On Teaching High School Chemistry

I have thoroughly enjoyed studying these two enterprises in the teaching of chemistry at school level, and in my opinion teachers of chemistry at all levels could read these books with profit. The projects were conceived and carried through almost simultaneously in response to a widespread demand in the United States for changes in high school chemistry courses, and they had the same aim of introducing chemistry as a live, developing science. On cursory examination the routes chosen by the authors to achieve this aim are very different, but a closer look will show that very similar teaching methods have been chosen. Thus, both projects develop systematically the relations between experiment and theory, or conceptual model, and emphasize the principles underlying chemical structure, combination, and energy. They both insist that ideas should be introduced in a tentative fashion, rather than dogmatically, be examined in the light of experimental evidence, and then be accepted, modified, or discarded. Throughout each book the various principles are interwoven and developed as threads, so that they become familiar by application and use, and understood rather than learned. Each book should therefore be regarded as a systematic course, and not as an elementary reference book; in this respect, one must be cautious in sampling either book at random. Another common feature is the insistence on the value of speculative questions and discussion as a means of promoting and sustaining curiosity. Thus, in the preface to **Chemical Systems** (McGraw-Hill, New York, 1964. 772 pp., $6.96), the Chemical Bond Approach project (CBA), it is said that "Throughout the book many questions are raised. Some are raised and discussed in the text itself, while others are raised for the student to discuss. A few questions are raised to point out aspects of chemistry for which chemists do not yet have satisfactory understanding. Chemistry continues to be a development which is incomplete and in which many people participate." Similarly, in the text of the *Teachers' Guide* to **Chemistry: An Experimental Science** (Freeman, San Francisco, 1963. 480 pp., $5.80), the CHEM Study project (CS), it is said that "These questions (Questions To Wonder About) are to stimulate thinking but are not to be assigned as written work. They vary in scope and difficulty, and some have no specific answers. Discussion of some of these questions will be included soon; of others, later in the Textbook."

Now it is likely that none of these pedagogic methods is new, but they are rarely found *in extenso*, and they are woven so skillfully into the texts that the main impression, after reading these books, is of something new and refreshing. The value of the material is enhanced by the excellent production and layout of the books, with diagrams and tables that compel examination and highlight the essential information with extraordinary clarity. Teaching chemistry is revealed and sustained as a fascinating exploration, jointly conducted by teacher and pupil, and compounded of personal investigation and critical study of the work and ideas of lively minded scientists, rather than the offering of a corpus of unchangeable facts and rigid interpretations for assimilation by passive students.

In the past most school textbooks of chemistry used in Europe and America have been built around the experience of one or two teachers, albeit modified by wider discussion and criticism. The authors, with an eye to the economic barometer, have been constrained by conventional curricula and, in England, by the syllabuses of the examining boards. Far too often the result has been a careful and ponderous approach along the well-worn paths of the 19th century. Changes have been made by rearranging subject matter, or by cautious omission of some backwater and introducing hints of contemporary experiment and thinking. This is particularly true with respect to general and physical chemistry, where teaching has concentrated for too long on the tortuous emergence of the logic of the chemical evidence for the atomic theory, and on the work on gases and dilute solutions which brought fame to the great European schools of chemistry during the late 19th century. Those who find difficulty in emerging from that chrysalis of modern chemistry may be shocked on reading CBA and CS by some of the omissions that stem from the directive, "Naturally, this reconstruction of the entire course gives a unique opportunity to delete obsolete terminology and out-moded material." They will find, for example, no use of equivalent weights, only the very briefest mentions of valence (and that, in CS, to dismiss it as too confusing a noun to be useful!) and of colligative properties, and the complete absence of the law of mass action in either equilibrium or rate studies. Nevertheless, I assure such readers that in CBA and CS there is no lack of discussion of the chemical evidence for the atomic theory, for the mole concept, and for the structure of molecules; moreover, very clear pictures emerge of the factors that control chemical reaction and the transfer of matter between phases, and of the factors that lead to the establishment of chemical and phase equilibria. Some of the old, familiar (and, frankly, slightly rusty) hatpegs are missing, but the reasons why we have hats and wish to leave them in particular places are made abundantly clear.

The necessity of new approaches to the teaching of science in the United States was formally recognized some 8 years ago, when the National Science Foundation provided funds for the study and development of new courses for high schools by groups of university and high school teachers. Of the two chemistry projects chosen for support, the Chemical Bond Approach is slightly older, counting its origin from a summer school at Reed College (Portland, Oregon), in 1957. Its first texts were used in schools in 1959, and two successive revisions received wider trials in 1960 and 1961 before the final revision for the hardback editions of *Chemical Systems* and *Investigating Chemical Systems*; these appeared in 1963. The experience gained in the trials produced not only revisions of the texts but two large

Teachers' Guides. The guide to the textbook emphasizes the major ideas in the course and how they are related, develops teaching suggestions, explains suitable demonstrations, and discusses the exercises that appear in the textbook. The guide to the laboratory manual is very comprehensive; it not only advises on problems encountered in the conduct of the experiments at schools during the trial periods, and provides sample student data from these experiments, but discusses the philosophy of each experiment, the essential points that should be made in prelaboratory and postlaboratory discussions, and much supplementary information.

