THE SCIENTIFIC METHOD IN PRACTICE

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Mathematics, physics, and chemistry inherently have greater possibilities for the encouragement of thinking than other subjects. Therefore they should be presented with this end in view. Any science is based upon experiment and classification. Thus it is in the laboratory that a science is best learned, and most is accomplished toward acquiring that coördination and association of observations, facts, causes, and effects known as thinking. The laboratory work is of primary importance from this standpoint with lectures parallel to and supplementing it.

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Within recent years the passive conviction that the educational system is basically unsound has led to active experiment, especially in colleges and universities. At the present time seven colleges and universities are experimenting with systems of education greatly changed from the classical American type commonly observed. This is based upon the assumption that all persons are capable of being educated. In a recent lecture on American education, Dr. Nock, of Columbia University, stated that student bodies in general are not capable of being educated. His definition of an educable person was a person who could accept discipline, and who could preserve an earnest, tolerant, and detached attitude toward life. This definition is general and not quite complete though the last phrase implies a desire to acquire the art of thinking. It might be added that an educable person is one who will try to acquire the power of thinking by thinking, by practicing, whether his latent brain power be high or low.

Some subjects are more suitable for thinking by doing than others. Mathematics, chemistry, and physics all have the necessary inherent qualities to a high degree, but to derive the most benefit from them they should be presented in a manner as scientific as that employed in solving the problems encountered in the advance of the science. A tabulation of results sought, factors involved in the solution, methods, or procedures, and final results should be made exactly as is done in the solution of any scientific research problem. This was done in solving the problem of education in general chemistry at this university. The final results indicate that, while not flawless, a scientific method of presentation is the best. In short, the same method used by investigators in developing the science is used in presenting the material of general chemistry to beginners. Naturally, a method of this kind encourages the power of thinking by practice, and the success attained in any particular case depends upon the extent to which a given student fulfils the above definition of an educable person. But in general, the inductive method which has been developed, based upon the student's own experiments in laboratory has been found to be better than any other method.

On the average, material presented in a course in general chemistry is the same. The difference in courses lies in variations and degree of emphasis. Excluding this possibility, logical improvements can be made only through organization and classification of the subject matter. The particular sequence followed in any individual case would depend on the scope of the course and the type of student constituting the majority of the class but in any event it is essential that laboratory and lecture work progress side by side as far as possible. Very often there is little or no connection between the two.

It is usually found that laboratory work begins with manipulations such as filtration, crystallization, etc., and continues with the nature of chemical change, elements, compounds, and mixtures. At the same time the lectures start with a chemical view of matter followed by descriptions of various simple elements. Then compounds and fundamental laws are gradually introduced. Laboratory work is minimized and from the start becomes a succession of isolated, unrelated experiments with no association for the aid of memory, and no logical sequence to encourage thinking and assist assimilation and understanding.

Any science is based upon experiment and classification. Thus in chemistry, as in any other science, it is in the laboratory that chemistry is best learned. Although text and recitation are relatively important adjuncts, their contribution is subsidiary to that of the laboratory. A successful laboratory system of instruction requires the collection, selection, and organization of a large number of experiments in order to enable a student to acquire the method of inductive thinking from his own observations. Laws, theories, hypotheses, and definitions are written generalizations of a series of observations. To understand them, and the difference between them, a student must learn to generalize from his own observations.

Admittedly then, learning general chemistry in the laboratory is an excellent plan, at least theoretically. Practically, a number of points might be brought forth which would appear to offer considerable difficulty. First, what experiments should be chosen to illustrate fundamental principles? Second, not all laboratories have either the facilities or the funds for extensive apparatus. Consequently, how much apparatus is absolutely necessary? Third, the same question is pertinent with regard to chemicals. Especially in high schools, the question of a large quantity of expensive chemicals is a serious consideration. Fourth, is the laboratory method of teaching by experiment rapid enough to cover the usual ground of fundamental and descriptive chemistry in only nine months?

The answers to these questions will be based upon observations made at the University of Virginia where this method of teaching general chemistry has been developed during the past ten years. While not perfect, the method has given satisfactory results, and it is believed to be considerably better than a textbook procedure. The course thus consists of laboratory work interwoven with which is the actual teaching and explanation of lecture material.

A laboratory method would be expected to stress the importance of a laboratory notebook. If a student learns nothing else, the ability to take accurate, neat notes at first hand and derive correct conclusions from those notes is great justification for the method. If a student is able to make use of his own notes, with little recourse to other sources of knowledge, in order to pass the examinations to test his knowledge, he is on a par with the research investigator who makes use of his notes in like manner to solve his own particular problem. Only too often even the graduate student doing research for a higher degree has to spend some time acquiring this ability before making the progress of which he is capable.

