Elements of Chemistry

ELEMENTS OF CHEMISTRY

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PREFACE

ELEMENTS OF CHEMISTRY undertakes to provide a thorough introduction to general chemistry for the college-preparatory course. It includes up-to-date treatment of modern chemical theory enriched by historical background and development. Thus it reveals the changing nature of chemistry as an evolving and expanding science. In addition, the text provides a laboratory-related framework of descriptive chemistry of the major groups of elements, which gives substance and meaning to the chemical theory. Selected practical applications in industry and the home enable students to develop an appreciation of the fundamental role of chemistry in modern life. Quantitative aspects of problem-solving are carefully developed with the use of sample problems and graded exercises.

The main concern of the text is with the fundamental theories and principles on which modern chemistry rests. These are introduced early and make up most of the first half of the text. In this latest revision, chapters 3, 4, and 6, plus chapters 15, 16, 17, and 19 have been largely rewritten and re-illustrated. Extended and updated treatment is given to the kinetic-molecular theory, atomic structure based on quantum mechanics, and ionic, covalent, polar covalent, and metallic bonding. A new chapter on chemical kinetics discusses reaction rates, mechanisms, and catalysis. The roles of energy and entropy in determining physical and chemical equilibria are discussed, and quantitative treatment of equilibrium is expanded. The Bronsted-Lowry approach to acid-base theory, oxidation-reduction, and electrochemistry (including standard electrode potentials) are other topics which have been rewritten and expanded. Practical applications of modern chemistry are included in updated treatment of spectroscopy, crystallography, colloids, metallurgy, fuels, classes of organic compounds, complex polymers, nutrition, and peaceful applications of nuclear energy.

Like the previous edition, this new revision of *ELEMENTS OF CHEMISTRY* is divided into nine units preceded by brief introductory statements of text coverage and historical perspective. Each of the forty-one chapters opens with a STUDY OUTLINE in question form, which provides a survey of the principal topics discussed. TEST YOURSELF questions are included at frequent intervals within each chapter to help the student check his comprehension. Throughout the text, important definitions and principles are set in **boldface** type and *italics* so that they stand out from the body of the text material. Selected topics which go beyond the usual curriculum requirements are indicated by a star (★).

At the conclusion of each chapter, a concise SUMMARY reviews the major points considered. This is followed by a selected list of KEY WORDS. QUESTIONS include both simple recall type and applications and extensions of content. These are divided into *Group A* and *Group B* according to degree of difficulty. The same is true of the numerous PROBLEMS, which involve student computation. STUDENT ACTIVITIES provide suggestions for out-of-class projects and areas of investigation. The REFERENCES FOR FURTHER READING include standard textbooks, popular readings, and scientific journals commonly available in high school libraries.

The text is functionally illustrated by over two hundred drawings and diagrams in two colors, plus numerous selected black-and-white photographs. In addition, there are several pages of four-color photographs and drawings. Numerous tables and graphs are distributed throughout the text, and several general tables are placed in the APPENDIX and inside the back cover for ready reference. The GLOSSARY contains over four hundred chemical terms.

ELEMENTS OF CHEMISTRY contains considerably more material than an instructor would be likely to include in a one-year course. From the beginning of Unit V on, each chapter is largely self-contained, so that portions or even whole chapters can be selected or omitted with a minimum of difficulty at the discretion of the instructor. Thus the text and its accompanying laboratory manual are sufficiently flexible to be adapted to varying classroom situations and levels of instruction.

Grateful appreciation is hereby expressed to the many teachers and others who have made valuable suggestions for improving the text. Appreciation is also expressed to the individuals and organizations who have furnished the outstanding illustrations. Illustration acknowledgments are listed on pages 695 and 696 following the INDEX.

CONTENTS

"Experiences and observations alone never lead to finalities. Theory, however, creates reliable roads over which we may pursue our journeys through the world of observation."

(Anton Reiser, 1930.)

UNIT I

THE BASIS OF CHEMISTRY

Throughout history man has pondered the nature of the materials around him. What is the composition of the substances which make up his world? Is matter a continuous substance without ultimate particles? Is it composed of four basic "elements"—earth, air, fire, and water—as some early Greeks thought? Or is all matter made up of tiny, indivisible particles called "atoms," as Democritus believed?

