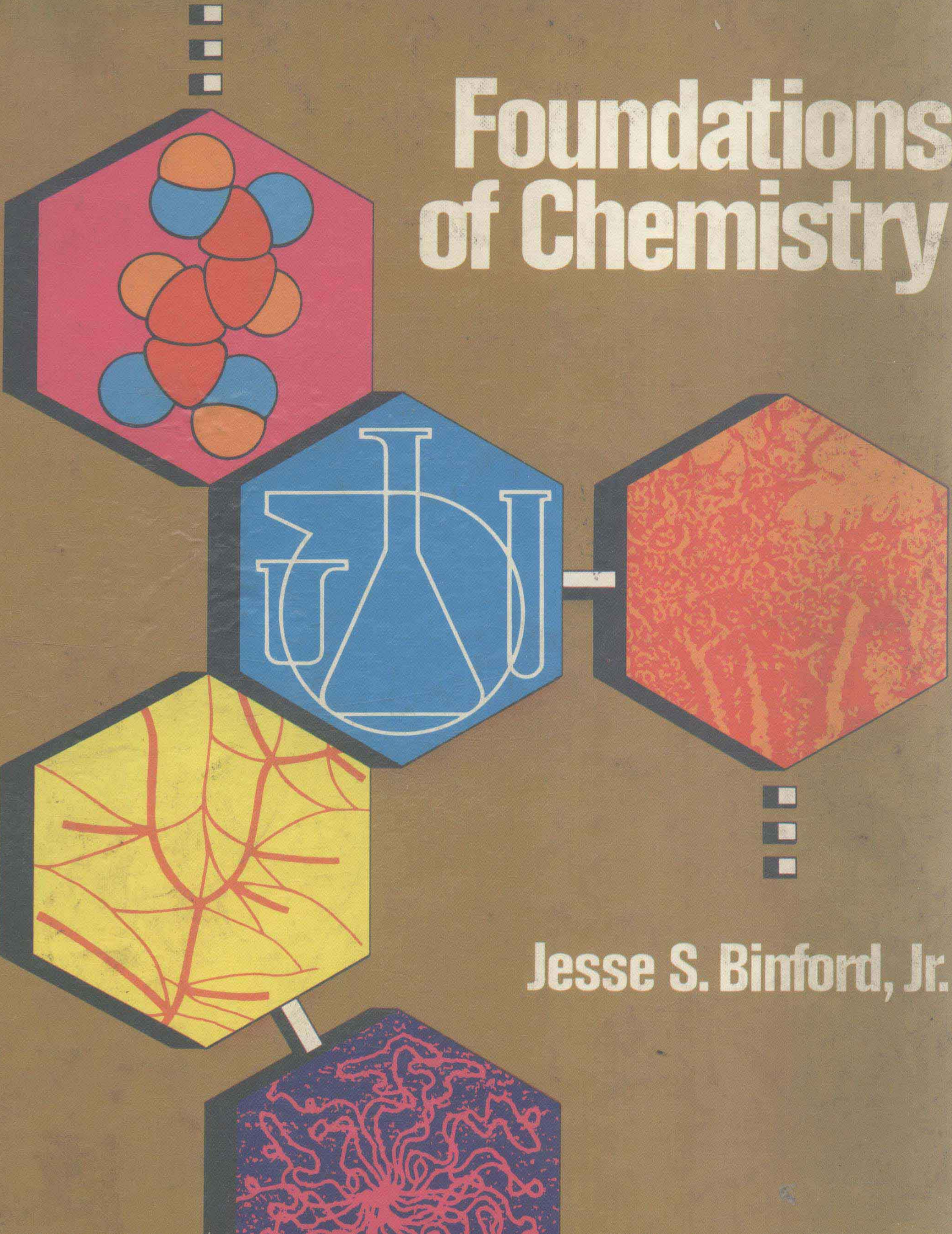
Foundations of Chemistry



Jesse S. Binford, Jr.

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PREFACE

This book was written because no satisfactory text was available to prepare college students for general chemistry. To avoid lowering the standards of the general chemistry course and help the poorly prepared student, we developed a new one-term course that lies somewhere between high school and college levels. In it we emphasize the topics students find most difficult in general chemistry, but we treat these subjects in a more fundamental manner than a college course usually does.

