Chemistry and Life

An Introduction to General, Organic, and Biological Chemistry

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Preface

Why write a book?

Arnold Toynbee, British historian and author, says that the "only good reason . . . is because one's wish to write it is a master passion." We have experienced that desire. But writing is also hard work. A consuming passion must come from an important purpose. What is our purpose in writing this book? After all, there are other chemistry texts available for the life and health sciences. Briefly, we have set out to give you a book which:

Is readable, enjoyable. We feel that a chemistry text need not be stodgy in order to present good chemistry. Learning chemistry isn't easy, but it can be fun. A text can be readable and enjoyable. The use of humor at appropriate points can add to the excitement and satisfaction of learning.

Is consistently and directly related to life. Most texts do relate the biochemistry sections to the health and life sciences. We feel that all the basic principles and the inorganic chemistry as well, throughout the book, should also be related to life and living.

Has abundant examples, worked out in detail. We have provided sample problems, with detailed solutions, wherever appropriate throughout the text. These make both teaching and learning easier and more enjoyable.

Is a thoroughly integrated text. The text is extensively cross-referenced. In early chapters on chemical principles, we anticipate biological applications. These are then fully developed in subsequent chapters.

Explains difficult concepts in detail. Students don't have to depend on a collection of words alone to gain an understanding of abstract concepts. The drawings, diagrams, and photographs used render abstractions less formidable. Analogies drawn from everyday life illustrate concepts.

Is designed for future professionals yet has a strong liberal arts component. Health and life science professionals need a sound course in chemistry, but they will also be citizens. We have provided material on drugs, pollution, bioethics, and similar topics to help our future professionals be better-informed citizens.

Provides a liberal selection of problems at the end of each chapter. Students can immediately check their understanding of the material. Answers to selected problems are given in appendix D.

Presents references and suggestions for further reading. At the end of each chapter, books and articles are listed. Students whose interest has been kindled can delve more deeply into the subject.

Uses units most likely to be encountered in professional practice. Health professionals in the United States are in the last stages of the transition from the British and apothecary systems to the metric system. At the same time, the use of SI units is increasing in international scientific circles. We have retained many of the familiar "old" metric units such as *calorie* for energy and *millimetres of mercury* for pressure. These units are easy to visualize and will continue in use among many chemists and health and life scientists for years to come. On the other hand, we have used international spellings (*litre*, not *liter*) and symbols (K, not °K) where these do not present a barrier to learning.

Is exceedingly flexible. This book contains optional material that can be selected to suit individual needs. You can tailor a course to best serve your students. The book provides ample material for a full year's course. Suggested outlines for shorter courses of one semester (and for one or two quarters) are included in the *Instructor's Guide*.

Uses tested and tried methods for presenting materials. The approach that we have chosen has been proved sound in practice for a broad spectrum of students with widely varying backgrounds, both at private liberal arts colleges and at open-admissions state-supported schools. Students still have to study, but their study will be rewarded with success. We believe that any student, even one with modest preparation, can succeed if he or she invests time in the study of these materials.

Is designed to aid teachers. We, like you, never seem to have enough time to teach all the things that we would like to in a chemistry course. We have designed this book as an aid to the teacher. No book—or other educational device—can ever replace the classroom teacher. We are confident, though, that you will find this book easier to teach from than the usual text, because we have used only those techniques that have worked best for us in our classrooms.

We would like to thank all of those who helped with this work. Thanks to C. A. VanderWerf, who read the entire manuscript and made many helpful suggestions. We are indebted to Patti Organ, a student at Saint Mary's, who also read every word of the manuscript. A special thanks to Alanna Lucas, a typist who knows chemistry and who caught some of our errors. Cindy Hill provided the originals of several drawings and read some of the chapters. We especially want to thank our editor, Bob Lakemacher, for his patience, kindness, and good humor throughout.

Your comments, corrections, suggestions, and criticisms are eagerly solicited.

To the Student

What is chemistry?

Chemistry is such a broad, all-encompassing area of study that people almost despair in trying to define it. Indeed, some have taken a cop-out approach by defining chemistry as "what chemists do." But that won't do; it's much too narrow a view.

Chemistry is what we all do. We bathe, clean, and cook. We put chemicals on our faces, hands, and hair. Collectively, we use more than 10 000 consumer chemical products in our homes. Professionals in the health and life sciences use thousands of additional chemicals as drugs, antiseptics, or reagents for diagnostic tests.

