TEACHING CHEMISTRY

M. Laffitte

University of Marseille, France

WHAT IS TEACHING?

The teacher has a message to transmit, so that his students can later on work without him. His first task is then to make sure that his message is presented in a form adequate to be *received*. He must then be aware of the needs and aspirations of his students. Consequently, a real harmony should become established between him and them. The teacher has necessarily an aim and the students must accept it otherwise this object will not be reached. I feel it is essential to state this aim clearly in terms understandable to the students. Except during the early school years, each student is educated by several teachers, who must come to an agreement on their aims.

The modern student looks for something different from the acquisition of a few techniques: recent incidents in almost all universities all over the world prove clearly that students refuse more and more to be satisfied with this as the only aim. Actually they do not decline to learn and use these techniques, but they want to go further. Their professor must go further with them.

Just as tradespeople understood a long time ago that a good presentation of their goods is an important sales promotion factor, so must a good teacher do his utmost about presentation; audio visual techniques for instance are very much appreciated by young people and it would be nonsense to neglect them. A precise definition of the terms used is also necessary to improve the presentation of a subject. Any dialogue is elaborated with words: it is important to point out the need for a perfect definition of all terms which convey our thoughts.

WHAT IS SCIENCE?

As an example of what I am saying, may I read the first lines of a book on thermodynamics published recently:

'Thermodynamics is a science of immense power, but it is also a science seriously incomplete. It offers impressively accurate predictions of *what* can happen, but affords us little or no insight into the *why* of those happenings. Thus it permits us to calculate what is the position of equilibrium in the system N_2–H_2–NH_3, for example, but it fails entirely to tell *why* that is the equilibrium condition for this particular system. To be sure, we see that—the free energies being what they are—this equilibrium condition is entailed, but we can find in thermodynamics no *explanation* of why the free energies are what they are. And in general, thermodynamics teaches us to see important relations among the various properties of a substance, so that many values can be calculated from few experimental numerical data. What is it about ammonia that determines the magnitude of the free energy characteristic of this compound? In principle this question should, we feel, be answerable; but to find an answer, we must look far beyond the realm of classical thermodynamics. For it seems evident that we can hope to *explain* the free energy of a substance only by showing how a particular free energy arises from the particular values of the atomic or molecular parameters of that substance (e.g. atomic masses, intranuclear distances, bond flexibilities, etc.). That is, given the molecular parameters of NH_3, we must be able to see that its free energy could not be other than it is.'

Well, but . . . we must add we do *not* know why the atomic or molecular parameters of that substance are what they are. Saying, for example, in the very beginning of calculations on the NH_3 molecule that its shape is such and such is not an explanation but only an *observation.*

In this example, the words 'why' and 'explain' are misused. Science in general (and not only thermodynamics) will never *explain* the *why* questions. To understand that, we must well understand what science is: the scientist observes how phenomena occur, what structures are, etc. . . . He measures relationships and nothing more. He observes connections or consistencies among different phenomena. This is less pretentious than to say that science explains or will explain the world, as some people believe it, overlapping metaphysics. In the July 1969 issue of the *Journal of Chemical Education* a question asked by a reader is 'Why are 4*s* rather than 3*d* electrons involved in the first and second ionizations of the first row of transition elements?' A very good reply was given: 'Because we have chosen to designate as 4*s* electrons those which happen to be ionizable with the least energy input.'

Some of you will know the chemistry lesson given by an honest teacher to an intelligent pupil, reported by Prof. McGlashan (from the University of Exeter).

Teacher: 'Why does the reaction $H_2 + Cl_2 \rightarrow 2HCl$ go virtually to completion under ordinary conditions?'

Pupil: 'I know that it does, but I don't know why.'

Teacher: 'Then I must tell you. It goes to completion because the standard free energy change is large and negative.'

Pupil: 'But what is the standard free energy change? How is it defined and how is it measured?'

Teacher: 'It is defined by the relation $\Delta G^0 = -RT \ln K_p$ where ΔG^0 is the standard free energy change and K_p is the equilibrium constant expressed in partial pressures. So it is measured by measuring K_p.'

Pupil: 'Is your answer to your original question then exactly equivalent to the answer: Because $K_p \gg 1$?'

Teacher: 'Yes that follows.'

Pupil: 'How then is K_p defined and how is it measured?'

Teacher: 'It is defined by the relation $K_p = p^2(\mathrm{HCl})/p(\mathrm{H_2})p(\mathrm{Cl_2})$.'