For which students is this course necessary, and why do they take it? We have found that most are majoring in the life sciences (nursing, premedicine, and biology), a significant number are in engineering, and a large number are still undecided. Their reasons for taking the course are that they did not have chemistry in high school (40%), or they think their high school course was weak (30%). Most of the others think they have been out of high school too long or simply need a science course. A large proportion (80%) have definite plans to take general chemistry.

Students usually do unsatisfactory work in general chemistry because of (1) an inability to use systematic methods, (2) an inability to apply simple arithmetic and algebra to chemical problems, (3) an inability to understand concepts and models, and (4) a lack of interest in chemistry. The intent of *Foundations of Chemistry* is to overcome these deficiencies. The text has been tested since 1971. The first year it was little more than a weekly syllabus and was used in conjunction with commercial textbooks. Revised and expanded as the result of student reaction in 1972, and again in 1974, it has developed into a textbook. The final revision resulted in the elimination of considerable extraneous material and brought the text to its present form. The emphasis has always been (1) basic explanation of the concepts that are often misunderstood in college chemistry, (2) problem solving, (3) practical everyday examples and applications, and (4) systemization of chemical facts. The last-mentioned is particularly important, because many essential topics for beginning students are almost pure memory work. The more systematically these subjects are presented, the easier they are to assimilate. As a result of student requests, many examples with detailed solutions and exercises with answers have been added. Furthermore, the problems at the end of each chapter are paired, and the answers to one complete set are provided.

In my own course, which does not have laboratory sessions associated with it, I supplement this text with required film and videotape demonstrations. There are weekly problem assignments and weekly quizzes supplemented by audiotape problem solutions and videotape quiz reviews. *Foundations of Chemistry* is not meant to be a book for independent study but rather one that requires encouragement and leadership from the teacher.

We have found the course to be a success in providing the necessary foundations for general chemistry. Our experience with several hundred students who have now taken both the "foundations" course and the first term of general chemistry indicates that the students make one letter grade higher than predicted on their placement examinations. Also, their average grade in general chemistry is the same as the class average, although comparison of performance on placement examinations would predict a lower average.

This text uses the "one-factor" method, or dimensional-analysis, to solve problems almost to the exclusion of other methods. The word "one-factor" is used to emphasize the superiority of the method. More understanding is required in using this method because the student must go back to the physical reality or to the definition in each problem and not just blindly use memorized formulas or take a 50-50 chance on a supposed proportion. However, more and more algebra is introduced in later chapters and by the last chapter, algebraic formulas are used almost exclusively.

Special thanks are given to Conard Fernelius and Mike Holloway, who made a number of helpful suggestions early in the project. Special credit is due my wife, Lolita Fritz Binford, who created the original artwork and who gave her help and encouragement throughout the project.

J. S. B.

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METHODS, PROPERTIES, AND THE PERIODIC TABLE

Science is a human enterprise. Its most significant achievements are results of the systematic application of ordinary logic to knowledge gained through observation.

A conversation with a three-year-old will give examples of the scientific method. Turn the pages of a magazine and ask the child to point out the pictures of animals. The child has observed cats, birds, and horses and might readily identify them as animals. But a picture of a dog might get a negative response. "That's not an animal. That's a dog!" If you then ask what the child knows about animals, you might be answered, "Well, they are made of meat." The child has not only accumulated information through observation but has organized it and found regularities. If you then point out that dogs are made of meat, the child may learn from this generalization that dogs are animals. Most examples of the learning process are applications of the scientific method.

Often a scientific discovery is said to be an accident. But, as in the case of the child "discovering" that dogs are animals, the scientist merely remembers something almost forgotten. One could say the scientist suddenly recognizes a relationship that could have been seen earlier, because all the information was there; however, the connection between the facts is noticed for the first time when something falls into place. Unfortunately such events do not usually occur until a considerable amount of work and mental effort have been expended, often in wrong directions.

1.1 THE SCIENTIFIC METHOD

A complete sequence of actions which comprise the scientific method are as follows: (1) obtaining facts by **observation,** that is, collecting data, (2) **organization** of these facts in a systematic way, (3) deriving from this organization of facts a "law," which is so-called not merely because it has stood the test of attempts to disprove it but mainly because it can be used in the **prediction** of facts not yet observed.

