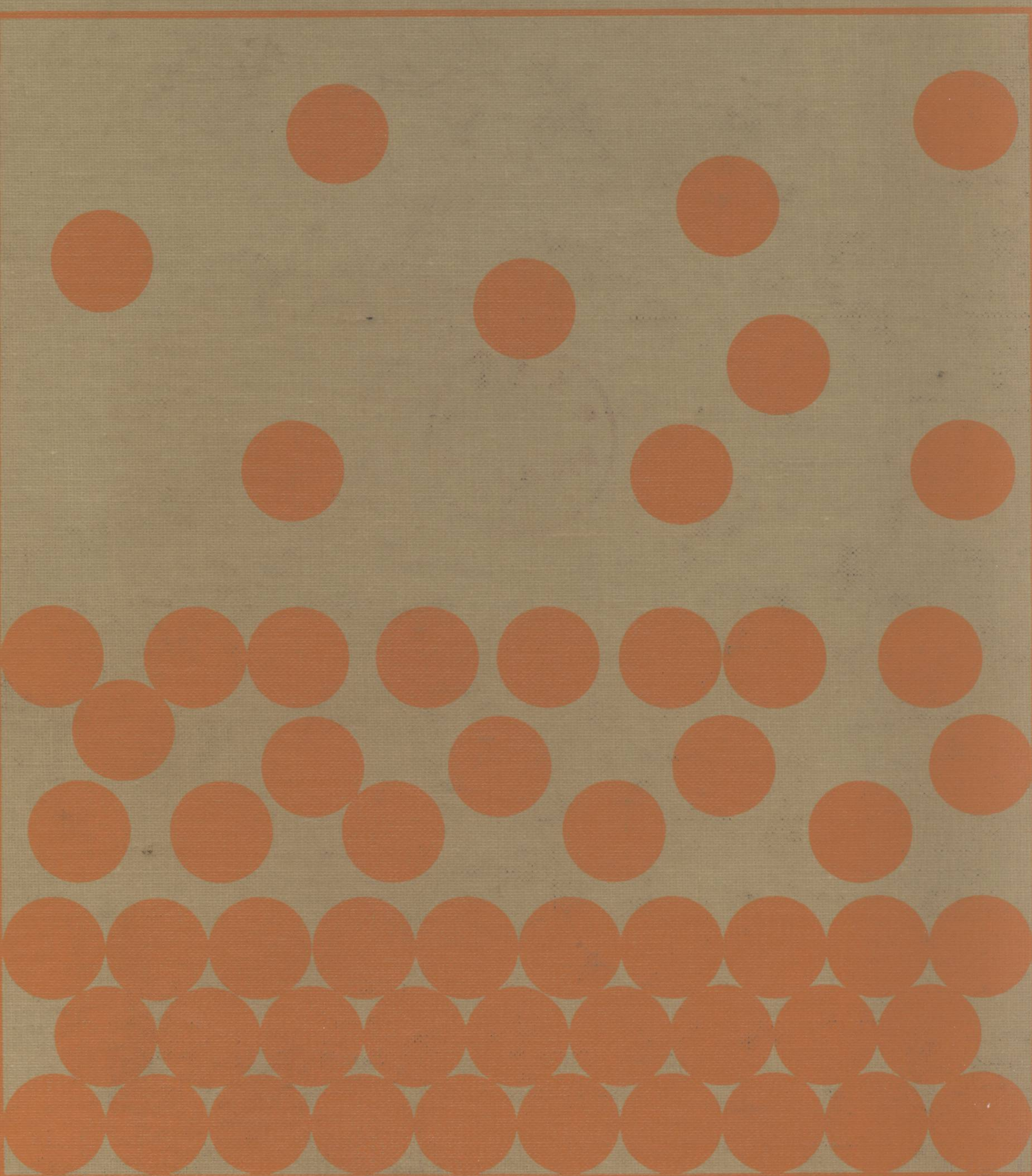
R. T. SANDERSON

Fundamentals of Modern Chemistry



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R.T. SANDERSON
Arizona State University

Scott, Foresman and Company
Glenview, Illinois London

Library of Congress Catalog No. 76-121971.

