atoms and Elements

Self-Check 3.7

Which statement is true of the quantum mechanical model, but not of the Bohr model?

a. Electrons orbit the nucleus in simple circular orbits, just like planets orbit the Sun.
b. The exact path that an electron follows within an atom cannot be specified.
c. The electron is attracted to the nucleus of the atom.

3.10 Families of Elements

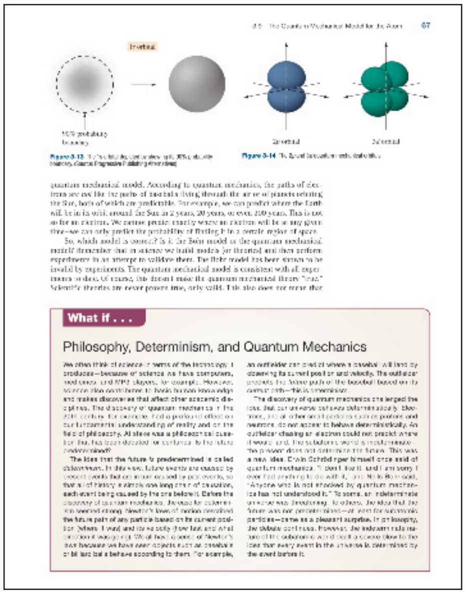
Elements such as He, Ne, and Ar that have similar outer electron configurations (in this case, full outer orbits) have similar properties and form a family or group of elements. These groups fall in vertical columns on the periodic table. Each column in the periodic table is assigned a group number, which is shown directly above the column (Figure 3-16). Some groups are also given a name.

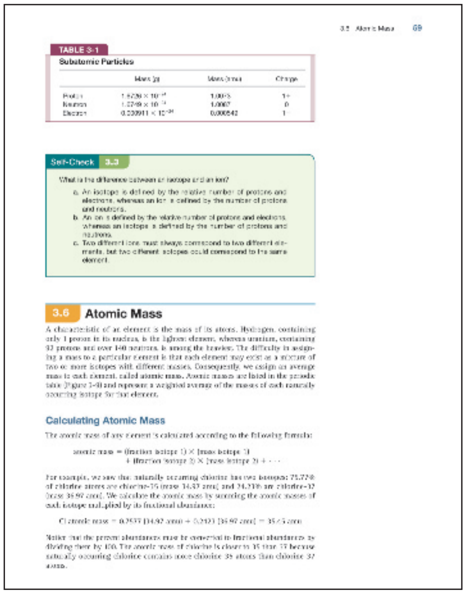
The Molecular Revolution

The Reactivity of Chlorine and the Depletion of the Ozone Layer

What if . . .

What if . . . boxes discuss topics with societal, political, or ethical implications. At the end of the discussion there are one or more open-ended questions for group discussion. Topics include the Manhattan Project, government subsidies for the development of alternative fuels, stem cell research, and others.



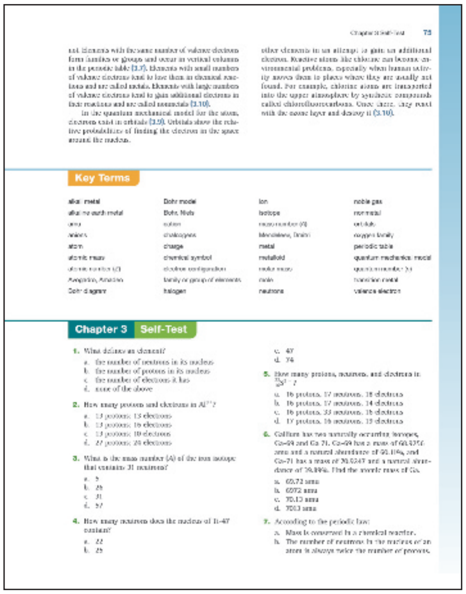


Self-Check

The *Self-Check* boxes consist of questions that allow students to periodically check their comprehension. The questions reinforce the key concepts in the text, develop students' critical thinking skills, and help them relate the material to the world around them.

Self-Test

At the end of Chapters 1–18 a *Self-Test* is provided to allow students to further test their comprehension of the entire chapter's material. The questions are designed to complement the Self-Check boxes the student has already encountered within the chapter.



Chapter summaries review main molecular concepts and their societal impacts.

