Introduction to
Chemical Principles

H. Stephen Stoker

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Macmillan Publishing Co., Inc.

NEW YORK

Collier Macmillan Publishers

LONDON

Front cover (clockwise from top): copper sulfate ($CuSO_4$), cobalt nitrate ($Co(NO_3)_2$), cobalt chloride ($CoCl_2$).

Back cover (clockwise from top right): nickel chloride ($NiCl_2$), manganese sulfate ($MnSO_4$), sodium carbonate (Na_2CO_3), potassium dichromate ($K_2Cr_2O_7$), chromium sulfate ($CrSO_4$).

Printed in the United States of America.

Macmillan Publishing Co., Inc.
866 Third Avenue, New York, New York 10022

Collier Macmillan Canada, Inc.

Library of Congress Cataloging in Publication Data

Stoker, H. Stephen (Howard Stephen), Date
Introduction to chemical principles.

Includes index.
1. Chemistry. I. Title.
QD33.S86 540 82-6537
ISBN 0-02-417620-6 AACR2

Printing: 3 4 5 6 7 8 Year: 3 4 5 6 7 8 9 0

ISBN 0-02-417620-6

Preface

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

Many texts written for preparatory chemistry courses are simply "watered-down" versions of general chemistry texts. Such texts treat almost all topics found in the general chemistry course but only at a superficial level. *Introduction to Chemical Principles* does not fit this mold. The author's philosophy is that it is better to treat extensively fewer topics and have the student understand those topics in greater depth. Topics treated in this text are those most necessary for a solid foundation upon which further chemistry courses can build.

Because of the varied degrees of understanding of chemical principles possessed by students taking a preparatory course, development of each topic in this text starts at "ground level" and continues step by step until the level of sophistication required for further courses is attained.

Problem solving is a major emphasis of this text. Years of teaching experience indicate to the author that student "troubles" in general chemistry courses are almost always centered in the student's inability to set up and solve problems.

Whenever possible, dimensional analysis is used in problem solving. This method, which requires no mathematics beyond arithmetic and elementary algebra, is a most powerful problem-solving tool with wide applicability. Most important, it is a method that an average student can master with an average amount of diligence. Mastering dimensional analysis also helps build the confidence that is so valuable for success in further chemistry courses.

Numerous Examples — worked-out problems — are found in the text. In each case the solution is given step by step, and detailed commentary accompanies each step in the worked-out solution. In addition, many types of problems are explored through more than one Example.

Working practice exercises is a necessary activity for students if they are to become proficient at problem solving. Consequently, an abundant selection of end-of-chapter Questions and Problems is provided. Most chapters offer at least forty exercises, many of which contain subparts. The Questions and Problems are grouped according to topic and arranged in order of chapter coverage. Thus, instructors can assign some problems before students have completed the chapter. This section-by-section arrangement of exercises also enables the student to test his or her understanding of each section before moving to another section. Answers to many of the Questions and Problems (all those whose numbers or letters appear in color) are given in the back of the text.

The availability of inexpensive electronic calculators has introduced into general chemistry courses a "new problem" that is treated in depth in this text. This "problem" relates to significant figures. Routinely, electronic calculators display answers that contain more digits than are needed. It is a mistake to record these extra digits, since they are meaningless — that is, they are not significant figures. In every Example students are reminded of this potential for error by the appearance of two answers after the sample problem has been solved: the calculator answer (which does not take into account significant figures) and (in color) the correct answer (which is the calculator answer adjusted to the correct number of significant figures).

Many learning aids are found in the text. The important skills and ideas that students need to absorb are summarized as Learning Objectives at the end of each chapter. There follows a list of new terms and concepts defined in the chapter. Throughout the text important terms and statements are highlighted. The key words are printed in boldface when defined and repeated in the margin (in color) for easy reference. Related topics are extensively cross-referenced with particular attention to informing students of previous sections needed as a foundation for understanding the topic currently under discussion.

More material than can be conveniently covered in one semester or quarter is present in the text. Thus, instructors will have a choice of chapters or sections to cover in class. The later chapters particularly lend themselves to selective assignment.

Three topics not traditionally included in preparatory chemistry texts are included in this one: (1) chemical calculations involving simultaneous reactions and series of consecutive reactions (Sec. 8.9), (2) quantum numbers (Secs. 9.6–9.8), and (3) molecular geometry using VSEPR theory (Sec. 10.12). Instructors should consider these subjects as optional topics that can provide additional insights for some students or that can be omitted without affecting overall topic coverage. All three optional topics are completely self-contained and do not serve as prerequisites for any material that follows.