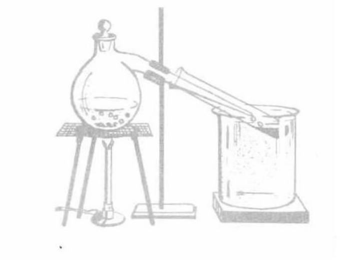
The various forms of matter which make up our world are the basis of the study of chemistry. We shall examine the kinds of matter, their properties and reactions. We shall discover a relationship between matter and energy, and learn how to measure various properties of matter in the principal systems of measurement. We shall learn the characteristic steps of the scientific method which lead to hypotheses theories, and laws.

In chemistry we learn the meaning of such terms as elements, compounds, solutions, and mixtures; atoms and molecules; electrons, protons, and neutrons. We find that these units of matter build molecules and crystals held together by forces called chemical bonds. We learn that chemistry is an organized body of knowledge in which the different kinds of matter are so related that they can be represented by various charts and tables.

Throughout this book we learn that chemistry is a growing science whose investigations have been carried out by ordinary people of great curiosity, such as: John Dalton, who proposed an early theory of atomic structure; Albert Einstein, who showed a mathematical relationship between matter and energy; Niels Bohr, who gave us a working model of the atom; Dmitri Mendeleyev, who proposed an acceptable periodic table of the elements; and Edward Frankland, who suggested an explanation of why atoms unite in various combinations.

This, then, is the beginning of the study of chemistry.

CHAPTER 1



THE MEANING OF CHEMISTRY

STUDY OUTLINE

1. What is **science** and what is **chemistry**?
2. Can you distinguish clearly between **matter** and **energy**?
3. What are some important **properties** of and **changes** in matter?
4. How many **forms of energy** can you name? What do they all have in common?
5. Is there a **relationship** between matter and energy?
6. What are the **fundamental units** of measurement?
7. How many different **systems of measurement** are you familiar with?
8. Can you show relationships between the units of measurement in the **English** and **metric** systems?
9. How is **temperature** measured?
10. What is meant by the terms **doubtful** and **significant** figures?
11. How may very large and very small numbers be written more conveniently in **powers-of-ten notation**?
12. About when did **chemistry** become a true **science**?
13. What is meant by the **scientific method**?
14. Can you distinguish clearly between **facts** and **laws** on the one hand, and **hypotheses** and **theories** on the other?

MATTER, ENERGY, AND THEIR CHANGES

1-1. What is Chemistry?

As a student approaches a particular subject which he is to study for the first time, such as chemistry, certain questions come to mind. What is chemistry? What relationship does it have with other branches of science such as physics or biology? Why is chemistry considered such an important subject?

First of all, chemistry is a branch of science, and **science** *is an organized body* *of knowledge* and at the same time a *process of inquiry or investigation.* As man progressed from primitive beginnings in the control of the world around him, he gradually and systematically recorded the information which resulted from his observations, experiments, and discoveries in the physical world. This classified body of knowledge is often called *science.* Scientists try to solve the problems of man's environment by a procedure called the *scientific method.* This systematic process of investigation is also called *science.* In fact, this is the aspect of science which challenges the imagination of the large number of men and women who are called scientists.

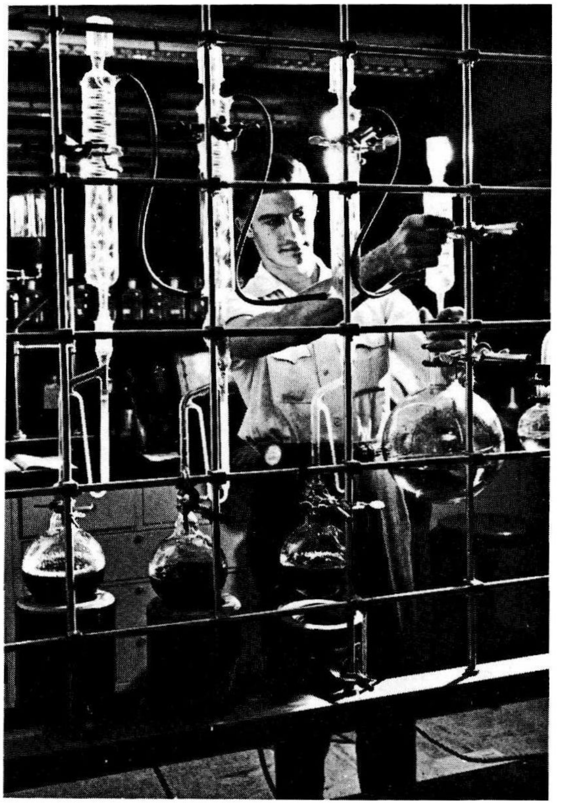
All branches of science are concerned in some way with the materials which make up our environment. *Physics* deals with the various forms of energy—such as heat, light, sound, electric energy, and mechanical energy—and the interaction of matter with energy. *Biology* treats of living matter in the plant and animal kingdoms—its origin, growth, reproduction, and structure. *Chemistry* also considers matter, but in a different way than either physics or biology. **Chemistry** *is that branch of science which deals with the composition of substances and the changes that take place in their composition.* Since energy is either given off (as from a candle flame) or absorbed during a chemical change, it is clear that chemistry and physics are closely related. The intimate relationship of the various sciences is indicated by such designations as *physical chemistry* and *biochemistry.*