Your body itself is a remarkable chemical factory. You eat and breathe, taking in raw materials for the factory. You convert these supplies into an unbelievable array of products, some incredibly complex. This chemical factory—your body—also generates its own energy. It detects its own malfunctions and can regenerate and repair some of its component parts. It senses changes in its environment and adapts to these changes. With the aid of a neighboring facility, this fabulous factory can create other factories much like itself.

Everything you do involves chemistry. You read this sentence; light energy is converted to chemical energy. You think; protein molecules are synthesized and stored in your brain. All of us are chemists.

Chemistry affects society as well as individuals. Chemistry is the language—and the principal tool—of the biological sciences, the health sciences, and the agricultural and earth sciences.

Chemistry has illuminated all of the natural world, from the tiny atomic nucleus to the immense cosmos. We believe that a knowledge of chemistry can help you. We have written this book in the firm belief that beginning chemistry can be related immediately to problems and opportunities in the life and health sciences. And we believe that this can make the study of chemistry interesting and exciting, especially to nonchemists.

For example, an "ion" is more than a chemical abstraction. A mercury ion in the wrong place can kill you, but a calcium ion in the right place can keep you from bleeding to death. "$P \times V = c$" is an equation, but it is also the basis for the respiratory therapy which has saved untold lives in hospitals. "Hydrogen bonding" is a chemical phenomenon, but it also accounts for the fact that a dog has puppies while a cat has kittens and a human has human offspring. Hundreds of similar fundamental and interesting applications of chemistry to life can be cited.

A knowledge of chemistry has already had a profound effect on the quality of life. Its impact on the future will be even more dramatic. At present we can control diabetes, cure some forms of cancer, and prevent some forms of mental retardation because of our understanding of the chemistry of the body. We can't *cure* diabetes or cure *all* forms of cancer or *all* mental retardation, because our knowledge is still limited. So learn as much as you can. Your work will be enhanced and your life enriched by your greater understanding.

Be prepared. Something good might happen to you—and to others because of you.

Contents

chapter 1

Matter and Measurement

This book is called *Chemistry and Life*. What does chemistry have to do with life? What is chemistry? For that matter, what is life?

The last question is more than rhetorical. Progress in science, technology, and medicine has blurred the distinction between life and death. Is someone whose heart has stopped beating dead? Is someone whose vital functions are being maintained by machine alive? We won't even attempt in this book to supply a definitive answer to the question "What is life?" We'll simply note its critical significance for our society.

How about the first question, "What does chemistry have to do with life?" A chemist would say, "Just about everything." The human body, for example, is the most extraordinarily complicated, most elegantly designed, and most efficiently operated chemical laboratory there is. Our attempt to answer that first question will fill most of this text.

That leaves the middle question, "What is chemistry?" And that is the subject of this first chapter. We shall see how science in general and chemistry in particular have developed from earlier human endeavors. Our study will include a consideration of the methods of science and the manner of its progress. Finally, we shall also develop some basic concepts necessary to our study of chemistry and its relationship to life.

1.1 Science and the Human Condition

We are taught in elementary school that people have three basic needs: food, clothing, and shelter. Certainly those three things—if adequate in quantity and quality—are enough to keep us alive. Most of us, however, would also agree to adding two more requirements for the good life: reasonable health and some chance for happiness.

In early human societies, nearly all human efforts were directed toward the hunting and gathering of food, the making of clothing, and the provision of shelter. Our early ancestors had no knowledge of the biological

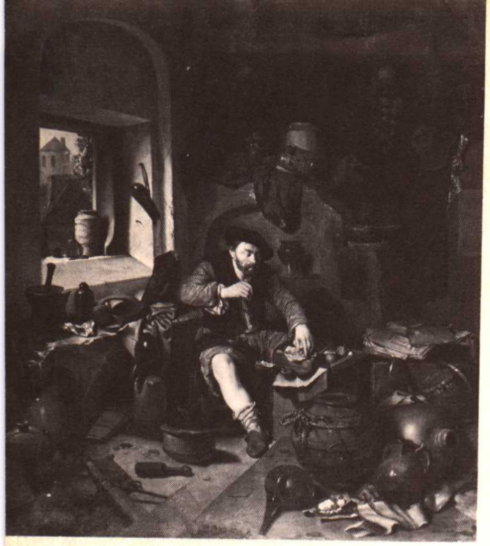


Figure 1.1 *The Alchemist,* a painting done by the Dutch artist Cornelis Bega around 1660, depicts a laboratory of the 17th century. (Courtesy of Aldrich Chemical Company, Milwaukee.)