The Chemical Education Materials Study emerged from the work of a committee of the American Chemical Society, and was established as the CHEM Study project late in 1959. Its development followed similar lines to the CBA project, the first drafts being used in schools in 1960 and revised drafts in 1961. The final revision led in 1963 to the publication of the textbook *Chemistry: An Experimental Science* and the *Laboratory Manual*. There is a one-volume *Teachers' Guide* to the textbook and laboratory manual. In this guide the discussion of the laboratory experiments and the student exercises is slightly less thorough than in the corresponding portions of the CBA guides; but, on the other hand, the background discussions in CS appear to be somewhat deeper, and I found them more directly informative. A particularly interesting and useful feature of the CHEM Studies project is the provision of 20-minute films (16-mm sound) on a wide variety of subjects; I have found those on catalysis, ionization energy, and shapes and polarities of molecules instructive and provocative, although I have reservations about some points in others—for example, that on molecular spectroscopy overemphasises the classical concept of resonance and neglects the quantum nature of light absorption.

It would be interesting to speculate on the part played in formulating the two new approaches by the contemporary pedagogic climate, by the experimental nature of the projects through trial and revision, and by individual personalities on the teams that were responsible for the two projects. Most of the features that I have mentioned so far are common to both courses and might fairly be attributed to the first two factors. Nevertheless, with all their similarities, each project has its own distinctive flavor, and this must surely be due to more personal influences. I am not thinking of the clear differences in style, or of the innumerable small differences of presentation or example. There is a difference of depth and emphasis, which can be summed by saying that the CBA project presents a considerably more advanced and sophisticated approach, with the emphasis placed from the outset on conceptual models, and proceeds a long way with quantitative treatments of energy changes, electrode potentials, and chemical equilibrium. There is a feeling that experienced teachers are giving themselves a revision course in the fundamentals of elementary work. On the other hand, the CS project seems to be more genuinely a beginners' course, with rather more direct connection between experiment, interpretation, and theory. A good deal of thought and many difficult decisions must have been taken over the precise points at which to stop various themes in the CS textbook and transfer any further treatment into the *Teachers' Guide*. Partly because it does not attempt to go so far with some points of theory, the textbook is able to give more applications of the principles that it has introduced. Often it chooses to apply them to chemistry outside the laboratory. Thus, for example, it tells of the way that molecular structure affects the properties of proteins and of polymers; it indicates the molecular composition of living systems and applies energy cycles to metabolic processes; and it relates nuclear stability to the use of nuclear energy.

The early parts of the CBA textbook explain how to investigate and how to describe the properties of mixtures, the connections between chemical changes and heat, electrical and other forms of energy, and the electrical nature of matter. This gives a sound introduction to chemical systems and to changes in them, focusing attention on the identification of initial and final states. The text then concentrates on the space-filling property of matter, using as models first atomic nuclei or cores and electron charge clouds, next the kinetic-molecular theory, and then atomic orbitals and energy levels. The main theme of the project, which is very ably expounded, then emerges strongly to show how the nature and diversity of chemical bonds accounts for many properties of isolated molecules, of metals, of ionic solids, and of solutions of electrolytes. In these chapters, coordination numbers and oxidation numbers are fully discussed, to the exclusion of "valency," and the very thorough treatment of the mole concept seems to obviate any need for "equivalents" in stoichiometry or in dealing with ionic compounds and solutions. There are features of the electron cloud model that bother me, however. The model entails the acceptance of a large number of postulates in return for "predictions" about the shapes of polyatomic molecules. It is not at all clear why the "self-energy"—kinetic energy introduced to prevent the cloud from collapsing around the nucleus—should increase as the cloud decreases in diameter. Nor are the reasons why only two electrons can be accommodated in one cloud as attractive as the reasons for introducing the Pauli principle when relating atomic structure to the periodic table. And, when considering the gains from the postulates, it is doubtful whether the qualitative balancing of opposing tendencies would lead, for example, to the selection of N_2 and P_4 from the various possible models, if we had no experimental evidence. In many ways I wonder whether the time spent in grasping the postulates is commensurate with the gains.

In the last part of *Chemical Systems*, the CBA book, the energetics of electrical cells are used to introduce free energy, and changes in the potential of a chemical cell are linked to the distance from equilibrium of the cell reaction. In this way a realistic connection is made first between free energy changes and the tendency to move toward equilibrium, and eventually between standard free energy changes and equilibrium constants. The fundamental basis of the law of chemical equilibrium is thus provided in a convincing manner, and the equilibrium constant appears without the very dubious "proof" from the old law of mass action. The dynamic nature of chemical and phase equilibrium is suitably emphasized, however, throughout the book. Another very instructive feature of the treatment of chemical energy is the profusion of energy-level diagrams used to illustrate enthalpy and free energy changes in bond breaking, in phase changes, in the process of solution, and in chemical reactions. It is much easier for most students to grasp sign changes and algebraic differences from visual presentations than from equations. The difference between the enthalpy and the free energy of a change is identified as the organizational energy, $T\Delta S$. The resulting discussion of entropy as a measure of organization is accompanied by a wholly delightful analogy drawn from a simple ball game. Success in the game is shown to depend on the expenditure of energy and the number of targets provided at various energy levels, giving a very homely demonstration of the effects of minimizing energy demands, on the one hand, and maximizing the disorder, represented by the number of available states, on the other. This is one of the best ways I have seen of introducing a fundamental concept at an elementary level.