Printed in the United States of America.

Regional offices of Scott, Foresman and Company are located in Atlanta, Dallas, Glenview, Palo Alto, Oakland, N.J., and London, England.

Periodic Table of the Chemical Elements

MAJOR GROUPS

	M1	M2	M2′	M3	M4	M5	M6	M7	M8
1					H 1 1.0080				He 2 4.0026
2	Li 3 6.939	Be 4 9.0122		B 5 10.811	C 6 12.01115	N 7 14.0067	O 8 15.9994	F 9 18.9984	Ne 10 20.183
3	Na 11 22.9898	Mg 12 24.312		Al 13 26.9815	Si 14 28.086	P 15 30.9738	S 16 32.064	Cl 17 35.453	Ar 18 39.948
4	K 19 39.102	Ca 20 40.08	Zn 30 65.37	Ga 31 69.72	Ge 32 72.59	As 33 74.9216	Se 34 78.96	Br 35 79.909	Kr 36 83.80
5	Rb 37 85.47	Sr 38 87.62	Cd 48 12.40	In 49 114.82	Sn 50 118.69	Sb 51 121.75	Te 52 127.60	I 53 126.9044	Xe 54 131.30
6	Cs 55 132.905	Ba 56 137.34	Hg 80 200.59	Tl 81 204.37	Pb 82 207.19	Bi 83 208.980	Po 84	At 85	Rn 86
7	Fr 87	Ra 88							

TRANSITIONAL

	T3		T4	T5	T6	T7	T8	T9	T10	T11
4	Sc 21 44.956		Ti 22 47.90	V 23 50.942	Cr 24 51.996	Mn 25 54.9380	Fe 26 55.847	Co 27 58.9332	Ni 28 58.71	Cu 29 63.54
5	Y 39 88.905		Zr 40 91.22	Nb 41 92.906	Mo 42 95.94	Tc 43	Ru 44 101.07	Rh 45 102.905	Pd 46 106.4	Ag 47 107.870
6	La 57 138.91	Lu 71 174.97	Hf 72 178.42	Ta 73 180.948	W 74 183.85	Re 75 186.2	Os 76 190.2	Ir 77 192.2	Pt 78 195.09	Au 79 196.967
7	Ac 89	Lw 103	104							

INNER TRANSITIONAL

6	Ce 58 140.12	Pr 59 140.907	Nd 60 144.24	Pm 61	Sm 62 150.35	Eu 63 151.96	Gd 64 157.25	Tb 65 158.924	Dy 66 162.50	Ho 67 164.930	Er 68 167.26	Tm 69 168.934	Yb 70 173.04
7	Th 90 232.038	Pa 91	U 92 238.03	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102

PREFACE

We live in a time when, especially in the sciences, new information is being accumulated far more rapidly than we know how to assimilate it. Chemistry is in a state of expansion so rapid that it is leading to more and more fragmentation into highly specialized subjects. No longer can all of these subjects be neatly classified as inorganic, physical, organic, and analytical. Instead they overlap in all directions, not only with each other but with all other sciences and mathematics as well. The resulting educational problems are vast and formidable. What indeed is the appropriate educational background for the omniscience which tomorrow's citizen would seem to require?

Substantial improvements in the teaching of high-school chemistry have occurred in recent years, largely because of the heroic efforts of dedicated teachers at both secondary and college levels. Unfortunately, however, many students still enter the college general chemistry program inadequately prepared for the rigorous presentation of physical chemical principles now in vogue at many colleges and universities. In part, this may be due to the atmosphere at many public high schools, where even the most talented teachers find it difficult to maintain standards appropriate for college preparation. In part, it may be the result of the practice of taking high-school chemistry during the junior year, which allows a whole year for memory leakage before college entrance. Whatever the cause, many students need help in the form of college-level preparation for the usual general chemistry course. It is the purpose of this book to provide such help.