Figure 1.2 Theophrastus Bombastus von Hohenheim, better known as Paracelsus. (Courtesy of the National Library of Medicine, Bethesda, Md.)

and chemical bases of illness, and there was little they could do about their health except to pray and make sacrifices to their gods. With the coming of civilization, some people gained enough leisure to turn their thoughts to the human condition and to the natural world around them. Over the centuries what we now call science grew out of their speculations. As this scientific study of the material universe progressed, the responsibility for adding to the growing body of knowledge was divided among various disciplines. Among these disciplines was chemistry.

Modern chemistry's roots are firmly planted in alchemy, a kind of mystical chemistry which flourished in Europe during the Middle Ages. And modern chemists have inherited from the alchemists an abiding interest in those aspects of their study that relate to human health and to the quality of life.

Consider, for example, the fact that alchemists not only searched for a "philosopher's stone" that would turn cheaper metals into gold but also sought an "elixir" that would confer immortality on those exposed to it. Alchemists never achieved their primary goals, but they did discover many new chemical substances. As early as the ninth century, a Persian alchemist, Al-Razi, described the use of plaster of Paris for casts to set broken bones. And alchemists perfected techniques such as distillation and extraction that are still useful in our time.

It was a Swiss physician, Theophrastus Bombastus von Hohenheim (1493–1541), who urged alchemists to turn away from their attempts to make gold and to seek instead medicines with which to treat disease. Possessed of a monstrous ego, von Hohenheim (who preferred the self-chosen name Paracelsus) alienated many of his contemporaries. His followers, however, were numerous enough to ally forever the science of chemistry with the art of medicine.

By the 17th century, a changed attitude, characterized by a reliance on experimentation, had been adopted by astronomers, physicists, physiologists, and philosophers. It was this change in orientation that signaled the emergence of chemistry from alchemy. The English philosopher Sir Francis Bacon (1561–1626) had visions of these new scientific methods endowing human life with new inventions and wealth.

By the middle of the 20th century, it appeared that science and its application in technology had made the dreams of Bacon and von Hohenheim a reality. Many diseases had been virtually eliminated. The coordination of chemistry and medicine had also made the difference between operations in which four strong men were employed to hold the patient down and ones in which the patient was painlessly anesthetized. Fertilizers, pesticides, and scientific breeding had made food more abundant. Nutritionists were applying their science to designing diets that would produce healthier, stronger people. New materials were being developed to improve our clothing and shelter. Industry was offering an almost endless variety of products at relatively low cost to the average consumer.

Indeed, it seemed that, despite its sometimes less than honorable intentions, science could do no wrong. For example, during World War I, when the German armies' supply of ammonia (which they needed to make nitrate explosives) was cut off, the Haber process provided them with an alternate supply. Fritz Haber's work probably lengthened the war, but it is far more significant for its influence on modern agriculture. Ammonia and nitrates are the stuff of which fertilizers are made, and fertilizers are essential to modern high-yield farming. In fact, most of the ammonia made by the Haber process today goes into fertilizer.

Much of the technology of the mighty 20th century had grown out of scientific discoveries. New technological developments were used in turn by scientists as tools to make new discoveries. These developments in science and technology became hallmarks of the modern world. Hardly anyone questioned that science in the early part of the 20th century had significantly improved the human condition.

Figure 1.3 Sir Francis Bacon, English philosopher and Lord Chancellor to James I. (Duplication courtesy of the Smithsonian Institution, Washington, D.C.)

1.2 Problems in Paradise

If during the first half of the 20th century science was viewed as humankind's savior, during the latter half it is being viewed as quite the opposite. Those anesthetics that made surgery painless for the patient have caused female anesthesiologists, surgeons, and surgical nurses to suffer a high percentage of miscarriages compared to other health personnel. Fertilizer runoff from farms has polluted streams, and insecticide residues have had a devastating effect on wildlife. Some of those industrial workers making modern products for our use have died from diseases caused by the chemicals they worked with.