There is a hierarchy of terms expressing the degree of confidence in the correctness of the organization of data that may eventually be accepted as a law. The preliminary idea is usually called a **hypothesis,** and several hypotheses may be proposed for the same set of data, just for the sake of argument. A single new fact will frequently destroy a given hypothesis. After the hypothesis has been around for a while and has been found resistant to disproof, it is promoted to the level of **theory.** A theory is accepted by most scientists as an adequate explanation of the facts but usually with some reserve. The ultimate expression of acceptance is to describe a theory as a **law,** which signifies that it is generally accepted by scientists. The acceptance of the law does not usually occur until it has demonstrated repeatedly its powers of *prediction* of yet undiscovered knowledge. Some scientific ideas which, because of their abstractness are difficult to use for prediction, such as Einstein's theory of relativity, will be described as theories for many years. There was a famous hypothesis made by Avogadro in 1811 that explained certain aspects of chemical reactions between gases (Section 4.1). It was not accepted for such a long time (about 50 years) that it is still ironically referred to as "Avogadro's hypothesis."

1.2 AN EXAMPLE OF THE SCIENTIFIC METHOD—ARCHIMEDES' LAW OF FLOATING BODIES

An interesting set of experiments* has been devised by psychologists for children in which the children try to reconstruct Archimedes' law using the equipment shown in Figure 1.1. A child is given a bucket of water and several objects and asked to classify them on the basis of floating or sinking. Then the child is asked to summarize the observations and to devise a law if possible.

To describe an object it is necessary to list its properties. A **property** is a characteristic of an object that distinguishes it from other objects, such as color, size, and weight. As a result of this experiment, children develop the idea that the properties of weight and size considered separately are not very useful in characterizing the

*This is a part of the life-long study of the Swiss psychologist Piaget, who began as a zoologist. His interest in the development of intelligence in children and his observations on his own three children have resulted in important new evidence that IQ is not "fixed at birth" but depends on stimulation of the very young. See Bärbel Inhelder and Jean Piaget: *The Growth of Logical Thinking from Childhood to Adolescence*. Basic Books, New York, 1958.

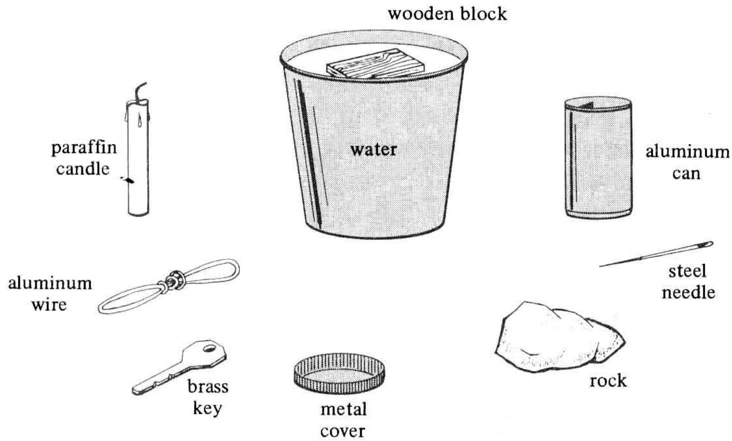


Figure 1.1. Archimedes' law of floating bodies. Why do some objects float and others sink?

phenomenon of floating; however, they discover the property of weight for equal volumes is very helpful.

The kinds of results obtained by the children are reported in the following paragraphs according to age groups. The psychologists can obtain evidence for new learning theories in this way, and you will be able to see the necessity for each of the steps in the scientific method. You will also see how an inferior hypothesis must be rejected when confronted by a single fact with which it is not compatible.

Children who are *four years of age* fail to see any relation between the properties of the objects and whether they float. In other words their powers of observation are too limited at this age for this kind of experiment.

Children at *five or six years of age* give as reasons for an object not floating that it is "big," "heavy," "long," or "small." Every object that sinks is described in terms of a similar property of another object that sinks. However, they are not bothered by the contradictions that, although the "heavy" block of wood floats as well as the "small" cork, the "heavy" rock sinks as does the "small" key.

Children of about *seven or eight years of age* typically classify the objects in three categories: (1) those that float (wood, candle), (2) those that sink (key, rock), and (3) those that sink or float depending on whether they are pushed through the surface and are filled with water (cover, aluminum wire, needle, can). Furthermore, they may hypothesize that *small-light* objects float while *small-heavy* objects sink and *large-light* objects float while *large-heavy* objects sink.