Today's chemistry teacher, viewing the increasingly chaotic condition of chemical science, is perhaps more aware than ever before that we must cling to the fundamentals or all is lost. Immediately we are confronted by the problem that *fundamental chemistry is not simple.* Our sense of logic tells us that before we try to erect a comprehensive structure of chemistry, we should build a firm foundation of fundamental principles. Our experience tells us that no real understanding of such principles is possible until a substantial part of the structure of chemistry is available to make the principles meaningful. Our problem is that a completely logical development of chemistry would be incomprehensible to beginners. It is not easy to teach a subject in which the most difficult topics come first.

So, like all reasonable approaches to the learning of chemical science, this book represents a compromise. I have tried to introduce the material as logically as seems practical. Recognizing, however, the inherent sterility of concepts unrelated to practical experience, I have tried constantly to show the relationships between fundamental principles and practical applications. No student, it seems to me, should be expected to acquire a truly useful understanding of a science by a once-through coverage even if in considerable depth. I have tried to implement this conviction by explaining all new material and by repeatedly referring back to the principles studied earlier. If this book has any central guiding principle or motivation, it is my fervent desire that all serious students should acquire from it a sense of appreciation of chemistry as a science and as a human activity—an appreciation based on *genuine understanding.*

My sole concern in the writing of this book has been for the student, for whom I have tried to make every figure and illustration meaningful and instructive. To this end, many of the figures are accompanied by unusually detailed explanations that give the student a fresh and independent view of concepts and principles already detailed in the text. Both the laboratory manual and instructor's manual, written by Raymond F. O'Connor, are designed to complement and enhance the basic text while providing both student and instructor with the necessary tools for a fundamental approach to the study of chemistry.

Despite the difficulties, mainly mathematical, which bar the way to highly sophisticated modern chemical theory, I am convinced that there is much that can be presented to beginning students in terms which, although simple enough for comprehension, still contribute significantly to the student's genuine appreciation of the science. I sincerely believe that much more can be accomplished in this direction than has previously been achieved. Throughout my own professional career my principal research has been directed toward explaining chemistry simply yet honestly. This book reflects, I trust, my conviction that understanding is the heart of true learning.

Paradise Valley, Arizona

R. T. Sanderson

INTRODUCTION

WHAT IS CHEMISTRY?

This is the story of chemistry. It begins with man's earliest struggle with Nature, long before the dawn of history. It leads through the mysterious arts of ancient and medieval alchemy and into the awakening intellects of the first scientific chemists three hundred years ago. With ever-accelerating progress it brings us to the modern world of fantastic theoretical understanding and incredible materialistic achievement. The story never ends. Wherever chemical scientists are working, still more fascinating chapters are being written. As long as man has curiosity and brains to seek the answers, the study of chemistry will go on and on forever.

To each of you, if you choose, comes the opportunity to add your own individual paragraph to this unending story. More remains to be discovered than has been learned since the very beginning of time. And whether you choose to add to this story or write another, you will need some knowledge of chemistry to become an educated person, one who knows how to put the most into life.

The story of chemistry is a story of all that is gaseous, liquid, or solid. Chemistry is the science of matter. It seeks to answer three basic questions about matter: What is matter? Why does matter have the properties it has? How can changes from one form of matter to another be controlled?

When we ask what matter is, we are really asking what it is made of: What are its components? When we observe different properties, we ask why some materials are gases, others liquids, and still others solids. Why are some materials colorless, some red, some green, and some purple? Why are some hard, some soft, some weak, and some strong? Why are some materials harmless, some nutritious, and some poisonous? When we ask how chemical and physical changes can be controlled, we are essentially implying that we are familiar with the remarkable changes that matter may undergo. Iron rusts;

wood burns; food is digested. Thousands of different substances can be made from the familiar materials at hand. Rocks and minerals, water, air, vegetation—all serve the chemist in his quest to create new kinds of matter which will hopefully improve the quality of man's life.

If the new substances are more useful than those from which they are produced, we wish to learn how to *bring about* the change. If the new substances are less useful, we need to learn how to *prevent* the change. The very essence of practical chemistry is the *control of chemical change*. One of the purposes of this book is to explore the various ways of effecting such control. Consider these three questions together. What is matter, why does it have the properties it has, and how can we control its changes from one form to another? The answer to the last question must depend on the answer to the second, which, in turn, must depend on the answer to the first. Chapter 1 therefore begins by trying to answer the question, What is matter?