Why is chemistry so important? The answer lies in the fact that our world is a world of chemistry. Through an *understanding* of chemistry we can *appreciate* the changes which take place around us in the variety of natural and manmade substances. A knowledge of chemical principles helps us to understand phenomena ranging from such common events as the burning of wood to such unusual changes as the nuclear transformations in an atomic reactor.

Through chemistry we can *create* totally new products—such as orlon and nylon—*develop* useful substitutes for wood and ordinary metals with new plastics and alloys, and *improve* a variety of familiar products—such as fertilizers, paints, and insecticides.

Through a knowledge of chemistry we can *solve* many of the critical problems facing us in the modern world. Typical of these problems are the disposal of atomic wastes, the reduction of air and water pollution, and the creation of new materials to withstand the high temperatures generated by the amazing speed of modern aircraft and rockets.

Fig. 1-1. Analytical chemists play an important role in industrial research.



1-2. The Nature of Matter

If we examine any familiar objects—such as our books, clothing, or money—we will find that, varied as they may be, they all have two common characteristics: *they occupy space and have weight.* There is another characteristic quality also present which is not so evident. If we try to push a heavy ball on a smooth, level surface, we notice that it resists our efforts to move it. We say the object has *inertia* because it tends to stay where it is. This same quality tends to keep an object moving in a fixed direction unless acted upon by some outside force such as friction. From this concept of inertia we define **mass** as *a measure of the inertia of a body.*

Let us further examine the terms *mass* and *weight.* The **weight** *of a body is the force with which it is pulled toward the center of the earth by gravitational attraction.* Since this varies slightly from place to place on the surface of the earth, weight is not considered as fundamental a characteristic of matter as is mass, the magnitude of which does not depend on an object's location. At any given place, the weight of a body is proportional to its mass. However, weight varies with location because the value of the proportionality constant changes. At sea level this factor is about half of one per cent larger at the north pole than at the equator. Therefore an explorer who weighs 200 pounds at the equator will weigh 201 pounds at the north pole. Large variations occur when one leaves the earth. An astronaut who weights 200 pounds at Cape Kennedy will weigh only 34 pounds on the surface of the moon, yet his mass has not changed.

Fig. 1-2. Astronauts in earth orbit and long-distance space travelers lose all sense of the earth's gravitational attraction. What problems result from this apparent weightlessness?

Since any object which has weight must also have inertia and therefore mass, **matter** may be defined as *anything which occupies space and has mass.* In science we use exact definitions. Therefore we shall speak of *materials* when referring to *all* kinds of matter, and *substances* when referring to *particular* kinds of matter having uniform composition and properties—such as iron or water.

We measure the mass of an object by comparing it with a known mass, or *standard.* If an object placed in one pan of an equal-arm balance exactly balances a standard mass in the other pan, their weights must be equal, for the earth is exerting the same force of gravitational attraction on them. Since the distance between the masses is small, the proportionality constants relating mass to weight must be essentially the same. Therefore, as their weights are the same, the masses are equal. In this way masses are measured in the laboratory by comparing weights.