Supporting materials, to assist both the student and the instructor, have been especially written for use with this text. For the student both a study guide and a laboratory manual (for courses that include a laboratory period) are available. Both of these items reinforce many of the concepts covered in the text. They also employ the same notation and methodology for problem solving as are used in the text. For the instructor a solutions manual is available.

Writing a text such as this is never accomplished without cooperation and contributions from many sources. The help of the following people who reviewed the text prior to its publication is acknowledged: Elliott L. Blinn, Bowling Green State University; Owen C. Gayley, San Antonio College; Ethelreda Laughlin, Cuyahoga Community College; Ruth Sherman, Los Angeles City College; and Linda N. Sweeting, Towson State University. The reviewers offered many valuable comments and suggestions that have been incorporated into the text. The help and prodding of Elisabeth Belfer of Macmillan Publishing Co. during the production stages of this project are also appreciated.

H. S. S.

Contents

1 The Science of Chemistry

1.1 Chemistry — A Scientific Discipline

During the entire time of their existence on earth, human beings have been concerned with and fascinated by their surroundings. This desire to understand their surroundings — an attribute that distinguishes them from all other living organisms — has led them to accumulate vast amounts of information concerning themselves, their world, and the universe. **Science** *is the study in which humans attempt to organize and explain in a systematic and logical manner knowledge about themselves and their surroundings.*

science

The enormous range of types of information covered by science, the sheer amount of accumulated knowledge, and the limitations of human mental capacity relative to mastering such a large and diverse body of knowledge have led to the division of the whole of science into smaller subdivisions called scientific disciplines. **Scientific disciplines** *are branches of scientific knowledge limited in their size and scope to make them more manageable.* Chemistry is one of these disciplines. Astronomy, botany, geology, physics, and zoology are some of the other disciplines that have resulted from this substructuring of science.

scientific disciplines

In a sense, the boundaries between scientific disciplines are artificial, because all scientific disciplines borrow information and methods from each other. No scientific discipline is totally independent. This overlap requires that scientists, in addition to having in-depth knowledge of a selected discipline, also have limited knowledge of other disciplines. Problems scientists have encountered in the last decade have particularly pointed out the interdependence of disciplines. For example, chemists attempting to solve the problem of chemical contamination of the environment find that they need some knowledge of geology, zoology, and botany. Because of this overlap, it is now common to talk not only of chemists, but also of geochemists, biochemists, chemical physicists, etc. Figure 1-1 shows how chemistry merges with selected other scientific disciplines.

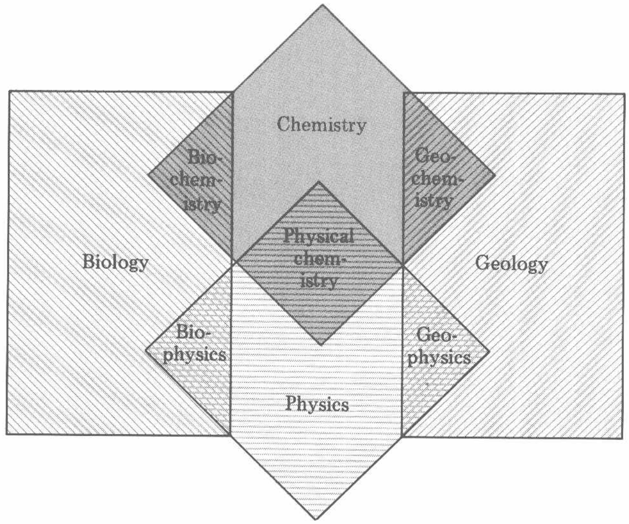

Figure 1-1. Interrelationship of scientific disciplines.

The overlap of the various scientific disciplines affects not only practicing scientists but also today's college students. It means that students must necessarily study in disciplines other than those of primary interest to them. The knowledge they gain from such studies is often useful and many times essential if they are to be competent in their chosen field. Many students in courses for which this textbook is written are studying chemistry because of its applicability to other disciplines in which they have a more specific interest.

1.2 The Scope of Chemistry

Although chemistry is concerned with only a part of the scientific knowledge that has been accumulated, it in itself is an enormous and broad field. Chemistry touches all parts of our lives because of its broadness in scope. There is no getting away from chemistry, nor should anyone try to avoid it.

Most of the clothes we wear are made from synthetic fibers produced by chemical processes. Even natural fibers, such as cotton or wool, are the products of naturally occurring chemical reactions within living systems. Our transportation usually involves vehicles powered with energy obtained by burning chemical mixtures, such as gasoline. Drugs used to cure many of our illnesses are the result of much chemical research. The paper on which this textbook is printed was created through a chemical process and the ink used in printing the words on each page is a mixture of many chemicals. The movies we watch are possible because of synthetic materials called film. The images on film are produced through interaction of selected chemicals. Almost all of our recreational pursuits involve objects containing materials produced by chemical industries. Skis, boats, basketballs, bowling balls, musical instruments, and television sets all contain materials that are not naturally occurring.