CHAPTER SUMMARIES

Summary

Molecular Concept

Societal Impact

Chapters end with a two-column summary of the ideas presented in the main body of the chapter. In this summary, students get a side-by-side review of the chapter, with molecular concepts in one column and the coinciding societal impact in the other. The chapter summary allows the student to get an overall picture of the chapter and strengthens the connection between principles and applications.

KEY TERMS

Each chapter has a set of key terms from within that chapter for review and study. Each of the key terms is defined in the Glossary at the end of the text.

STUDENT EXERCISES

All chapters contain exercises of four types: *Questions*, *Problems*, *Points to Ponder*, and *Feature Problems and Projects*. The *Questions* ask students to recall many of the key concepts from the chapter. The *Problems* ask students to apply what they have learned to solve problems similar to those in the chapter *Examples* and *Your Turn* boxes. The *Points to Ponder* consist primarily of open-ended short-essay questions in which students are asked about the ethical, societal, and political implications of scientific issues. The *Feature Problems and Projects* contain problems with graphics and short projects, often involving Web-based inquiry.

NEW TO THIS EDITION

The sixth edition of *Chemistry in Focus* contains several changes from the previous edition.

Each chapter now has a Self-Test that consists of 10–15 multiple choice questions. Students can use these Self-Tests to assess their knowledge of the chapter material and to help them prepare for exams.

- Interest boxes have been updated or revised to reflect progress and current issues. See, for example, the *Molecular Thinking* box in Section 10.6, *What If . . .* box in Section 10.7, and *The Molecular Revolution* boxes in Sections 10.11 and 14.6.
- All real-world information in figures and tables has been updated to the latest possible data. See, for example, Figures 2-7, 3-15, 9-2, 9-6, 9-7, 9-13, 9-14, 10-2, 11-7, 11-8, 11-14, 13-6, and 13-7; Tables 9-1, 9-7, 10-1, 10-2, 11-3, 11-4; and Example 2-4.
- Selected end-of-chapter problems have been modified, and some new problems have been added. See, for example, problems 3.46, 3.48, 4.25, 4.26, 6.49, and 6.50.
- All photos have been analyzed and updated as needed.

- Placement of margin notes has been evaluated, and pointers have been added throughout to better connect the basal text to the margin notes.
- The placement of figures has been evaluated and adjusted for ease of reference. Some previously numbered figures and existing numbered figures have been renumbered.
- The flow chart style has been revised and updated. See, for example, Figures 1-3, 1-4, 1-8, 6-4 and 12-19.
- The data in end-of-chapter problems has been updated. See, for example, the problems 2.37, 9.57, 9.58, 10.43, 17-75, and 17-76.

Below is a list of some of the specific changes in the book.

- In Chapter 9, the section on nuclear waste disposal was updated to reflect the latest recommendations of the Blue Ribbon Commission on America's Nuclear Future. The section on the future of nuclear power has also been updated to reflect changes in international attitudes toward nuclear power since the Fukushima accident.
- The unit of radiation exposure has been changed from the REM to the SI unit, Sievert. This change is reflected throughout the basal text, the tables, and the end-of-chapter problems (see Section 8.10).
- Section 9.2 has been updated to reflect changes in world energy consumption.
- Section 10.9 has been updated to reflect changes in nuclear power.

Supporting Materials

Please visit http://www.cengage.com/chemistry/tro/cheminfocus6e for information about student and instructor resources for this text.

Acknowledgments

I am grateful to my colleagues at Westmont College, who have given me the space to write this book. I am especially grateful to Mark Sargent, Allan Nishimura, David Marten, Kristi Lazar, Michael Everest, and Steven Contakes for their support. Thanks to Don Neu for his great help with the nanotechnology chapter. I am grateful to my editor, Elizabeth Woods, who has been incredibly gracious and helpful to me throughout this revision, and to Karolina Kiwak, who handled the creation of the supplementary material. I am also grateful to Teresa Trego, the production manager at Cengage Learning, and the team she worked with at MPS Limited.

Thanks also to those who supported me personally while writing this book. I am particularly grateful to my wife, Ann, whose love healed a broken man. Thanks to my children, Michael, Ali, Kyle, and Kaden—they are my raison d'être. I come from a large and close extended Cuban family who have stuck by me through all manner of difficult circumstances. I thank my parents, Nivaldo and Sara, and my siblings, Sarita, Mary, and Jorge. Thanks also to Pam—may her spirit rest in peace.