If we compare the weights of the same volume of different materials, such as a cubic foot of air and a cubic foot of water, we find that the *same volumes* have *different weights.* Water weighs 62.4 pounds per cubic foot, while air weighs less than 0.1 pound per cubic foot. We say that water is more compact, or *denser,* than air. **Density** *is the weight of a substance per unit volume.*

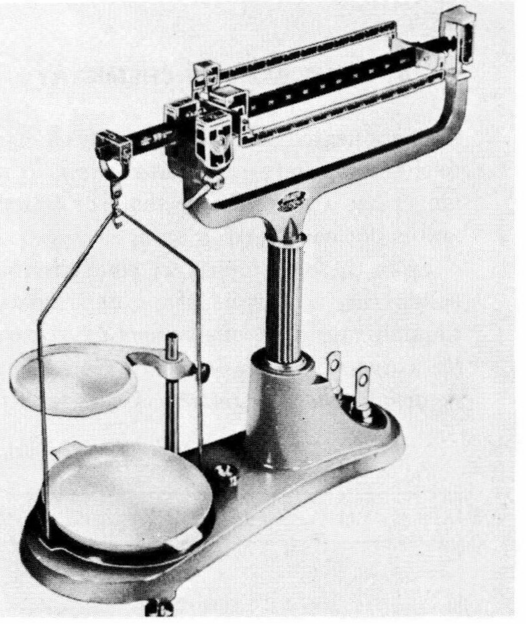


Fig. 1–3. By use of this triple-beam balance scientists are able to weigh small amounts of chemicals quickly and accurately.

1-3. The States of Matter

When we heat pieces of roll sulfur in a test tube, they first change to molten sulfur and then to sulfur vapor. Similarly, if heat is applied to an ice cube, it first changes to water and then to steam. From such examples we see that matter may exist in the *solid, liquid,* or *gaseous* states. In each case the change in state is brought about by a change in the amount of heat. Thus, ice is a solid below 0° C, becomes liquid water between 0° and 100° C, and becomes a gas (steam) above 100° C (at atmospheric pressure).

Solids, liquids, and gases have certain characteristics which distinguish them from each other. The pieces of sulfur mentioned in the previous paragraph have a definite shape and size as we can see by examination. These pieces of sulfur tend to retain their particular form unless force is applied to crush them. When the sulfur is heated in the test tube, it loses its original shape as it melts, and occupies a definite volume. Liquid sulfur takes the shape of the containing vessel and has one free surface so that it may be contained in an open vessel. When the test tube is

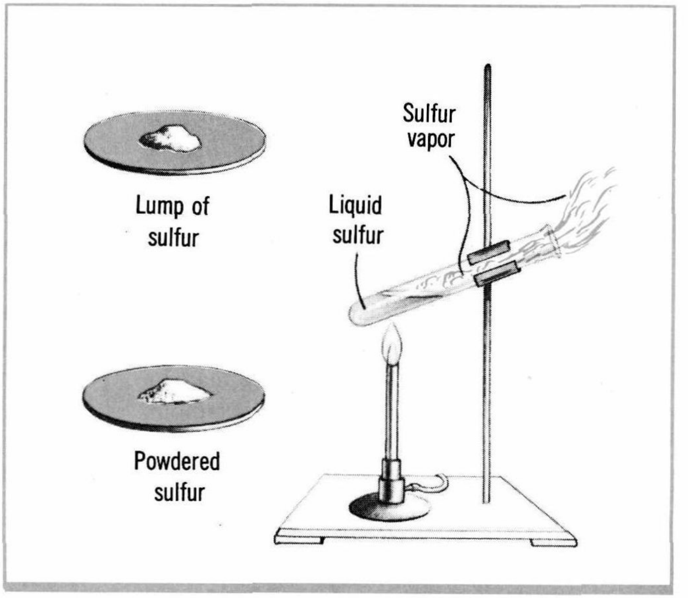


Fig. 1–4. The three states of matter are shown in this diagram. How could you change each one into the other two states?

strongly heated, the molten sulfur changes to sulfur gas and escapes into the air. It no longer has a recognizable shape or volume and is not contained in an open vessel.

From these examples, we conclude that **solids** *have a definite shape and volume.* **Liquids** *have a definite volume but assume the shape of their containers.* **Gases** *have no definite shape or volume.* Gases tend to *expand* indefinitely unless confined in a closed container. In order to specify gas volumes it is necessary to state the *pressure* and *temperature* since the volume of a gas varies with these factors. Gases and liquids can be poured and hence are called *fluids*. The characteristics of the three physical states are summarized in Table 1–1.