A premium is placed upon accurate, neat notebooks in several ways. Permission is granted to use laboratory notebooks on one or more quizzes during the term, the quizzes being designed expressly for that purpose. Notebooks may be used in the identification of unknown substances. Notebooks may be consulted in the preparation of some substance that has not been prepared but whose method of preparation is analogous to that of other substances that have actually been made. Thus to be of any value the notebooks must, of course, be complete, accurate, and neat. They are kept in racks in the laboratory at all times and are written up in the laboratory continually as the work progresses. Primarily, the notebook is for the student's own information and it is obvious that with this system those students with the best notebooks would make the highest grades, exclusive of the fact that notebooks are graded unannounced once or twice during a term. Besides emphasizing the importance of the notebook, the system has the added advantage of eliminating excess memorizing at the expense of reasoning. The beginner in chemistry should assuredly have the same opportunity to think as has the original investigator who does not attempt to memorize all of his own and previous investigators' work before formulating a new conclusive bit of information or theory. The significance of the notebook has been discussed in some detail but this was deemed advisable since the notebook is an integral part of the system and the basis for the style of the laboratory manual.

The laboratory manual is written expressly for the laboratory method in use at this university. The lectures are grouped around the subjects and organization of subjects in the laboratory manual for the purpose of keeping laboratory and lecture work parallel. The manual is composed of eighteen chapters. By roughly scanning the material and arrangement of the laboratory manual, a general idea of the manner in which general chemistry is presented may be obtained. The chapters are as follows: Chemical Change, Metals and Non-Metals, Acids, Metals, Metallic Oxides, Bases, Salts, Electrolytic Dissociation (this chapter concludes the work covered the first term), Oxidation and Reduction, Factors in the Speed of Reaction, Equilibrium, Neutralization and Its Use in Analysis, Some Applications of the Type Reactions, the Seventh Group of the Elements (this chapter concludes the work covered the second term), The Sixth Group of the Elements, the Fifth Group of the Elements, The Fourth Group of the Elements, Groups One, Two, and Three of the Elements.

The laboratory work starts with the sentence, "All scientific knowledge begins with classification." This sentence is the keynote of the laboratory manual and the corresponding method of teaching.

By means of the material covered the first term, the student is able to deal with all of the basic types of chemical calculations with the exception of oxidation-reduction equations and volumetric analysis problems. If he has had chemistry in high school, the work of the first term constitutes a thorough review coupled with new material from a different viewpoint. When the student has not had chemistry before, he finds the first term the most difficult of the three, but the foundation gained in this term through learning to think and to apply the scientific method himself proves, in the majority of cases, to be a better basis than that of the previous-chemistry student. The latter quite naturally tends to more or less ride through the first term on his previous knowledge, if any. This statement is supported by the fact although a no-previous-chemistry student may fall in a lower grade group at the end of the first term than a previous-chemistry student, he is almost invariably in a higher grade group at the end of the year when his grades for the three terms are averaged.

Oxidation-reduction reactions, a much dreaded topic in most courses, are taken up at the beginning of the second term. The method of balancing this type of equation was gradually developed at the University of Virginia and the final form as given in the present laboratory manual is believed to be as fool-proof as possible. Requests for the method have been made by both high-school and university teachers and in every case the use of the method has proved successful. The new significance of valence and the characteristics of oxidation-reduction reactions are logically developed in the several introductory paragraphs of chapter nine. After showing why the convention of calling the valence of an elementary substance zero was adopted, oxidation is defined as the loss of electrons (or increase in positive valence) and reduction as the gain of electrons (or decrease in positive valence). The first equation balanced by this method will be quoted from the laboratory manual to illustrate the method. The experiment is to examine the oxidizing action of the nitrogen atom in nitric acid when the acid is in concentrated solution. The data obtained consists of the facts that a brown gas is evolved and a blue solution is left after the reaction has stopped. The discussion of the reaction brings out the point that the products of any reaction must, of course, be known, either by deduction or some other means.

Explanation.—The explanation, of course, consists simply in writing a reasonable equation which describes the observations.

To write this equation there are four steps to take. Since these same steps are necessary in all equations to follow in this chapter, it might be well to consider them carefully and commit them to memory.