I am greatly indebted to the reviewers of each of the editions of this book, who are listed below. They have all left marks on the work you are now holding. Lastly, I thank my students, whose lives energize me and whose eyes continually provide a new way for me to see the world.

—Nivaldo J. Tro
Westmont College

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Science, like art, is fun, a
playing with truths. . . .

—*W. H. Auden*

1

Molecular Reasons

Chapter Outline

Brooks/Cole, Cengage Learning; Charles D. Winters

For up-to-date URLs, visit this text's Companion Site, which is accessible from **www.cengagebrain.com.**

In this book, you will learn about chemistry, the science that investigates the small to understand the large. You will, in my opinion, be a deeper and better-educated person if you understand one simple fact: *All that is happening around you has a molecular cause.* When you understand the molecular realm that lies behind everyday processes, the world becomes a larger and richer place.

In this chapter, you will learn about the scientific method—the method that chemists use to learn about the molecular realm. Contrary to popular thought, the scientific method is creative, and the work of the scientist is not unlike the work of the artist. As you read these pages, think about the modern scientific method—its inception just a few hundred years ago has changed human civilization. What are some of those changes? How has the scientific method directly impacted the way you and I live?

We will then move on to some fundamental chemical principles that help us make sense of the vast variety of substances that exist in the world. As you learn the details of atoms, elements, compounds, and mixtures, keep in mind the central role that science plays in our society today. Also remember that you don't need to go into the laboratory or look to technology to see chemistry because—even as you sit reading this book—*all that is happening around you has a molecular cause.*

QUESTIONS FOR THOUGHT

- What is chemistry?
- How do scientists learn about the world?
- How did science and chemistry develop?
- What is matter and how do we classify it?
- What is matter composed of?
- What is the structure of an atom?

1.1 Firesticks

Flames are fascinating. From the small flicker of a burning candle to the heat and roar of a large campfire, flames captivate us. Children and adults alike will stare at a flame for hours—its beauty and its danger demand attention. My children have a beloved campfire ritual they call "firesticks." They find dry tree branches, two to three feet long, and ignite the tips in the campfire. They then pull the flaming branches out of the fire and wave them in the air, producing a trail of light and smoke. My reprimands about the danger of this practice work for only several minutes, and then waving wands of fire find their way back into their curious little hands.

As fascinating as flames are, an unseen world—even more fantastic—lies beneath the flame. This unseen world is the world of molecules, the world I hope you see in the pages of this book. We will define molecules more carefully later; for now think of them as tiny particles that make up matter—so tiny that a single flake of ash from a fire contains one million trillion of them. The flame on my children's firesticks and in the campfire is composed of molecules, billions of billions of them rising upward and emitting light (Figure 1-1).

The molecules in the flame come from an extraordinary transformation—called a **chemical reaction**—in which the molecules within the wood combine with certain molecules in air to form new molecules. The new molecules have excess energy that they shed as heat and light as they escape in the flame. Some of them, hopefully after cooling down, might find their way into your nose, producing the smell of the fire.

Let's suppose for a moment that we could see the molecules within the burning wood—we would witness a frenzy of activity. A bustling city during rush hour