One solution to these problems would be simply to throw out science. But do we really wish to return to surgery without anesthetics? Most of us don't. We need scientists, for it is they who will search for safer anesthetics, for approaches to increased agricultural production compatible with the natural environment, and for analytical techniques which will ensure healthful working conditions for industrial personnel.

The simple fact is that chemistry and its products, both good and bad, are so intimately involved in determining the quality of life that to ignore the subject is to court disaster. It will take an educated, informed society to ensure that science is used for the human good.

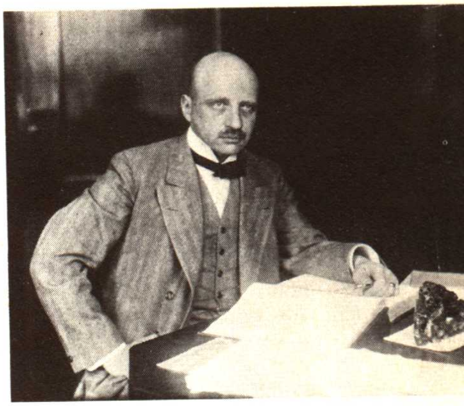


Figure 1.4 Fritz Haber, the German chemist who invented a process for manufacturing ammonia. (Courtesy of Encyclopaedia Britannica, Inc., Chicago.)

1.3 The Way Science Works—Sometimes

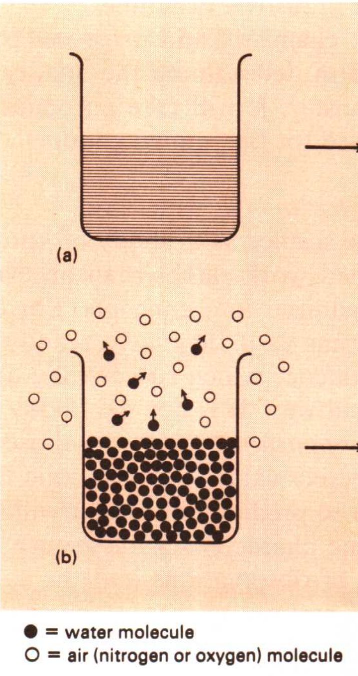
Textbooks often define science as a "body of knowledge," and it is frequently taught as a finished work rather than an ever-changing approach to learning. Science is organized into concepts. For example, even though we will often speak of atoms as if they were readily observed, the atomic concept is merely a convenience which successfully describes many observable facts in a metaphorical way. It is not the "body of facts" that characterizes science but the *organization* given to those facts. To be useful, concepts must have predictive value. If the atomic theory is to be useful, it should enable a scientist to predict how matter will behave.

The most distinguishing characteristic of science is its use of processes or methods. The making of observations and the cataloguing of facts are bare, though necessary, beginnings to these intellectual processes. Scientists must be able to make careful measurements, but they must also be able to

Scientists use the word *model* somewhat differently than nonscientists. A scientific model helps one "visualize" the invisible. For example, when a glass of water is allowed to stand for a period of time, the water apparently disappears. This process is called *evaporation.* Scientists explain this phenomenon by means of a model referred to as the *kinetic-molecular theory.* According to this theory, the liquid is made up of small, invisible particles called molecules. These molecules are in constant motion. In the bulk of the liquid, each molecule is surrounded on all sides by other molecules. These molecules can bump back and forth against one another, but because they are totally surrounded they are trapped. However, for a molecule at the surface, there is the possibility of escape. If one molecule is hit hard enough by another molecule, the first can be knocked free of the surface. It then becomes part of the air, which is simply another collection of molecules. The air, unlike the liquid, is a gas in which all the molecules are very far apart. They are so far apart that essentially all light passes right through them, so they can't be seen; thus, the water disappears. It is far more satisfying for the scientist to understand evaporation by means of a model such as this than merely to have a name for the process.

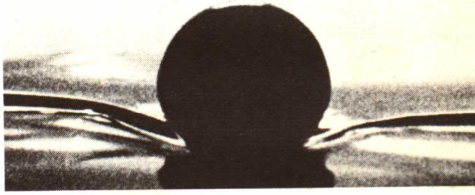
grasp the central theme of these observations. They must recognize the variables and be able to note the effect of changing one variable at a time. Scientists must be able to sort out the useful aspects of information and ignore irrelevancies. Perhaps basic to these intellectual processes is the ability to formulate testable hypotheses. Even an educated guess is of little value to scientists unless an experiment can be devised to test the guess. Successful scientists can deduce evidence from a model. Truly outstanding scientists may invent original models.