Pupil: 'Is your answer to your original question then exactly equivalent to the answer: Because when we mix hydrogen and chlorine under ordinary conditions we find that at equilibrium the mole fractions are such as correspond to a virtually complete reaction?'

Teacher: 'Yes, that follows too.'

Pupil: 'But do you mean that your answer to your original question "Why does the reaction $H_2 + Cl_2 \rightarrow 2HCl$ go virtually to completion under ordinary conditions" is that it goes virtually to completion because it is found to go virtually to completion?'

Teacher: 'Yes, of course. But please stop being difficult and learn the original by heart.'

WHAT IS CHEMISTRY?

It is commonplace to pretend that no limit can be determined between physics and chemistry. It is obvious that the fields are more and more closely related to each other, despite the scientists' increasing specialization. It has been said that chemistry can be defined as that which is done by chemists and physics is that done by physicists. Nevertheless, I think we can attract pupils to chemistry with another reply. I may even add that this reply is in accordance with the implicit thinking of many boys and girls when interested in chemistry at an early stage.

The fundamental difference between physics and chemistry is not related to the object of the study, but to its aim. Both chemists and physicists investigate the piece of metal formed by the nib of my pen, but they do it with different purposes. The physicist endeavours to determine the constitution of that metal: he wants to determine what the metal is, he is interested in its nature and behaviour. On the contrary, a chemist examines what will become of this metal, how it will react in such or such condition. So the chemist is interested in the changing of things, while the physicist is interested in the things as they are. Moreover, we can understand why chemistry becomes more and more closely related to physics: this is because a deeper and deeper knowledge of the present allows us to a better prediction of the future. One can say that physics and chemistry progress so much that physics actually provides answers to the chemists' questions.

WHAT MUST BE TAUGHT IN CHEMISTRY AT UNIVERSITY LEVEL? AND HOW MUST WE DO IT?

I do not pretend to give an answer to these questions, but I would like to make three observations:

(a) In high school chemistry elementary notions such as atom, molecule, reaction, stoichiometry are introduced. Acids and bases, oxidizing and reducing agents, metals and non-metals are also presented.

So the university programme should start with a reconsideration of these notions. We shall have to define carefully all the terms used especially those which we employ so often that the students do not even question them (their difficulty for defining correctly the terms 'temperature' and 'heat' is an illustration of this). It is relatively easy to depict an object by a word, but it is more difficult for a concept. For example, what does the word 'reduction' mean? An inexperienced student believes he can quickly answer that question, but his imperfect answer does not always allow him to understand why the reaction $Cl \stackrel{\rightharpoonup}{=} Cl \rightarrow Cl^-$ is a reduction, while the reaction $H \stackrel{\rightharpoonup}{=} Cl \rightarrow Cl^-$ is not.

(b) During recent years, an important effort has been made to introduce notions of structure in the elementary chemistry course. This introduction offers the great advantage of a possible qualitative discussion when the student has no mathematical training for a quantitative study, while it tends to organize the apparently heterogeneous experimental observations.

During the first years at university, besides other matters (structural problems, for example) it is essential to spend a long time presenting to the students the very precious tool of thermodynamics. There are several reasons for this. It is a well-constructed science, based on only a few principles—it provides a good example of what science is, teaching how to search for relations between apparently independent properties, by logical means based only on principles. It will also show the students what a principle is: a principle results from experience and there is no other proof. There is no explanation. Remember the question asked to Newton: 'Why do two masses exert a force of attraction on one another?' Newton replied: 'I frame no hypothesis'. The conservation of energy is *observed* but cannot be *explained.*

This is the first reason, even for students who will not specialize in chemistry. There is a second reason to support an early-as-possible study of thermodynamics. Students must be properly trained to use thermodynamic concepts, if we want them to possess this mighty tool in chemistry. It is known from experience that they encounter difficulties in this field. It has to be recalled several times during their studies.

(c) Finally, I would also like to emphasize an important bearing of a chemist's training which must be used somewhere during his studies. Le Chatelier wrote: 'Achievement of good experiments is one of the most essential stages in science, but also the most difficult to perform. Only one wrong measurement is enough to hinder the discovery of a law or, which is still worse, bring about the expression of non-existing laws'.