At later stages the psychologists recognize that some children will use knowledge acquired in school on this subject. They have identified these children through their questioning and have not included them among their reported interviews.

For the *twelve-year-old* Fran, the following encounter was recorded.

Fran does not manage to discover the law, but neither does he accept any of the earlier hypotheses. He classifies the objects presented correctly but hesitates before the aluminum wire.—Why are you hesitating?—Because of the lightness, but no, that has no effect.—Why?—The lightness has no effect. It depends upon the sort of matter; for example the wood can be heavy and it floats. And for the cover: I thought of the surface.—The surface plays a role?—Maybe, the surface that covers the water, but that doesn't mean anything. . . . Thus he discards all of his hypotheses without finding a solution.

Ala, who is the same age as Fran, makes the following hypotheses:

Why do you think this key will sink?—Because it is heavier than water.—This little key is heavier than water? (The bucket is pointed out.)—I mean the same quantity of water would be less heavy than the key.—What do you mean?—You would put them (metal or water) in containers which contain the same amount and weigh them.

Finally, Wur, who is *fourteen years old,* suggests the following very enlightening hypothesis:

I take a wooden cube and a plastic cube which I fill with water. (The cubes are the same size [and the plastic cube is hollow].) I weigh them and the difference can be seen on the scale according to whether an object is heavier or lighter than water.

In this way he has eliminated volume as a variable by basing the hypothesis on weight per unit volume, taking the equal size cubes as the unit of volume.

The usual way of stating **Archimedes' law** is as follows: *The force causing an object to float on water (the buoyant force) is equal to the weight of the water it displaces.* The law of Archimedes will be put to the test every time a new ship is launched on the waters. A quantitative example of the law that shows further predictive powers will be given in the next chapter (Section 2.7).

The degree to which young children use the scientific method in the development of their own intelligence is remarkable. Although it would not be practical in a text of this kind to insist that you relive the processes of thought that led to all the scientific concepts described, we hope that the concepts will be presented in such a way that you will want to make use of the scientific method yourself to solve chemical problems in your everyday life. It is after all, a natural method for the human species.

Exercise 1. If you introduce the needle into the water (Figure 1.1) end first, it will sink to the bottom. However, if you carefully lay it horizontally on the water surface, it will float. The same is true of a straight piece of aluminum wire. Does this disprove Archimedes' law? If not, can you propose a hypothesis to account for the new observation? Can you propose new experiments to test your hypothesis?

1.3 THE SCIENCE OF CHEMISTRY

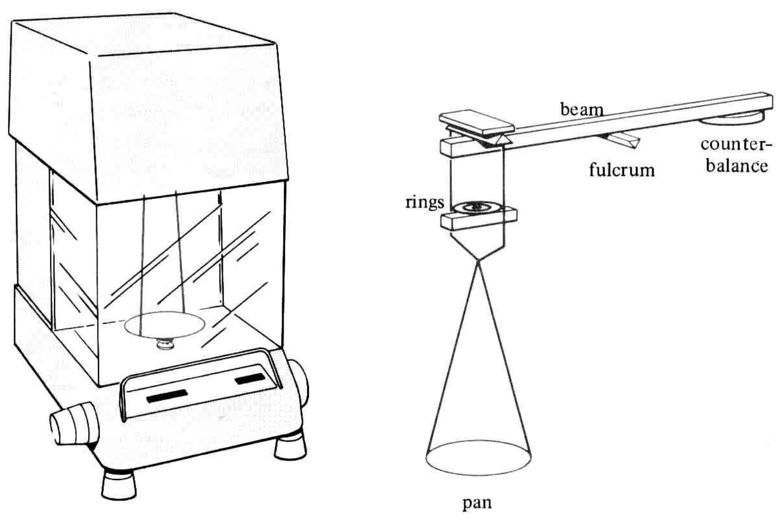
Chemistry is the science of matter—its properties; its composition; its structure; its synthesis; its behavior under changing conditions of pressure, temperature, light, and electrical forces; its interactions with other kinds of matter, and its changes in energy during these interactions.