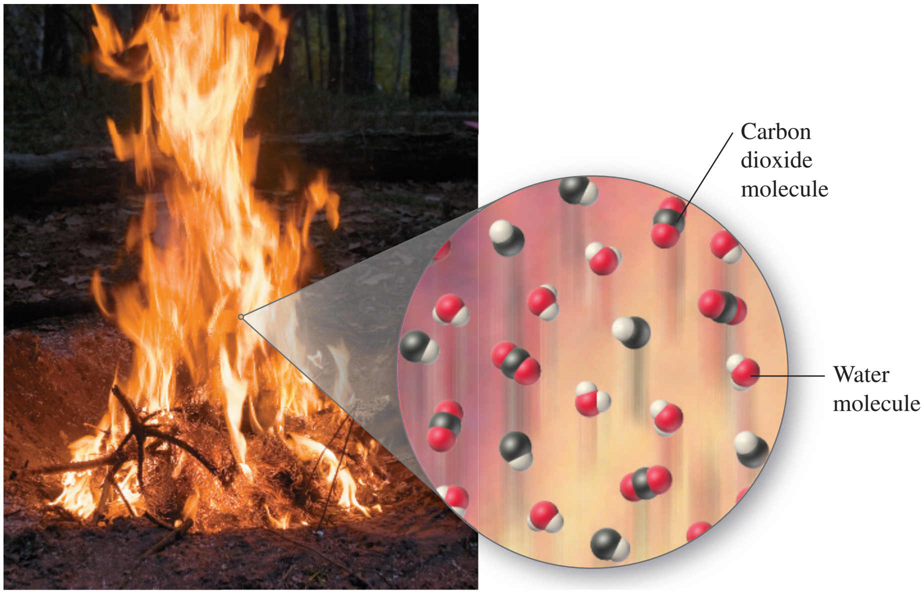

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Figure 1-1 The flame you see in a fire is composed of newly created, energetic molecules. They form from the reaction between the molecules within the log and the molecules in the air. They move upward, away from the log, giving off heat and light as they travel.

would appear calm by comparison. The molecules in the wood, all vibrating and jostling trillions of times every second, rapidly react with molecules in the air. The reaction of a single molecule with another occurs within a split second, and the newly produced molecules fly off in a trail of heat and light, only to reveal the next molecule in the wood—ready to react. This process repeats itself trillions of times every second as the wood burns. Yet on the macroscopic scale—the scale that we see—the process looks calm. The wood disappears slowly, and the flame from a few good logs lasts several hours.

1.2 Molecular Reasons

All that is happening around you has a molecular cause. When you write, eat, think, move, or breathe, molecules are in action, undergoing changes that make these things happen. The world that you can see—that of everyday objects—is determined by the world you cannot see—that of atoms, molecules, and their interactions. **Chemistry** is *the science that investigates the molecular reasons for the processes occurring in our macroscopic world.* Why are leaves green? Why do colored fabrics fade on repeated exposure to sunlight? What happens when water boils? Why does a pencil leave a mark when dragged across a sheet of paper? These basic questions can be answered by considering atoms and molecules and their interactions with each other.

For example, over time you might see a red shirt fade as it is exposed to sunlight. The molecular cause is energy from the sun, which decomposes the molecules that gave the shirt its red color. You may notice that nail polish remover accidentally spilled on your hand makes your skin feel cold as it evaporates. The molecular cause is molecules in your skin colliding with the evaporating molecules in the nail polish remover, losing energy to them, and producing the cold sensation. You may see that sugar stirred into coffee readily dissolves (Figure 1-2). The sugar seems to disappear in the coffee. However, when you drink the coffee, you know the sugar is still there because you can taste its sweetness. The molecular cause is that a sugar molecule has a strong attraction for water molecules and prefers to leave its neighboring sugar molecules and mingle with the water. You see this as the apparent disappearing of the solid sugar, but it is not disappearing at all, just mixing on the molecular level. Chemists, by using the scientific method, investigate the molecular world; they examine the molecular reasons for our macroscopic observations.

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Chemists investigate the molecular reasons for physical phenomena.