First, however, it is important to know something about how chemists work. For modern chemistry is living proof of the remarkable effectiveness of the methods of science.

THE METHODS OF SCIENCE

Much has been said about the scientific method. People generally agree that use of this "method" has been the primary cause of today's tremendous acceleration in the acquisition of new information. It has been estimated that the total quantity of information on chemistry is now doubling every dozen years. Acceleration in other areas of science is comparably rapid. If this is the result of application of the scientific method, then we had better learn something about what this method is.

Strangely, there is no general agreement on exactly what the scientific method is. This is not, however, as strange as it may seem. The scientific method is actually a combination of methods by which scientists work. Since scientists are only individual people, their methods may vary according to their individual qualities and talents. Certain fundamental principles do, however, underlie the work of all scientists. These we can profitably examine. In the process, perhaps some of the confusion commonly existing concerning the meaning of the word "scientific" can be dispelled. Commercial advertisers, anxious to capitalize on the successes of science, have been major contributors to this confusion. A more fundamental source of this confusion is the gulf between the imagined ideals of scientific discovery and the truth about how such discoveries are made.

The Method of Experiment

Deliberate scientific experimentation is so common these days that it is difficult to realize how scarce it was three centuries ago. Then, anyone who had the time and an inclination to wonder about the mysteries of nature could observe naturally occurring events only if he were lucky enough to be present when the events happened. He could think about these occurrences, too, and speculate about the magic that caused them. But seldom, if ever, did it occur to him that he might avoid waiting by himself manipulating nature. Seldom did he recognize that a simple experiment might tell him whether his speculations were correct. Little did he realize the importance of identifying all the factors that might have influenced what he observed. Consequently, the discovery of new knowledge was erratic and extremely slow.

Gradually, beginning about three hundred years ago, man began to realize that he himself could *initiate* natural phenomena. At his own convenience he could bring together the ingredients and control the conditions under which he wished to observe their reactions. Furthermore, he could create experimental conditions rare or nonexistent in nature. As he learned to conduct his own experiments, he found he could study nature over a much wider range of conditions and make much more accurate observations. He could repeat experiments exactly, as often as he wished, to see whether his observations could be reproduced. Equally important, he learned to record his experiments in such a way that other investigators could duplicate them and make the same observations anywhere else in the world at any later date. To borrow a phrase from the TV commercials, this development was the original "scientific breakthrough." It was the dawn of a new era in civilization. From this time on, our knowledge of the physical world has increased at an ever-accelerating rate.

Experimental design is largely a technical matter. A scientist chooses conditions, designs equipment or apparatus, and plans experiments that will produce maximum information at the least cost in money and time. He tries to produce results that can be observed with ease and accuracy. Ideally, they should be results whose meaning is completely clear. Often such experiments require a combination of mechanical ingenuity and manipulative skill. Their planning requires originality, logical thinking, and most of all, a sound knowledge of the subject under investigation. Every scientist, therefore, must keep continuously up to date in his reading of the work of other scientists. This not only gives him knowledge of the field in which he wishes to experiment, but also tells him what others have already done. Without this knowledge he might waste months duplicating what someone else has already accomplished.

The information obtained from experiments is of course their very reason for being. Careful, complete, and totally honest observations are, therefore, absolutely essential. No informed person can avoid having opinions or expectations concerning the probable nature of the results of the experiments he undertakes. But a scientist must school himself to keep his observations of fact entirely separate from his opinions or preconceived notions of what the facts "ought to be." His opinions *must not* influence the accuracy of his observations. The truth of this statement is emphasized by the fact that many, if not most, truly great scientific discoveries have been unexpected. A scientist, or anyone else, would be ill prepared to recognize the unexpected if he were too sure in advance that it would not happen.