Figure 1.5 The evaporation of water. (a) When a container of water is left standing open to the air, the water slowly disappears. (b) Scientists explain evaporation in terms of the motion of molecules.



Science is not totally different from other disciplines. For example, creativity is central to both science and the humanities. Science does not involve cold logic to the exclusion of other human characteristics. Albert Einstein recognized that there was no *logical* path to some of the laws that he formulated. Even he relied on intuition based on experience and understanding.

It is important that you realize there is no single "scientific method" which, when followed, produces guaranteed results. Scientists observe, gather facts, and make hypotheses, but somewhere along the way they test their hunches and their organization of facts by experimenting. Scientists, like other human beings, use intuition and may generalize from a limited number of facts. Sometimes they are wrong. One of the strengths of science lies in the fact that results of experiments are published in scientific journals. These results are read—and often checked—by other scientists in all parts of the world. To become an accepted part of the "body of knowledge," the results must be reproducible. Scientists also extend each other's work, sometimes to the point that we see a "bandwagon" effect. One breakthrough sometimes results in the unleashing of vast quantities of new data and leads to the development of new concepts. For example, early in the 19th century it was thought that certain chemical substances, called *organic* compounds, could be produced only by living tissue, such as someone's liver or the leaf of a plant. These substances were in contrast to other materials, labeled *inorganic,* which could be prepared by a chemist in a laboratory. In 1828, a German chemist named Friedrich Wöhler (1800–1882) succeeded in making an organic compound from an inorganic one in the laboratory. The belief that such a compound could not be prepared in this manner was so strong that Wöhler did the same thing over and over again to assure himself that he had really done the "impossible." When he finally published his work, other chemists quickly repeated it and then proceeded to make hundreds of thousands of organic compounds. That bandwagon is still rolling today, with chemists making hormones, vitamins, and even genes in the laboratory.


(a)

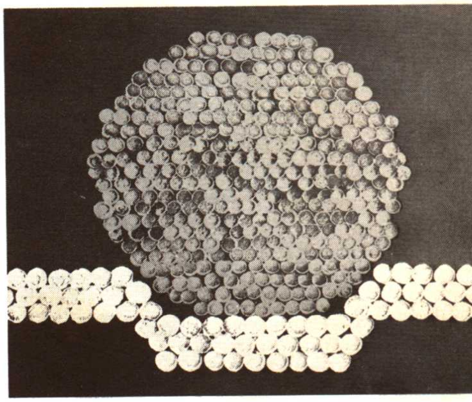

(b)

Figure 1.6 (a) A steel ball striking the surface of a silicone liquid. (b) How a scientist might visualize the process in terms of an atomic model. (Courtesy of Dow Corning Corporation, Midland, Mich.)

Thus, contrary to an often-expressed popular notion, scientific knowledge is not absolute. Science is cumulative, and the "body of knowledge" is dynamic and constantly changing. Old concepts or even old "facts" are discarded as new tools, new questions, and new techniques reveal new data or generate new concepts. To truly understand what science is, one has to observe what the whole, worldwide community of scientists has done over a period of several years rather than look over the shoulder of a single scientist for a few days.

1.4 What Is Chemistry? Some Fundamental Concepts

Nowadays, chemistry is often defined as a study of matter and the changes that it undergoes. Changes in matter are accompanied by changes in energy. Since the entire universe is made up of nothing more than matter and energy, the field of chemistry extends from atoms to stars, from rocks to living organisms. Matter and energy are such fundamental concepts that definitions are difficult. *Matter* is the stuff which makes up all material