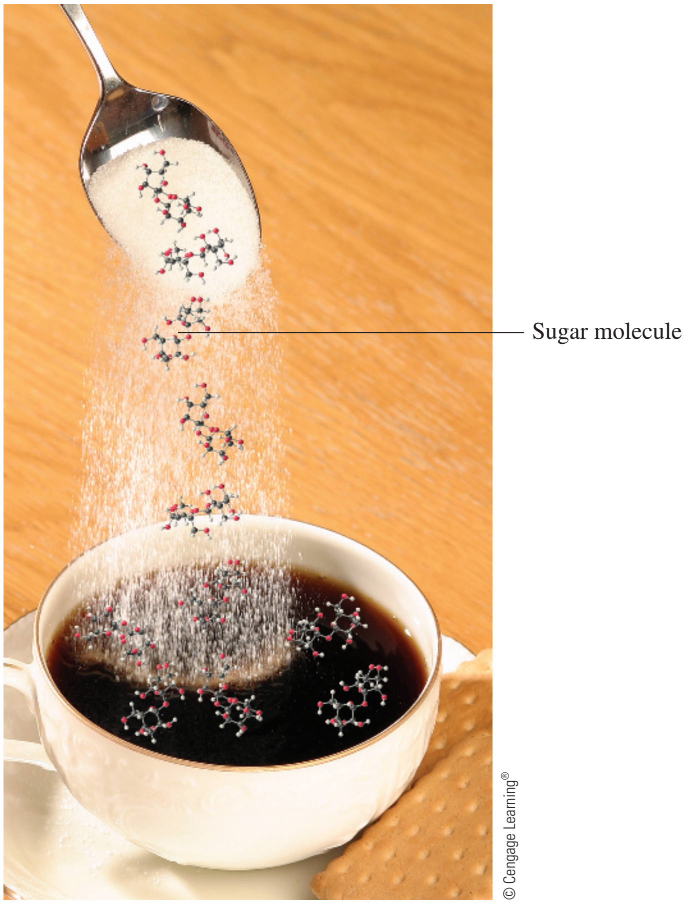

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Figure 1-2 When sugar dissolves into coffee, the sugar molecules mix with the water molecules.

1.3 The Scientist and the Artist

Science and art are often perceived as different disciplines, attracting different types of people. Artists are often perceived to be highly creative and uninterested in facts and numbers. Scientists, in contrast, are perceived to be uncreative and interested only in facts and numbers. Both images are false, however, and the two professions have more in common than is generally imagined.

We can begin to understand the nature of scientific work by studying the **scientific method**, outlined in Figure 1-3. The first step in the scientific method is

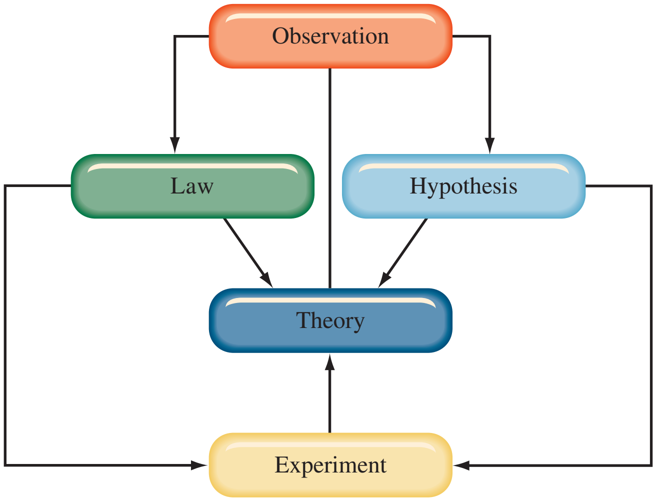


Figure 1-3 The scientific method.

What if . . .

Why Should Nonscience Majors Study Science?

You may be reading this book because it is required reading in a required course. You are probably not a science major and might be wondering why you should study science. I propose three reasons why you should study science, specifically because you are not a science major.

First, modern science influences culture and society in profound ways and raises ethical questions that only society as a whole can answer. For example, in the early part of this century, scientists at a biotechnology company in Massachusetts succeeded for the first time in cloning (making a biological copy of) a human embryo. Their reason for cloning the embryo was *not* human reproduction (they were not trying to make a race of superhumans or clones of themselves) but rather to cure and treat diseases. This kind of cloning, called *therapeutic cloning* (as opposed to reproductive cloning), holds as its goal the creation of specialized cells (called stem cells) to be used, for example, to cure diabetes or to mend damaged spinal cords. The potential benefits of this research are significant, but it also carries some moral risk. Does the benefit of curing serious disease outweigh the risk of creating human embryos? Only society as a whole can answer that question. If our society is to make intelligent decisions on issues such as this, we, as citizens of that society, should have a basic understanding of the scientific principles at work.