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

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

1.3 How Chemists Discover Things — The Scientific Method

Chemistry is an experimental science; that is, chemical discoveries are made as the result of experimentation. This feature, experimentation, is what distinguishes chemistry (and other sciences) from other types of intellectual activity.

scientific method

A majority of the scientific and technological advances of the twentieth century are the result of systematic experimentation using a method of problem solving known as the scientific method. The **scientific method** *is a set of specific procedures for acquiring knowledge and explaining phenomena.* Procedural steps in this method are

1. Collecting data through observation and experimentation.
2. Analyzing and organizing the data in terms of general statements (generalizations) that summarize the experimental observations.
3. Suggesting probable explanations for the generalizations.
4. Experimenting further to prove or disprove the proposed explanations.

Occasionally a great discovery is made by accident, but the majority of scientific discoveries are the result of the application of the above steps over long periods of time. There are no instantaneous steps in the scientific method; applying them requires considerable amounts of time.

There is a vocabulary associated with the scientific method and its use. This vocabulary includes the terms fact, law, hypothesis, and theory. Understanding the relationship between these terms is the key to a real understanding of how chemical knowledge has been and still is obtained.

fact

The beginning step in the search for chemical knowledge is to identify a problem concerning some chemical system which needs study. After determining what other chemists have already learned concerning the selected problem, one may begin experimentation. New firsthand information is collected about the system via observation; that is, new facts about the system are obtained. A **fact** *is a valid observation about some natural phenomenon.* Facts are reproducible pieces of information. If a given experiment is repeated, under exactly the same conditions, the same facts should be obtained. All facts, to be acceptable, must be verifiable by anyone who has the time, means, and knowledge needed to repeat the experiments that led to their discovery.

Next an effort is made to determine ways in which the facts about a given chemical system relate to each other and to those known for similar chemical systems. Quite often repeating patterns become apparent among the collected facts. These patterns lead to generalizations, called laws, about how the chemical systems of concern behave under specific conditions. A **law** *is a generalization that summarizes in a concise way facts about natural phenomena.*

law

It should not be assumed that laws are easy to discover. Often, years and years of work and thousands upon thousands of facts are needed before the true relationships between variables in the area under study become apparent.

A law is a description of what happens in a given type of experiment. There is no mention in a law as to why what happens does happen. It simply summarizes experimental observations without attempting to clarify why.

A law may be expressed as a verbal statement or as a mathematical equation. An example of a verbally stated law is "If hot and cold pieces of metal are placed in contact with each other, the hot piece always cools off and the cold piece always warms up."

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

Chemists, and scientists in general, are not content with just knowing about natural laws. They want to know why a certain type of observation is always made. Thus, after a law is discovered, plausible tentative explanations of the behavior encompassed by the law are worked out by scientists. Such explanations are called hypotheses. A **hypothesis** *is a tentative model or picture that offers an explanation for a law.*

hypothesis

Once a hypothesis has been proposed, experimentation begins again. Many, many more experiments, under varied conditions, are run to test the reliability of the proposed explanation. The hypothesis must be able to predict the outcome of as yet untried experiments. The validity of the hypothesis is dependent upon its predictions being true.

It is much easier to disprove a hypothesis than it is to prove it. A negative result from an experiment indicates that the hypothesis is not valid as formulated and that it must be modified. Obtaining positive results supports the hypothesis, but doesn't definitely prove it. There is always the chance that someone will carry out a new type of experiment, never before thought of, which disproves the hypothesis.

As further experimentation continues to validate the concepts of a hypothesis, its acceptance in scientific circles increases. If after extensive testing the reliability of a hypothesis is still very high, confidence in it increases to the extent of its acceptance by the scientific community at large. After further lapse of time and additional accumulation of positive support, the hypothesis assumes the status of a theory. A **theory** *is a hypothesis that has been tested and validated over long periods of time.* The dividing line between a hypothesis and a theory is arbitrary and cannot be precisely defined. There is not a set number of supportive experiments that must be performed to give a hypothesis theory status.

theory

Theories serve two important purposes: (1) They allow scientists to predict what will happen in experiments that have not yet been run, and (2) they simplify the very real problem of being able to remember all the scientific facts that have already been discovered.

Even theories often must undergo modification. As scientific tools, particularly instrumentation, become more sophisticated, there is an increasing probability that