(1) The atoms which gain and the atoms which lose electrons must be indicated. At the same time, it must be shown what probably happens to other atoms in the molecule when the valence of one atom is changed by loss or gain of electrons. In this case it may be shown as follows:

$$Cu - 2\epsilon = Cu^{++}$$
$$HNO_3 + 1\epsilon = H^+ + NO_2 + O^{--}$$

It seems reasonable to assume that the hydrogen and oxygen exist in the condition shown because if the hydrogen had gathered electrons it would have become zero and come off as elementary hydrogen gas or if the oxygen had lost electrons it would have appeared as oxygen gas.

(2) The electron exchange must be balanced. Thus for all electrons gained an equal number must be lost. In this case:

$$Cu - 2\epsilon = Cu^{++}$$
$$2HNO_3 + 2\epsilon = 2H^+ + 2NO_2 + 2O^{--}$$

(3) There must be added a sufficient number of other ions to form such other products as are known to form in the reaction. In this case nitrate ions must be added to form the copper nitrate. Here, as in all cases where oxygen ions are formed, the ions should be added by means of acid molecules, thereby furnishing H ions for the oxygen.

$$\begin{aligned} Cu - 2\epsilon &= Cu^{++} \\ 2HNO_3 + 2\epsilon &= 2NO_2 + 2H^+ + 2O^{--} \\ 2HNO_3 &= 2NO_3^- + 2H^+ \end{aligned}$$

(4) The proper ions should be united and the total number of molecules or atoms involved should be added into one complete and balanced equation, thus:

$$\begin{aligned} Cu - 2\epsilon &= Cu^{++} \\ 2HNO_3 + 2\epsilon &= 2NO_2 + 2H^+ + 2O^{--} \\ 2HNO_3 &= 2NO_3^- + 2H^+ \\ \hline Cu + 4HNO_3 &= Cu(NO_3)_2 + 2NO_2 + 2H_2O \end{aligned}$$

The facility with which even the poorer students are able to grasp this method and balance complicated oxidation-reduction equations is more than sufficient evidence of its value.

Up to this point the student has had various reactions involving electrolytic dissociation as well as oxidation and reduction. Consequently at this time the student carries out chemical problems experimentally to show him how various reactions and principles might be applied in an industrial plant. The student conducts his own analysis, or manufactures his product, calculates from his weights used and obtained the quantities that would be involved per ton of main product. He then submits a chart report which includes the equations of all reactions employed, quantities involved, and an estimate of the cost of a ton of product, based on market prices of the various chemicals, as he carried out the process. The student runs into difficulties which he solves as best he can, and makes mistakes which sometimes cause him to start over several times, but no more assiduous work is done on any part of the course. The lecture and laboratory work do not parallel each other during the progress of this problem. During this interval the periodic chart is historically developed up through elementary considerations of the present concept of the structure of the atom from chemical and physical viewpoints. The lectures then again parallel the laboratory in taking up the seventh group of the elements. Lecture and laboratory progress side by side throughout the course with the exception of the above instance. The seventh group of the elements begins what might be called the more descriptive part of the course. By this time the student is well grounded on oxidation-reduction and dissociation equations, and is capable of handling the various reactions of the atoms in the groups of the periodic table. The different valences of the elements provide a nucleus for a study of the reactions and chemical properties of the elements. The atom is taken from one to another of its valences and back again by means of carefully chosen reactions. This plan is continued throughout the other groups of the periodic table constituting the remaining chapters of the laboratory manual.

Charles Francis Thwing in *The Independent* several years ago said:

> Thinking is a practical art. It cannot be taught. It is learned by doing. Yet there are some subjects in the course which seem to me better fitted than others to teach you this art. . . . They are, I think, subjects which require concentration of thought; subjects which have clearness in their elements, yet which are comprehensive, which are complex, which are consecutive in their arrangement of parts, each part being closely, rigorously related to every other, which represent continuity, of which the different elements or parts may be prolonged unto far-reaching consequences. Concentration in the thinker, clearness, comprehensiveness, complexedness, consecutiveness, continuity—there are the six big C's which are the marks of subjects which tend to create the thinker.

Mathematics, physics, and chemistry all have most of the six connected with them. Chemistry, because of its far-reaching fields, has in abundance comprehensiveness and complexedness. Therefore it particularly should have consecutiveness and continuity to keep it from becoming a bewildering labyrinth of isolated facts. Chemistry is especially adapted to encourage the art of thinking, but to accomplish this in fullest measure requires that the method of presentation be as scientific as the subject itself and then classification, "consecutiveness, and continuity" become of major importance.

The course in general chemistry at the University of Virginia is based upon the laboratory work. Lectures supplement and are parallel to the laboratory. In both, as especially brought out in the laboratory manual, the material is logically arranged to encourage thinking as much as possible and to minimize memory.