TEACHING THE SCIENTIFIC METHOD IN COLLEGE GENERAL CHEMISTRY[1]

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THE laboratory work in an elementary chemistry course has three major aims: to teach some of the elementary facts and principles of chemistry, to train the student how to use laboratory equipment in performing manipulations, and to help the student learn how to think.[2] But these aims, particularly the last, cannot be attained if the student merely passively follows the directions and fills in the blanks in his laboratory manual. Thus, how sure can we be that a student really understands, say, the law of multiple proportions after he has calculated the weight ratios of tin and oxygen in the two tin oxides, even though he did use numbers that he himself obtained?

STUDENTS PLAN PROBLEM ATTACK

We have attempted to encourage independent thinking by discarding the laboratory manual, requiring instead that the student plan his own attack upon a problem and submit a written report describing his procedure, the results obtained, and the conclusions reached. Since this approach is new (or perhaps reactionary), comments and criticisms are invited.

Before the student can proceed without specific directions, he must be able to perform the basic manipulations: how to adjust a burner, how to bend glass, how to filter, how to collect a gas, how to weigh an object, etc. Also, the need for cleanliness, order, and safety must be taught. We have found part I of Deming's manual[3] suitable for this purpose. It takes about six laboratory periods to learn the necessary techniques and to develop good habits.

Following this, problems are assigned to pairs of students. The problems are selected from a pretested list and range from the simple to the more complicated. Upon completion of the first problem, successively more complex problems are assigned. Each is different; it is assigned in each laboratory section to only one pair of students. The instructor assists the students in the initial demonstration of the phenomenon assigned as their problem; he guides the preparation of solutions, the setting up of apparatus, etc. The optimum size of a laboratory section is twenty. Typical elementary laboratory equipment is usually sufficient. Occasionally devices are borrowed from the analytical or physical laboratories.

Why does anhydrous copper sulfate turn blue upon standing in an open beaker? Why does a concentrated solution of sucrose turn black upon the addition of anhydrous sulfuric acid? Why does a match head remain unignited when placed in the inner cone of a non-luminous burner flame? Why does a precipitate of zinc hydroxide dissolve when either acid or base is added? Why does a penny turn "silver" when immersed in a solution of mercuric nitrate? Why does a rubber balloon, when filled with a few grams of dry ice and tied at the neck burst after a few moments? Why does the lower layer, carbon tetrachloride, turn reddish brown upon shaking, when chlorine water is added to the aqueous solution of potassium bromide standing above the carbon tetrachloride? (This problem is detailed in greater length, more simply, before the question is posed.) Why does the color of a potassium chromate solution change when hydrochloric acid is added? Why is a hot, acidified solution of potassium permanganate not decolorized immediately upon the addition of an excess of sodium oxalate? Why does a copper wire become coated with a white deposit when immersed in a solution of copper(II) chloride but not when immersed in a solution of copper(II) sulfate? Why does silver chloride dissolve upon the addition of ammonium hydroxide and reprecipitate when zinc sulfate solution is added?

After the students carry out the procedure and note the phenomenon concerned they are required to propose an explanation. When the explanation does not suggest itself easily, the students are encouraged to repeat and to vary the original experimental setup, to investigate allied phenomena, to study their own text and other sources of information, and to consult with the instructor. Notes are to be kept. No emphasis is placed upon obtaining the "correct" explanation. It is only necessary that the hypothesis be testable in the laboratory.

HYPOTHESIS MUST BE TESTABLE

This requirement, that the proposed hypothesis be testable, is the heart of the matter. It is the essence of the scientific method and its use here, in an elementary

[1] Adapted from a paper presented at the Annual Meeting of the Pennsylvania College Chemistry Teacher's Association, Albright College, April 21, 1956.

[2] See, for example: BLICK, D. J., J. CHEM. EDUC., **32**, 264-6 (1955); KRUGLAK, H., *Am. J. Phys.*, **17**, 23-9 (1949); MALLINSON, G. G., AND J. V. BUCK, J. CHEM. EDUC., **31**, 634-6 (1954); SCHLESINGER, H. L., J. CHEM. EDUC., **12**, 524-8 (1935); STEWART, B. R., *Sci. Monthly*, **79**, 165-9 (1954).

For a more general discussion: AQUINAS, THOMAS, O. P., "Of the Teacher," H. Regnery, Chicago, **1949**, (Tr. by James P. Shannon); WEAVER, WARREN, *Science*, **122**, 1255-9 (1955).

[3] DEMING, H. G., "Practical Laboratory Chemistry," John Wiley & Sons, Inc., New York, **1955**, pp. 1-54.

course, is considered to be the *raison d'etre* for the pedagogy employed.