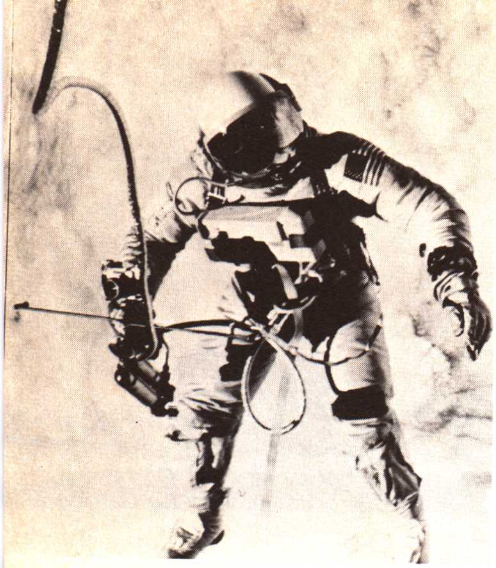


Figure 1.7 An astronaut who weighs 80 kg on earth is "weightless" in space. His mass (quantity of matter) is constant, however. (Courtesy of the National Aeronautics and Space Administration, Washington, D.C.)

Figure 1.8 A boulder on a cliff represents potential energy. A falling boulder represents kinetic energy. The falling boulder can do work (smash a house, for example). The boulder on the cliff has a potential for doing the same thing.

things. It occupies space and has mass. Wood, sand, water, and people have mass and occupy space. So does air, although one usually needs a flat tire or a 30-mi/hour wind to emphasize the point. *Mass* is a measure of the quantity of matter. *Weight,* on the other hand, is a measure of how strongly an object is attracted by the earth. On the earth's surface, weight is proportional to mass, and those two terms may be used interchangeably for most purposes. In space, however, an astronaut would have the same mass (i.e., the same quantity of matter) as on earth but would have no weight (because the pull of the earth's gravity is canceled while the spaceship circles the earth). Weight is determined by gravity; mass is invariant.

Matter comes in three familiar states: solid, liquid, and gas. Solid objects generally maintain their shape and volume regardless of their location. Many solids are crystalline in nature. Liquids assume the shape of their containers (except for a generally flat surface at the top). Like solids, however, liquids maintain a fairly constant volume. Unlike solids, they flow rather readily. Gases maintain neither shape nor volume. Rather, they expand to fill completely whatever container one puts them in and can be easily compressed. For example, enough air for many minutes of breathing can be compressed into a steel tank for underwater diving. We shall consider the states of matter in considerably more detail in later chapters.

Energy is often defined as the capacity for doing work. (By this definition, play involving exercise is called work.) But energy is more than that. It is the basis for change in the material world. When something moves or breaks or cools or shines or grows or decays, energy is involved. Energy is usually divided into two general categories, *potential* and *kinetic*. A system has potential energy by virtue of its position, that is, simply by being in a particular arrangement or place. The usual example given for such a system is a boulder on a cliff. Simply because it is at the top of the cliff and not at the bottom, the boulder has potential energy, which it can use to do work. The boulder can fall from the cliff and destroy a house at the base (thereby doing work), whereas a similar boulder sitting at the base of the cliff cannot do the same thing.

Kinetic energy is energy in motion. The boulder that was sitting at the base of the cliff could destroy the house if it were rolling along the ground at a good clip. Its ability to do work in this case would depend on its motion. If you were really determined to destroy that poor house using kinetic energy, your best bet would be to use a large boulder rather than a small stone. Given the choice, it would also be better to get it moving at a brisk rather than a leisurely pace. That is just another way of saying that kinetic energy depends on mass and velocity. The bigger an object is and the faster it is moving, the more kinetic energy it has and the more work it can do.

In addition to the two major categories described above, energy is sometimes divided into a number of subcategories. These classifications are based on some characteristic of the energy being considered, for example, its source. It is easier to discuss some of these various types of energy by indicating their significance in the overall pattern of energy flow on earth.

The source of nearly all the energy on earth is the sun. Solar energy radiates through space as light. A small portion of this *radiant energy* reaches the earth, where some of it is converted to *heat energy*. This heat causes water to evaporate and then rise to form clouds. The water in the clouds has potential energy. As the water falls through the air and then flows in rivers, the potential energy is converted to kinetic energy.

The kinetic energy of the flowing stream can be used to turn a turbine, which converts a part of the stream's energy to *electrical energy*. The electricity thus produced can be transported by wires to homes and factories, where it is converted to light energy or to heat or to still other forms of energy.

Some of the solar energy striking the earth is absorbed by green plants, which use a complicated chemical process called *photosynthesis* to convert solar energy into *chemical energy*. The chemical energy stored by plants—now and in ages past—is used by humankind for food and fuel. Nearly all the vast quantities of energy used in our modern civilization come ultimately from the sun by way of green plants. Plants of the current age are harvested in forestry and agriculture. Those of ancient ages are reaped as fossil fuels—coal, oil, and gas.