Seldom is it possible to observe experimentally the precise information really wanted. Practically always, one needs to interpret the observations in terms of the information he seeks. For instance, a dye called litmus turns pink or red when placed in a water solution containing acid. A water solution containing acid looks exactly like plain water. No one can see the acid. If one wishes to learn whether a water solution contains acid, he must perform some experiment. A simple experiment is to dip a piece of litmus paper (paper containing the blue dye litmus) into the solution. If the water does contain acid, the paper will turn pink or red. This fact we know from thousands of experiments with solutions which were known to contain acid because the acid was deliberately added to the water. But the point is, even in this very simple and seemingly direct experiment of dipping litmus paper into the water, one only *infers* from a pink color that acid is present. The paper does not come out of the water with a big ACID written on it. No bells ring or lights flash while a huge "acid" sign drops from the ceiling. Nevertheless, on the indirect evidence of the pink color, we confidently conclude that acid is present. If the paper remains blue, we conclude that no acid is present.

In this particular example, we are fairly safe. Although complications could confuse the interpretation of our observation, they are relatively unlikely. But in practically all experimental work, the scientist must interpret the observations he makes in terms of the information he seeks. The information is thus obtained *indirectly,* and there is always the possibility of faulty interpretation. There is the well-known example of the man who sought to discover the intoxicating ingredient of liquor. He drank whiskey and water and became intoxicated. He drank rum and water and became intoxicated. He drank gin and water and became intoxicated. Becoming sober once more, he studied his observations carefully and noted that all three drinks had similar effects. It was obvious to him what must be the intoxicating ingredient. What was common to all three was *water.*

It is in the interpretation of their experimental observations that scientists are most fallible. Usually, this is the most difficult part of the investigation. Unfortunately, it is also the least objective part. It is the part most susceptible to the influence of the scientist's previous experience—his training, his personality, his prejudices, his flaws and human weaknesses. Here the ideals of scientific methods encounter the non-ideal fact that all scientists are human beings. To the extent that scientists are widely informed, open-minded, objective, and clever, their interpretations can be enlightening and stimulating, and contribute usefully to understanding. To the extent that they are narrow, opinionated, or dull, their interpretations can be misleading or even nonexistent. Many scientific workers enjoy experimentation and are very good at it, but do not concern themselves much with wondering about the meaning of the measurements so carefully made. Although such people are essential in science and perform invaluable service, they should be recognized as technicians rather than scientists. The true scientist, fallible though he must be, has an active interest in understanding the significance of his observations. The methods of science have proven extremely effective because most scientists are able, most of the time, to interpret their experimental results in a way that is useful to the further development of their science.

The Role of Intuition and Luck

The unsung heroes of scientific research are *intuition* and *luck*. These factors seem so "unscientific" that their role is often minimized. One hardly expects the Nobel prize winner to say, "I just dreamed up the experiment and was plain lucky it came out the way it did." But understanding the importance of these uncontrollable factors is necessary to appreciate the full nature of science.

Intuition is a function of the human intelligence that seems to combine imagination and subconscious wisdom into a sometimes effective guide for guessing. In other words, intuition provides the "education" in an "educated guess." A good creative scientist rarely can say with assurance, "I will now carry out this experiment which will reveal this hitherto unknown result." He seldom knows for certain what new experiment to do or what it will reveal, but he thinks hard about all the possibilities he can imagine. In itself, this activity may be unproductive. Yet conscious thinking can set in motion certain thought processes that sometimes work more effectively while his conscious attention is directed elsewhere. These subconscious thoughts seem less inhibited than conscious thoughts. They may fit together facts seemingly so unrelated that his conscious mind would be embarrassed to consider them. But in this process of relating all stored knowledge to the problem at hand, the "subconscious" sometimes produces creative and original ideas. Later, while the scientist is shaving or weeding the garden, one of these ideas may pop suddenly into his consciousness; he has a "hunch." His intuition "tells" him that he should test the idea in the laboratory to see what happens.

The chances are good that the idea will not lead anywhere. The way to successful research is strewn with the remains of magnificent ideas that just did not work. But there is also a reasonable chance that his hunch may produce an important discovery. The scientist may never understand exactly what led him to the idea, but he will say with obvious satisfaction, "I finally figured out how to do it." The implication that he consciously organized and directed all the thought processes leading to the idea is quite misleading.