To obtain a testable hypothesis often requires considerable study and thought. For example, a bottle of gaseous hydrogen chloride is inverted over a bottle of gaseous ammonia and the paper septum, which was placed between the two adjacent bottle mouths, is removed. The ammonium chloride forms first in the upper bottle. When the experiment is repeated, this time with the ammonia container on top, the product forms first in the lower bottle. The question to be answered is: Why does the ammonium chloride first form in the bottle which contained the hydrogen chloride, irrespective of its relative position?

Usually the experimenters first explain the effect as being due to relative densities, or, more simply, to gravitational force. One of the partners will then object to the original suggestion, ultimately convincing his associate of its implausibility. A long discussion and some study of available references then follows, culminating in a better explanation: "Ammonia tends to expand more than hydrogen chloride." The students who proposed this hypothesis learned, after some attempts, that the hypothesis simply was not testable. During their fruitless attempts to test their hypothesis they determined upon a testable hypothesis: "Ammonia tends to diffuse more rapidly than hydrogen chloride." This was successfully tested by placing test tubes containing the gases at opposite ends of a long tube and noting where the ammonium chloride formed in the tube. Upon another occasion, two other students postulated: "The average velocities of the two gases are inversely proportional to their molecular weights" and calculated the temperature at which hydrogen chloride molecules would have an average velocity equal to that of ammonia molecules at room temperature. The hydrogen chloride was heated well above this temperature, while keeping the ammonia cool, the septum between the two containers removed, and the ammonium chloride was observed to form first in the flask containing the ammonia. The exultation was plainly evident upon the faces of these two students. Here was a challenge that they had met, and more than this, they knew why!

Depending upon the judgment of the instructor in helping the students to understand the complex nature of what appears to be simple, problems can be extended beyond their original scope. Thus: When a beaker is inverted over a lighted candle the flame is extinguished. In most cases the students almost immediately suggest that there is no oxygen in the inverted beaker since it has been replaced by carbon dioxide; and therefore the flame is extinguished. A test for carbon dioxide is made and the hypothesis confirmed. The matter can be dropped here and a new problem assigned; but if the instructor deems it wise, it is pointed out that carbon dioxide is heavier than air, hence it could not remain in the inverted beaker, despite the positive test which affirmed its presence. This paradox is a real challenge. Eventually it is suggested that the carbon dioxide is hot, and, therefore being less dense than air, can remain in the beaker. In one instance this hypothesis was tested by filling an angel food cake pan, which had a cap affixed over the center hole, with a salt-ice-water mixture. When the candle was inserted into the cooled center hole it continued to burn, thus confirming the hypothesis. (The year this happened the experimenters exulted so tumultuously that every student in the laboratory was compelled by curiosity to inspect the result.)

When a problem is completed, a report is written jointly by the pair of students and submitted for criticism. It contains the description of the phenomenon, the question to be answered, the proposed hypothesis, a detailed outline of the procedure which should test the hypothesis, the reasons why the proposed procedure is suitable, the results of the test, the conclusion. A typical report is from 400 to 1000 words in length. If progress on a particular problem is slow, a report describing the current status of the work, using the same outline, is submitted.

The reports are examined and criticized by the instructor in the presence of the two students. This critique is conducted seminar-fashion; the authors are required to defend their statements. At the same time, errors in grammar are corrected and suggestions are made to improve the style of writing.

Because of the variation in the complexity of the problems and in the previous experience and ability of the students, not all will solve the same number of problems during the year. Typically, by the third or fourth week of the second semester, most students will have solved eight to ten problems. At this time the nature of the assigned problems is changed. Up to this point, the problems require explanation of an observed phenomenon; now the task is to apply principles. Examples are:

What is the valence of aluminum? Show that iodide ion is a reducing agent. Prepare approximately 0.001 mole of hydrogen bromide. What is the composition of the atmosphere? Show, for any two chosen elements, that the law of multiple proportions is valid. What is the atomic weight of chlorine? What are some of the factors that affect the yield obtained in the synthesis of *n*-propyl acetate? What is the solubility product of lead chloride? What is the pH of a solution 1 *M* in acetic acid and 2 *M* in sodium acetate?

After some study and exploratory work in the laboratory, a preliminary written report describing the plan of attack is prepared, submitted, and examined. The work is performed and a final report prepared and submitted. As before, the problems assigned successively increase in complexity and are different for each pair of students. In a typical case, six to eight problems are completed by the end of the second semester.

Correlation between the laboratory work and the classroom is fortuitous. Usually a topic will be discussed in class and studied in the laboratory at different times. Thus, the second encounter serves to reinforce, rather than to supplement, the learning attained when the matter was first encountered. When material is covered in class that has already been studied by a pair of students in the laboratory, reference to this fact can be used to stimulate the interest of others. If the occasion warrants, the experimenters report the details to the whole class.

A substantial amount of learning also takes place outside the classroom and laboratory in informal discussions among the students.

A complete list of the problems used is available upon request to the author.