Table 1–1. Characteristics of the Physical States of Matter

Solids	Liquids	Gases
Rigid	Fluid	Fluid
Definite shape	Shape of container	Indefinite shape
Noncompressible	Noncompressible	Highly compressible
Definite volume	Definite volume	Indefinite volume

1-4. Physical and Chemical Properties of Matter

Properties *are the characteristics by which substances may be identified.* Those characteristics which describe physical appearance are known as *physical properties,* while those which describe chemical behavior are called *chemical properties.*

Some descriptive or *qualitative* physical properties are color, odor, taste, crystalline form, and physical state. *Quantitative* physical properties include density, hardness, solubility, melting point, and boiling point, each of which may be expressed by a number. For example, oxygen is a colorless, odorless, tasteless gas, is slightly soluble in water, and has a density of 1.43 grams per liter. **Physical properties** *are those characteristics which can be recognized without changing the nature of the substance.*

Chemical properties refer to the way in which materials behave with other materials. In this regard a substance may be *active, inactive,* or *inert.* For example, it may or may not react with oxygen, water, acids, and bases, or be affected by heat and light. To detect chemical properties, chemical changes or reactions which produce new substances are required. **Chemical properties** *are those characteristics which describe how a substance reacts with other substances.*

1-5. Changes in matter

There are two kinds of changes which affect matter, *physical* and *chemical changes.* If a piece of paper is torn into small bits, it loses its original shape and size. Ice melts to form water and in so doing changes from one state to another. A glass rod held in a flame gets red hot. In each case, however, there is no change in the *composition* of the substance. Although there are different shapes, states, or conditions of temperature, the paper, water, and glass remain the same material. The torn paper retains its original properties, and the water and glass, if sufficiently cooled, will return to their original state. No new substances are formed. A **physical change** *is one in which the composition of the substance is not altered.*

However, if we burn a piece of paper, the ash left behind in no way resembles the original paper. A current of electricity passed through water, to which a small amount of acid has been added, yields products which are gases: hydrogen and oxygen. Steel wool strongly heated in pure oxygen sparkles brightly as it forms an entirely different substance, iron oxide. In each case, the identity of the original substance is lost. The paper ash has quite different properties from the original paper. Hydrogen and oxygen formed in the electrolysis of water are totally different from the original liquid. Iron oxide does not have the same composition as the iron from which it was made. New substances are formed having new properties. *A* **chemical change** *is one in which the composition of a substance is changed.*

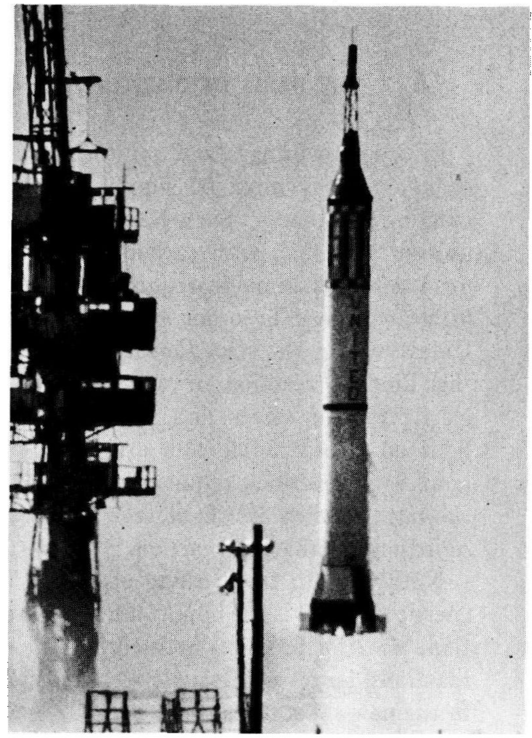


Fig. 1–5. Rocket fuels release energy to provide thrust. Chemists seek fuels which will be most efficiently converted into energy.

1-6. Energy

Heat is required to ignite paper and is also given off when the paper burns, forming ash. An electric current is necessary in order to bring about the decomposition of water into hydrogen and oxygen. Light is required to start the chemical change in a photographic film which will eventually produce a picture. *Heat*, *electricity*, and *light* are some of the forms of energy which bring about changes in substances. The process of producing a change in a substance often requires the expenditure of energy and involves work. We may define **energy** as *the ability to do work.* Other forms of energy include *mechanical*, *chemical*, and *nuclear* energy. Mechanical energy may be in the form of *potential energy*, due to the position or condition of an object, as in a coiled watch spring, or in the form of *kinetic energy*, due to motion, as when a watch spring unwinds.