A scientist needs intuition. To develop it, he must absorb information, not merely within his specialty, but in all areas of knowledge. Man has arbitrarily divided up his knowledge to help organize his facts in a useful way. Knowledge cannot really be organized in neat categories. Such artificial boundaries may hinder the free wanderings of the imagination, both conscious and subconscious, that facilitate effective intuition.

A scientist also needs information. He also needs practice in using it. This means practice in reasoning, practice in solving problems. He needs practice in using past experience as a guide to (but never a dictator of) future actions. This is why such practice is so important in the training of scientists, as well as in the education of people for any useful pursuit. A wise man has said that the mind of man is not a pot to be stuffed but a lamp to be kindled. True, but let us be sure that the fuel supply is ample. To be a good scientist, to possess useful intuition, one needs both information *and* the ability to think. Neither one comes without effort.

Now, what of the role of luck? This too must not be underestimated. We are tempted to judge the quality of a scientist by the fame he acquires. Were not fame, fortune, and fate so fickle, this might be a fair judgment. But we must remember that for every famous scientist there are many who may be equally skillful and hard-working, but who have had less luck. Even though the great scientist is usually exceptionally able and has a highly developed intuition, the final ingredient essential to his fame is *luck*.

Perhaps a simple illustration will emphasize the importance of luck. No one knows exactly what, if any, kind of compound will cure cancer without harming the patient. Imagine two equally competent and worthy chemists each engaged in synthesizing new compounds to be tested against cancer. Each makes a new compound. One proves to be of no value. The other one cures cancer. Which chemist do you think will receive the fame?

Luck probably comes more often to those making an effective effort to accomplish something, but it is luck nonetheless. Surely the *unpredictability of research results* that makes luck so important is one of the most significant characteristics of science.

In summary, the methods of science as actually practiced involve deliberate control of conditions wherever possible. Scientific methods require careful recognition and measurement of uncontrollable factors. They require experiments thoughtfully designed to reveal as much information as possible, as economically as possible. They involve impartial, objective observations and accurate records. They are based on the conviction that seeing or measuring what happens can be far more reliable than merely reasoning out what *should* happen. Also, they involve deep and careful thought directed toward understanding the results and building them into a firm structure of knowledge. Both the planning of new experiments and the interpretation of results require not only sound information and skillful reasoning but also effective intuition. All of this is of little avail without occasional good luck.

Despite human weaknesses and limitations and despite many failures, the practice of scientific methods has yielded more knowledge of the material universe and greater material progress within the past three centuries than all previous history had produced without scientific methods.

APPLICATIONS OF SCIENTIFIC METHODS TO OTHER AREAS

Physical scientists ordinarily have a great advantage over others in quest of understanding, because the systems they work with are *relatively* easy to isolate, control, and observe exactly. Hence they are much more vulnerable to attack by scientific methods. Physical scientists can usually be very methodical, systematic, precise, rigorous, quantitative, and reproducible in their work. The results of their experiments are therefore *relatively* more believable, reliable, and easily interpreted than the work of people in other fields. Scientific results can be checked by other independent experimenters much more easily. In general, they bring greater intellectual satisfaction to the simple, compartmentalized mind of scientific man.

On the other hand, scholars who study such things as the development of civilizations, the formation of personality, the emotional impact of art and music, economics, or the art and practice of politics have a much more difficult task. The systems they study are so complex, so difficult to define, so impossible to isolate, control, or reproduce, that the ideal methods of science are hardly applicable. Perhaps a major reason why man's material progress has so outstripped his social, economic, and cultural progress is that knowledge of material things has been much easier to acquire. It is easier to go to the moon than to eliminate the causes of human suffering.

Nevertheless, whether or not you intend to study chemistry as a profession, you will find that basic aspects of scientific methods can serve you in whatever you undertake. Logical thinking, quantitative experimentation, exact and honest observation, and drawing reasonable conclusions from the observed data are essential in any area of study. The experience you should receive in studying chemistry will help you maintain a broader perspective and a sense of the quality of life, even though you may never be able to control the emotions of a nation of people, place the Civil War inside a liter flask, or work out an exact mathematical equation for an artistic masterpiece.

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