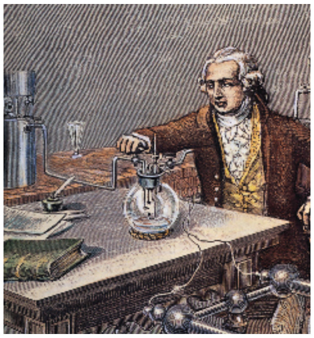
Second, decisions involving scientific principles are often made by nonscientists. Politicians are generally not trained in science, nor are the people electing the politicians. Yet politicians make decisions concerning science policy, science funding, and environmental regulation. A clever politician could impose unsound scientific policy on an uninformed electorate. For example, Adolf Hitler proposed his own versions of Nazi genetics on the German people. He wrongly proposed that the Aryan race could make itself better by isolating itself from other races. According to Hitler, Aryans should only reproduce with other Aryans to produce superior human beings. However, any person with a general knowledge of genetics would know that Hitler was wrong. Excessive inbreeding actually causes genetic weaknesses in a population. For this reason, purebred dogs have many genetic problems, and societal taboos exist for intrafamily marriages. History demonstrates other examples of this sort of abuse. Agriculture in the former Soviet Union still suffers from years of misdirected policies based on communistic ideas of growing crops, and South America has seen failures in land use policies that were scientifically ill informed. If you are at all interested in the sustainability of our planet, you need to have a basic understanding of science so that you can help make intelligent decisions about its future.

Third, science is a fundamental way to understand the world around us and therefore reveals knowledge not attainable by other means. Such knowledge will deepen and enrich your life. For example, an uninformed observer of the night sky may marvel at its beauty but will probably not experience the awe that comes from knowing that even the closest star is trillions of miles away or that stars produce light in a process that could only start at temperatures exceeding millions of degrees. For the uninformed, the world is a two-dimensional, shallow place. For the informed, the world becomes a deeper, richer, and more complex place. In chemistry, we learn about the world that exists behind the world we see, a world present all around us and even inside of us. Through its study we are better able to understand our world and better able to understand ourselves.

the **observation** or measurement of some aspect of nature. This may involve only one person making visual observations, or it may require a large team of scientists working together with complex and expensive instrumentation. A series of related observations or measurements may be combined to formulate a broadly applicable generalization called a **scientific law**. As an example, consider the work of **Antoine Lavoisier (1763–1794)**, a French chemist who studied combustion, a type of chemical reaction. Lavoisier carefully measured the weights of objects before and after burning them in closed containers. He noticed that the initial weight of the substance being burned and the final weight of the substances that were formed during burning were always equal. As a result of these observations, he formulated the **law of conservation of mass**, which states the following:

> In a chemical reaction matter is neither created nor destroyed.

Unfortunately, Lavoisier was part of the establishment at a time when the establishment was extremely unpopular. He was guillotined in 1794 by French revolutionists. His controlled observations, however, led to a general law of nature that applies not only to combustion but also to every known chemical reaction. The burning log discussed in the opening section of this book, for example, does not disappear into nothing; it is transformed into ash and gas. The weight lost by the log while burning and the weight of the oxygen that it reacted with exactly equal the weight of the ash and gas formed. Laws like these do not automatically fall out of a series of measurements. The measurements must be carefully controlled. But then the scientist must be creative in seeing a pattern that others have missed and formulating a scientific law from that pattern.


Science Source

Antoine Lavoisier, also known as the father of modern chemistry.

Scientific laws summarize and predict behavior, but they do not explain the underlying cause. A **hypothesis** is an initial attempt to explain the underlying causes of observations and laws. A hypothesis is a tentative model (educated by observation) that is then tested by an **experiment**, a controlled observation specifically designed to test a hypothesis. One or more confirmed hypotheses (possibly with the additional support of observations and laws) may evolve into an overarching model of reality called a **theory**. A good theory often predicts behavior far beyond the observations and laws from which it was formulated. For example, John Dalton, an English chemist, used the law of conservation of mass along with other laws and observations to formulate his atomic theory, which asserts that all matter is composed of small particles called atoms. Dalton took a creative leap from the law of conservation of mass to a theory about atoms. ◀ His ingenuity led to a theory that explained the law of conservation of mass by predicting the existence of microscopic particles, the building blocks of all matter.

The atomic theory is described in more detail in Section 1.9.

You can find the answers to Self-Check questions at the end of the chapter.

Self-Check 1.1

A chemist observes the behavior of a gas by filling a balloon and measuring its volume at different temperatures. After making many measurements, he concludes that the volume of a gas always increases with increasing temperature. Is this an example of a law or a theory?

Example 1.1

The Scientific Method

Suppose you are an astronomer mapping the galaxies in the sky for the very first time. You discover that all galaxies are moving away from Earth at high speeds. As part of your studies, you measure the speed and distance from the Earth of a number of galaxies. Your results are shown here.