Energy can move from one place to another, be transferred from one body to another, and undergo changes in form or kind. Thus, light and heat come to us from the sun and electrical energy can move through wires and vacuum tubes. A moving body may collide with another body and transfer part of its kinetic energy to the second body. The mechanical energy which operates a generator is transformed into electrical energy. When wood burns, the chemical energy stored in the fuel is changed into heat and light energy. *All matter possesses energy in some form or other.* A characteristic of chemical change and many kinds of physical change is a change in energy content.

In every chemical reaction energy is either given off or absorbed. The burning of wood, coal, and oil are examples of reactions which give off light and heat energy. *A chemical reaction which gives off heat energy is called an* **exothermic reaction.**

In order to bring about some chemical changes energy must be supplied to the reacting substances. Such reactions as the uniting of carbon with carbon dioxide to form carbon monoxide require the input of heat energy in order to take place. Unless energy is continuously put into this kind of reaction, it will stop. The electrolysis of water and the action of light on photographic film are other examples of reactions requiring energy. A *chemical reaction which absorbs energy is called an* **endothermic reaction.**

Note that, in the burning of fuels, the energy given off is the important consideration, not the products formed. In most reactions, however, chemists are interested in the new substances produced.

1-7. The Relation between Matter and Energy

As we saw previously, energy may be transformed or changed from one form into another: chemical energy to heat energy, mechanical energy to electrical energy, etc. During this process there is no change in the *total amount* of energy, merely in its *form.* Much of this energy may be rendered unusable, or wasted, as when the chemical energy of fuels is dissipated in heat losses. These facts may be summarized in the **law of conservation of energy:** *the sum of all forms of energy remains constant in time, though the amount of each form may change.*

In a similar fashion, if we were to examine carefully the weights of all substances involved when wood burns thereby uniting with oxygen to form ash, smoke, and various gases, we would find that matter is neither created nor destroyed, but merely changed into different substances. Investigations of numerous chemical changes have shown that no measurable weight is lost or gained in such reactions. These facts are summarized in the **law of conservation of mass:** *the products of a chemical reaction weigh exactly the same amount as the starting materials.*

Actually matter and energy are merely different forms of the same thing, as was first recognized by Albert Einstein. In 1905 he proposed the relationship between matter and energy given by the equation:

$$E = mc^2$$

where **c** is a constant, **m** represents the mass of the matter being changed into energy and **E** the energy produced. This law applies to chemical reactions, but the amount of mass converted to energy even in highly exothermic reactions is too small to measure. Therefore, as a practical matter, mass is conserved in chemical reactions, and Einstein's relating of mass to energy is significant only in nuclear reactions.

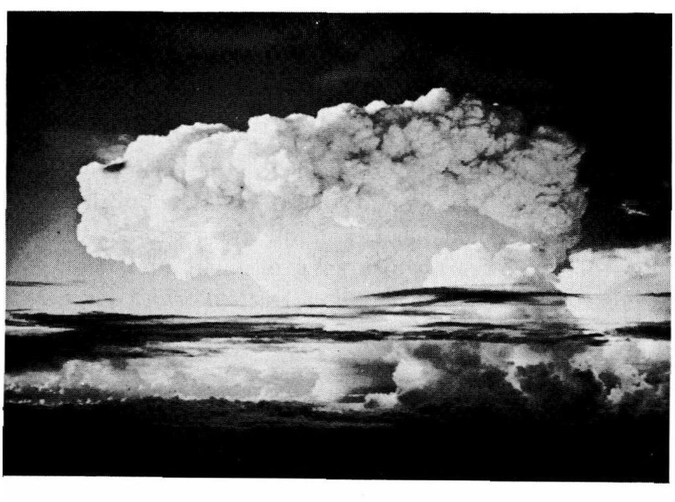


Fig. 1–6. The tremendous effect of a hydrogen bomb explosion comes from the conversion of matter into energy.

In terms of modern nuclear physics the **laws of conservation of energy and mass** can be stated in a single relationship: *Matter and energy can be neither created nor destroyed, but can be transformed one into the other.* Matter can be changed into energy and energy can be transformed into matter, but the sum total of matter and energy in the universe remains the same.

The above statements are the first of several *laws* with which we will become familiar in our study of chemistry. Therefore it is important for us to understand what is meant by a law. A **scientific law** *is a general statement which summarizes a number of related facts.* It is a statement of *what* takes place under a given set of conditions. Laws, or scientific principles, are *discovered by observation and experimentation.* They are not invented as explanations for observed facts. Explanations, which attempt to explain *why* things behave as they do, are called *hypotheses* or *theories.* We shall have more to say in the next two chapters about how facts and laws differ from hypotheses and theories.