One form of energy not attributable to the sun is nuclear energy. This type of energy was stored in the earth's crust when the solar system was formed some 4 or 5 billion years ago. We recover it for use or misuse when we mine uranium and build nuclear reactors or atomic bombs.

But chemistry is not concerned only with matter and its changes. It is also concerned with the energy transformations that accompany these changes. To deal with energy transformations, chemistry often borrows fundamental concepts from its neighboring discipline, physics. One such concept is *force*. A force is a push or a pull that sets an object in motion, or stops a moving object, or holds an object in place. *Gravity* is a force. Objects—including us—are held to the surface of the earth by gravity, the attraction of its mass for our mass. The weight of an object is the force of gravity that exists between it and the earth.

Electrical forces are extremely important in chemistry. Particles of matter bear two types of electrical charges, called positive (+) and negative (−). No one can really tell you exactly what an electrical charge is. We simply accept the fact that a particle with a "charge" can exert a force, that is, can

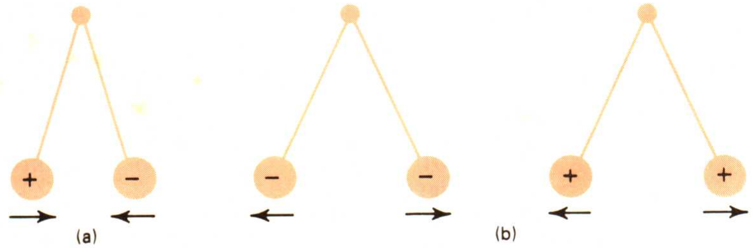


Figure 1.9 (a) Particles with unlike charges attract one another. (b) Those with like charges repel one another.

Figure 1.10 Static cling.

push or pull another particle which also has a "charge" on it. The particles do not have to be touching one another to attract or repel. For this reason, we say charged particles have force fields about them. Even at a distance they attract and repel one another, although these forces get weaker as the particles get farther apart. Particles with like charges (both positive or both negative) repel one another. Those with unlike charges (one positive and one negative) attract one another.

This phenomenon of charged substances is not unfamiliar to you. Anyone who has pulled clothes from an automatic dryer on a cold winter's day has probably seen what commercials like to call "static cling," pieces of clothing sticking to one another. The "cling" is due to the attraction of *unlike* charges. If, on the other hand, you brushed your hair vigorously on this same cold day, it might have become "unmanageable" (another great commercial term). Instead of lying flat against your head, it may have stuck out, each strand seemingly trying to get away from all the other strands. And that is exactly what was happening. The strands had *like* charges on them and were repelling one another.

1.5 Measurement: The Metrics Are Coming!

Accurate measurement of such quantities as mass (weight), volume, time, and temperature are essential to the compilation of dependable scientific "facts." Such facts may be used by a chemist interested in basic research, but similar information is of critical importance in every science-related field. Certainly we are all aware that measurements of both temperature and blood pressure are routinely made in medicine. It is also true that modern medical diagnosis depends on a whole battery of other measurements, including careful chemical analyses of blood and urine.

Table 1.1
Approved numerical prefixes

Exponential Expression	*Decimal Equivalent*	*Prefix*	*Phonic*	*Symbol*
10^{12}	1 000 000 000 000	Tera-	ter′ a	T
10^{9}	1 000 000 000	Giga-	ji′ ga	G
10^{6}	1 000 000	Mega-	meg′ a	M*
10^{3}	1 000	Kilo-	kil′ o	k*
10^{2}	100	Hecto-	hek′ to	h
10	10	Deka-	dek′ a	da
10^{-1}	0.1	Deci-	des′ i	d
10^{-2}	0.01	Centi-	sen′ ti	c*
10^{-3}	0.001	Milli-	mil′ i	m*
10^{-6}	0.000 001	Micro-	mi′ kro	μ*
10^{-9}	0.000 000 001	Nano-	nan′ o	n
10^{-12}	0.000 000 000 001	Pico-	pe′ ko	p
10^{-15}	0.000 000 000 000 001	Femto-	fem′ to	f
10^{-18}	0.000 000 000 000 000 001	Atto-	at′ to	a

*Designates most commonly used units.