Distance from Earth	*Speed Relative to Earth*
5.0 million light-years	600 miles/second (mi/s)
8.4 million light-years	1000 mi/s
12.3 million light-years	1500 mi/s
20.8 million light-years	2500 mi/s

Formulate a law based on your observations.

Because laws summarize a number of related observations, you can formulate the following law from the tabulated observations:

The farther away a galaxy is from Earth, the faster its speed.

Devise a hypothesis or theory that might explain the law.

You may devise any number of hypotheses or theories consistent with the preceding law. Your hypotheses must, however, give the underlying reasons behind the law. One possible hypothesis:

> Earth has a slowing effect on all galaxies. Those galaxies close to Earth experience this effect more strongly than those that are farther away and therefore travel more slowly.

Another possible hypothesis:

> Galaxies were formed in an expansion that began sometime in the past and are therefore moving away from each other at speeds that depend on their separation.

What kinds of experiments would help validate or disprove these hypotheses?

For the first hypothesis, you might devise experiments that try to measure the nature of the slowing effect that Earth exerts on galaxies. For example, the force responsible for the slowing may also affect the Moon's movement, which might be measured by experiment. For the second hypothesis, experiments that look for other evidence of an expansion would work. For example, you might try to look for remnants of the heat or light given off by the expansion. Experimental confirmation of your hypothesis could result in the evolution of the hypothesis into a theory for how the universe came to exist in its present form.

Finally, like a hypothesis, a theory is subject to experiments. A theory is valid if it is consistent with, or predicts the outcome of, experiments. If an experiment is inconsistent with a particular theory, that theory must be revised, and a new set of experiments must be performed to test the revision. A theory is never proved, only validated by experimentation. The constant interplay between theory and experiment gives science its excitement and power.

The process by which a set of observations leads to a model of reality is the scientific method. It is similar, in some ways, to the process by which a series of observations of the world leads to a magnificent painting. Like the artist, the scientist must be creative. Like the artist, the scientist must see order where others have seen only chaos. Like the artist, the scientist must create a finished work that imitates the world. The difference between the scientist and the artist lies in the stringency of the imitation. The scientist must constantly turn to experiment to determine whether his or her ideas about the world are valid.

1.4 The First People to Wonder About Molecular Reasons

The Greek philosophers are the first people on record to have thought deeply about the nature of matter. As early as 600 B.C., these scholars wanted to know the *why* of things. However, they were immersed in the philosophical thought of their day that held that physical reality is an imperfect representation of a more perfect reality. As a result, they did not emphasize experiments on the imperfect physical world as a way to understand it. According to **Plato** (428–348 B.C.), *reason alone* was the superior way to unravel the mysteries of nature. Remarkably, Greek ideas about nature led to some ideas similar to modern ones.

Democritus (460–370 B.C.), for example, theorized that matter was ultimately composed of small, indivisible particles he called *atomos,* or atoms, meaning "not to cut." Democritus believed that if you divided matter into smaller and smaller pieces, you would eventually end up with tiny particles (atoms) that could not be divided any further. He is quoted as saying, "Nothing exists except atoms and empty space; everything else is opinion." Although Democritus was right by modern standards, most Greek thinkers, especially Aristotle and Plato, rejected his atomistic viewpoint.

Thales (624–546 B.C.) reasoned that any substance could be converted into any other substance, so that all substances were in reality one basic material. Thales believed that the one basic material was water. He said, "Water is the principle, or the element of things. All things are water." **Empedocles** (490–430 B.C.), on the other hand, suggested that all matter was composed of four basic materials or elements: air, water, fire, and earth. This idea was accepted by **Aristotle** (384–321 B.C.), who added a fifth element—the heavenly ether—perfect, eternal, and incorruptible. In Aristotle's mind, the five basic elements composed all matter, and this idea reigned for 2000 years.

1.5 Immortality and Endless Riches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Alchemists sought to turn ordinary materials into gold and to make "the elixir of life," a substance that would grant immortality.

The predecessor of chemistry, called **alchemy**, flourished in Europe during the Middle Ages. Alchemy was a partly empirical, partly magical, and entirely secretive pursuit with two main goals: the transmutation of ordinary materials into gold, and the discovery of the "elixir of life," a substance that would grant immortality to any who consumed it. In spite of what might today appear as misdirected goals, alchemists made some progress in our understanding of the chemical world. Through their obsession with turning metals into gold, they learned much about metals. They were able to form alloys—mixtures of metals—with unique properties. They also contributed to the development of laboratory separation and purification techniques that are still used today. In addition, alchemists made advances in the area of pharmacology by isolating natural substances and using them to treat ailments. Because of the mystical nature of alchemy and the preoccupation with secrecy, however, knowledge was not efficiently propagated, and up to the 16th century, progress was slow.