Test Yourself

1. *What is chemistry? Why is it so important?*
2. *What is matter?*
3. *What is the property of inertia?*
4. *How can the weight of an object vary even though its mass remains the same?*
5. *What is density?*
6. *Compare the characteristics of the three physical states of matter.*
7. *Name several physical properties and several chemical properties.*
8. *Define:* (*a*) *physical change and* (*b*) *chemical change.*
9. *Name four types of energy. What do they have in common?*
10. *What is the law of conservation of energy? the law of conservation of mass?*
11. *What is the relationship between energy and matter? Who first stated this relationship?*

SYSTEMS OF MEASUREMENT

1-8. Fundamental Quantities of Measurement

Accurate measurement is important in all branches of science. The three fundamental quantities to which all measurements can be reduced are *length, mass,* and *time.* In chemistry, we are particularly interested in *volume,* which is derived from length measurements, and in *weight,* which we use as a measure of mass. Calculations that involve the third fundamental quantity, *time,* and those dealing with *temperature* and *pressure* are also important. In the following section, we shall consider the units involving length, volume, and weight.

1-9. English and Metric Systems

We are familiar with the common units of the foot, quart, and pound in the *English system* of measurement (sometimes called the *FPS system* for foot, pound, and second). But such units have no simple relationship and are difficult to convert from one to another, arithmetically. *The* **metric system** *is a decimal system* which defines length, volume, and mass in terms of the *meter, liter,* and *kilogram.* (This is called the *MKS system* from the meter, kilogram, and second.) Since the meter, liter, and kilogram are related and their derived units use ten as a base, metric calculations are simplified.

In the *English system* we have divisions and multiples of the basic length unit, the *foot*, expressed in inches, yards, rods, and miles. The *metric system* uses the prefixes *deci-* (one tenth), *centi-* (one hundredth), *milli-* (one thousandth), and *micro-* (one millionth) to show subdivisions of the units. To show multiples, the prefixes *deka-* (ten), *hecto-* (one hundred), *kilo-* (one thousand), and *mega-* (one million) are used. If you are not already familiar with these metric prefixes, you should certainly memorize them before going further into your study of chemistry.

Originally, the *meter* was proposed to be one ten-millionth of the distance from the earth's equator to either of the poles. Until recently, the standard meter was taken as the distance between two parallel lines marked on a platinum-iridium bar preserved under carefully controlled conditions at the International Bureau of Weights and Measures near Paris. It is now officially defined in terms of the wavelength of a particular spectral line emitted by an isotope (atomic mass 86) of the rare, gaseous element krypton.

Before 1964 the *liter* was defined as the volume of a kilogram of pure water at the temperature of maximum density and a pressure of one atmosphere. This made one milliliter (1/1000 of a liter) equal to 1.000027 cubic centimeters. However, the Twelfth General Conference on Weights and Measurements, meeting in Paris in 1964, redefined the liter as the volume of a cube of one decimeter (10 centimeters) on a side, making a milliliter and a cubic centimeter exactly the same size.

Fig. 1–7. Modern analytical balances are used to weigh accurately to 0.0001 gram.

The metric unit of mass, the *kilogram*, is defined as the mass of the standard kilogram, which is a cylinder of platinum-iridium kept at the International Bureau of Weights and Measures at Sèvres near Paris. In the United States, by act of Congress, the pound is defined as a body of mass equal to 0.45359237 kilogram. This makes a pound equal to approximately 454 grams, since there are 1000 *grams* in a kilogram. As the mass of a liter of water is still very nearly equal to one kilogram, the *density of water may be taken equal to one gram per milliliter* with sufficient precision for most purposes.

Note in passing that the unit of *time*, the *second*, is the same in both the English and metric systems. This was formerly defined as 1/86,400 part of the mean solar day (24 hours), and later as a fractional part of the year 1900. It has recently been redefined in terms of the vibration frequency of the atom of cesium 133—one second equals 9,192,631.770 vibrations at −210°C. These recent developments in the definition of our standard units of length and time are significant only to scientists who work with the extreme accuracies demanded by present-day investigations.

The common units of measurement of length, volume, and weight in the English and metric systems are given in Table 1–2, together with their equivalents. These are given for your ready reference rather than for you to memorize.