The strength of the CHEM Study books lies in the close relationship of experiment, principle, and theory, justifying the claim, "A clear and valid picture of the steps by which scientists proceed is carefully presented and repeatedly used." The style is personal, and there are many apt and witty comparisons between everyday behavior and the experimental method. There is repeated emphasis on careful and accurate observation, and on attention to the precision with which measurements can be made and should be reported. Atoms and molecules are brought in as working models at the start; current ideas on the structures of atoms and of molecules are introduced in chapter 6; the chemical and physical evidence for these ideas is reviewed in later chapters. In the meantime, a realistic but brief introduction has been given to chemical reactions and phase changes by linking experiments and demonstrations with discussions and exercises. I think that the CS textbook and the *Teacher's Guide* have to be considered together here; in some ways the textbook is rather lean, though the direct combination of textbook and guide might well have been too rich for the student. In this section of the book, there is a fair amount of descriptive chemistry of several groups of the periodic table, and chapters on energy effects in reactions and the factors affecting the rates of chemical reactions. The reactions chosen to demonstrate the rates in the school laboratory seem to me to be somewhat involved both chemically and mechanistically. These discussions lead to a chapter on chemical equilibrium, which contains very clear descriptions of the difference between true equilibrium and a steady state, and of the ways in which external variables affect the equilibrium proportions of the chemicals present. The equilibrium constant is introduced through direct experiments on equilibrium mixtures and generalized in the law of chemical equilibrium. This is a sound approach, not as basic as in the CBA treatment, but it is somewhat spoiled by the lack of qualification of the suggestions (in section 9.2.3 of the text and in the corresponding part of the *Teachers' Guide*) that reaction rate equations are convenient vehicles for deriving equilibrium constant expressions. This is true for single-stage reactions, but as most reactions are multistage, quite absurd equilibrium expressions can result from applying their rate laws derived under condtions far from equilibrium.

The section in the textbook on the factors that determine equilibrium is good, with another excellent analogy for "disorganization energy" in the behavior of golf balls on a split-level floor of a station wagon on smooth (low temperature) roads and on rough (high temperature) roads. This analogy is extended usefully to the effects of changing the areas available at each level, corresponding to the number of targets in the CBA scheme. However, the treatment is at a much lower pitch than in the CBA textbook. No mention is made of free energy or of entropy. In the *Teachers' Guide* some background discussion of these terms is given, but with a sad confusion of signs on page 294. The "reaction tendency" must be set equal to the *sum* of the tendency towards minimum energy and the tendency towards maximum randomness. The reaction tendency, being measured by the useful work $+w$ which can be obtained from the reaction, must be set equal to $-\Delta F$, the tendency toward minimum energy as $-\Delta H$, and the tendency toward maximum randomness as $+T\Delta S$, giving, as required,

$$-\Delta F = -\Delta H + T\Delta S$$

or

$$\Delta F = \Delta H - T\Delta S$$

Throughout the following paragraphs the signs for ΔF and ΔH, where they represent tendencies, need similar changes, so that when ΔF is a negative quantity the reaction has a positive tendency to go.

A particularly good feature of the discussions of equilibrium in both textbook and guide is the linking of vapor pressure, solubility, partition, gas and solid dissociation, complex ion formation, and acid-base and oxidation-reduction equilibria as examples of the application of a common equilibrium law to derive the particular equilibrium constants. This procedure demonstrates the common basis for relationships that only too often are treated separately and obscured under different names (for example, dissociation constants, instability constants, dilution law, solubility product, and so on).

The middle section of the textbook deals with the physical and chemical evidence for the atomic theory, the structure and energy levels of atoms, the bonding within molecules in the gas phase, the bonding in liquids and solids, and the molecular structure of carbon compounds. These very interesting chapters include an especially clear introduction to the way in which energy levels of the hydrogen atom can be deduced from the atomic spectrum and represented by a simple expression.

The final chapters apply the principles underlying chemical structure and energy to emphasize trends in physical and chemical properties within various columns or rows of the periodic table and to explain some properties of some natural large molecules and of some living systems.

It is difficult to do full justice to these two great experiments in providing courses of instruction that take account of the fundamentals of the subject and the different needs of teacher and pupil. They have evolved courses that appear to have many good qualities in common and many good individual features, with a few aspects that might be improved. It is entirely in the spirit of the design of these experiments that, although their results may be regarded as the most useful available at the time, further modifications and fresh approaches will be needed as the subject and the objectives of the courses slowly evolve.

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