1.6 The Beginning of Modern Science

The publication of two books in 1543 marks the beginning of what is now called **the scientific revolution**. The first book was written by **Nicholas Copernicus** (1473–1543), a Polish astronomer who claimed that the Sun was the center of the universe. In contrast, the Greeks had reasoned that Earth was the center of the universe, with all heavenly bodies, including the Sun, revolving around Earth. Although complex orbits were required to explain the movement of the stars and planets, the Earth-centered universe put humans in the logical center of the created order. Copernicus, by using elegant mathematical arguments and a growing body of astronomical data, suggested exactly the opposite—the Sun stood still and Earth revolved around it. The second book, written by **Andreas Vesalius** (1514–1564), a Flemish anatomist, portrayed human anatomy with unprecedented accuracy.

The uniqueness of these books was their overarching emphasis on observation and experiment as the way to learn about the natural world. The books were revolutionary, and Copernicus and Vesalius laid the foundation for a new way to understand the world. Nonetheless, progress was slow. Copernicus's ideas were not popular among the religious establishment. **Galileo Galilei** (1564–1642), who confirmed and expanded on Copernicus's ideas, was chastised by the Roman Catholic Church for his views. Galileo's Sun-centered universe put man outside of the geometric middle of God's created order and seemed to contradict the teachings of Aristotle and the Church. As a result, the Roman Catholic Inquisition forced Galileo to recant his views. Galileo was never tortured, but he was subject to house arrest until he died.


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Galileo Galilei expanded on Copernicus's ideas of a Sun-centered rather than an Earth-centered universe.

What if . . .

Observation and Reason

Throughout this text, I will pose a number of open-ended questions that you can ponder and discuss. Some will have better-defined answers than others, but none will have a single correct answer. The first one follows.

The field of science is relatively young compared with other fields such as philosophy, history, or art. It has, however, progressed quickly. In the four and one-half centuries since the scientific revolution, science and its applications have dramatically changed our lives. In contrast, the tens of centuries before 1543 proceeded with comparatively few scientific advances. A major factor in the scarcity of scientific discoveries before 1543 was the Greek emphasis on reason over observation as the key to knowledge. Although some Greek philosophers, such as Aristotle, spent a great deal of time observing and describing the natural world, they did not emphasize experimentation and the modification of ideas based on the outcomes of experiments. What if the Greeks had placed a greater emphasis on experimentation? What if Democritus had set out to prove his atomistic view of matter by performing experiments? Where do you think science might be today?

The scientific method progressed nonetheless, and alchemy was transformed into chemistry. Chemists began to perform experiments to answer fundamental questions such as these: What are the basic elements? Which substances are pure and which are not? In 1661, **Robert Boyle** (1627–1691) published *The Skeptical Chymist,* in which he criticized Greek ideas concerning a four-element explanation of matter. He proposed that an element must be tested to determine whether it was really simple. If a substance could be broken into simpler substances, it was not an element.

1.7 The Classification of Matter

Matter can be classified by its composition (what it's composed of) or by its state (solid, liquid, or gas). We examine each of these in turn.

Classifying Matter by Its Composition

Boyle's approach led to a scheme, shown in Figure 1-4, that we use to classify matter today. In this scheme, all matter is first classifiable as either a **pure substance** or a **mixture.**

Pure Substances

A pure substance may be either an element or a compound. An **element** is a substance that cannot be decomposed into simpler substances. The graphite in pencils (Figure 1-5) is an example of an element—carbon. No amount of chemical transformation can decompose graphite into simpler substances; it is pure carbon. Other examples of elements include oxygen, a component of air; helium, the gas in helium balloons; and copper, used in plumbing and as a coating on pennies. The smallest identifiable unit of an element is an **atom.** There are about 90 different elements in nature and therefore about 90 different kinds of atoms.

A **compound** is a substance composed of two or more elements in fixed, definite proportions. Compounds are more common in nature than elements because most elements tend to combine with other elements to form compounds. Water