Matter is that which has mass and volume. To have volume means that it occupies space to the exclusion of other forms of matter. The property that best describes mass is its **inertia,** which is its tendency to remain at rest when you attempt to move it or its tendency to remain in motion when you attempt to stop it. The greater the force needed to overcome the inertia of an object, the greater is its mass. Another important property of mass is the **weight** that is associated with it. The weight of matter is the force gravity exerts upon it.

The distinction between weight and mass is subtle, but in this time of weightless astronauts drifting around on your television screen it is obvious that such a difference exists. For example, the astronaut would have to use the property of inertia to obtain the mass of an object in his space ship. On earth, however, you can say two objects have the same mass if their gravitational attractions to earth (weights) are the same. An ideal piece of equipment for this comparison is a one-pan balance like the one shown in Figure 1.2. The beam (the horizontal bar which runs from front to rear at the top) is balanced when the pan is unloaded, or empty, because of the large counterbalance at the rear. The pan will descend when an object to be "massed" is placed upon it. By removing enough rings, which are on the same end of the beam as the pan and object, to regain balance, you can say that the mass of the rings removed and that of the object are equal. All that is needed to define mass quantitatively is a standard mass to which the rings can be compared. One such standard is maintained in the National Bureau of Standards in Washington, D.C. Because all the masses discussed in the remainder of this text will be subject to the gravitational force of the earth, "weight" will be considered to mean "mass" and "weighing" to mean "massing."

Volume can always be expressed in cubic length. The volume of a cube, shown in Figure 1.3, is the cube of the length of an edge, that is, the length of an edge multiplied by itself three times. The volume of any irregularly shaped object could be expressed in terms of small cubes that occupy the same volume. In order to express

Figure 1.2 The one-pan balance.



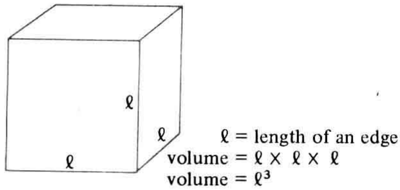


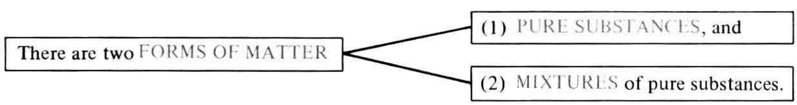
Figure 1.3. The volume of a cube.

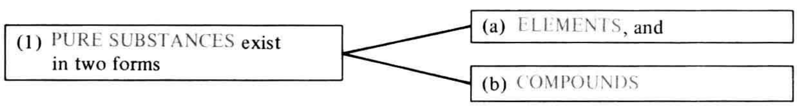
volume quantitatively, all that is needed is a standard of length. This standard could be the length of some object maintained at the Bureau of Standards. The best standard, however, is provided by a certain number of wavelengths of light (Section 13.2), which not only is accurately measurable but also does not change with temperature and other conditions.

The Forms of Matter

Chemists have developed a special vocabulary to describe the different forms of matter that are observed. The outline in Figure 1.4 will help you see the interrelations of the various forms.

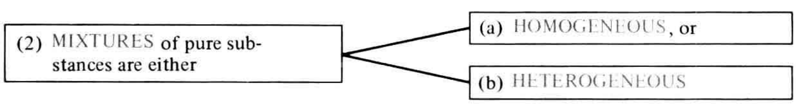
Figure 1.4. The forms of matter.





(a) ELEMENTS are pure substances which cannot be broken down into simpler elements by chemical means.

(b) COMPOUNDS are chemical combinations of two or more different elements.



(a) HOMOGENEOUS MIXTURES, also called SOLUTIONS, have no visible discontinuities between substances.

(b) HETEROGENEOUS MIXTURES have visible boundaries of separation between substances.

Separation of Mixtures by Physical Means

Physical changes are very common in nature. A **physical change** does *not* involve the formation of new compounds or the breakdown of existing compounds, and it is easily reversed. Most simple substances are capable of existing in three **phases: solid, liquid,** and **gas,** which are called the **states of matter.** Changes from one state to another are examples of physical change. By simply increasing the temperature, matter may be changed from solid $\longrightarrow$ liquid $\longrightarrow$ gas, provided that chemical decomposition does not occur. By decreasing the temperature, the changes may be reversed: gas $\longrightarrow$ liquid $\longrightarrow$ solid.