Science looks for relations between properties (like $\mathbf{F} = m\gamma$ for example), which must be measured. Scientists are actually, in their everyday life, engaged in metrology and the students who expect to become chemists must be aware of the long days they will spend determining some property, such as electric potentials, resistances, pressures (not vacuum), temperatures, lengths, volumes, energies, masses, times etc. As far as metrology is concerned, thermodynamics introduces thermometry and calorimetry.

These three remarks on the use of a correct vocabulary, the early introduction of thermodynamics and the necessity for an adequate training in metrology before the end of chemical studies seem vitally important.

DISCUSSION

N. N. Greenwood (*University of Newcastle upon Tyne*)—Dr Laffitte has done a great service by stressing the distinction between 'explanation' and 'description'. This is most important. It is not an explanation to say 'paper burns because it is combustible' but merely a restatement of the phenomenon. Many so-called explanations in elementary (and not so elementary) chemistry teaching are tautological in this way and therefore misleading because they imply that a student knows more than he really does. For example, it is frequently said that thallium forms thallium compounds and tin forms tin compounds *because* of the inert pair effect, as though this were an explanation. Even worse, we have all heard that CH_4 is tetrahedral because of sp^3 hybridization. Here we have confusion between description and explanation: hybridization is not a phenomenon that happens, it is one way (and only one of several possible ways) of describing electron distribution. It is certainly not an explanation of tetrahedral symmetry.

On another point I believe we should beware of too great a preoccupation with precise verbal definitions since this can so readily lead to sterile teaching. It also tends to encourage the belief that when a concept has been defined it is also understood. Precise verbal definitions are, of course, essential in some areas, but we should remember that many of the most useful concepts are defined by usage rather than by words and to verbalize the concept into a short formal definition may be too restrictive and do more harm than good.

J. C. Bailar, Jr (*University of Illinois, Urbana*)—Dr Laffitte has emphasized the importance of teaching thermodynamics early. I have no quarrel with this suggestion but, unfortunately, many of those who are interested in thermodynamics are inclined to believe that thermodynamics is *all* of chemistry, that is, that when they have taught their students a little thermodynamics they have accomplished their purpose. There is far more to chemistry than thermodynamics. I would refer you to an excellent article by Edward C. Fuller in the *Journal of Chemical Education* for April 1969 (page 237). He lists ten topics which should be included in every course in general chemistry. Thermodynamics is only one topic in the ten.

A. H. Guerrero (*University of Buenos Aires*)—The conclusions of this paper are quite acceptable—a limited amount of thermodynamics should be taught earlier; terminology and definitions must be precise. Science is often looking only for the 'how' of phenomena. This is a very respectable philosophical position but human nature wants to know 'why' as well. As an example, statistical thermodynamics is a consequence of looking further for explanations of macroscopic phenomena studied by classical thermodynamics. It is not a better explanation, it is a deeper one in the search for the 'why'.

H. Teterin (*UNESCO, Paris*)—I should like strongly to support Professor Guerrero in his attempt to defend the 'why' of science. I think the statement that science in general will never explain the *why* of the value of free energy and that scientists study only how phenomena occur is misleading. The question 'why' was the starting point of science. It was and still is the moving force of all scientific progress. I agree that we are not in the position now to answer all questions, but each generation will give more and more attention to this question 'why?'.

I would like to say something about the distinction between physics and chemistry. I do not think such distinction is valid. I believe that very narrow definitions could mislead students on their understanding of the profound relations between different branches of science.

L. Strong (*Earlham College, Richmond, Indiana*)—One most intriguing way of distinguishing chemistry from physics has been given by Max Planck in his book on thermodynamics. He says that physics is primarily concerned with continuously varying properties while chemistry is primarily concerned with discontinuous properties. In the sense that a chemical reaction is a fundamentally discontinuous change Planck's comment is still pertinent.

Dr Laffitte emphasizes the need to recognize that science in general and chemistry in particular do not deal with answers to questions that begin with 'Why'. Such an emphasis is only helpful when there is agreement on what constitutes an adequate answer to a 'Why' question. Dr Laffitte appears to have invoked a cause and effect sequence with no evidence of any primary cause. However, an alternative view is that science uses theory to build a network of logical relations among the diverse data from operations. For any observation the question 'Why' is answered to the extent that the observation can be fitted into the network.

J. W. Linnett (*University of Cambridge*)—I would like to support Dr Laffitte in his view that we should discuss the examining and assessment of students. It seems to me that we assess too much the past achievement and too little the possible potential of the student. In a survey within a section of the Cavendish Laboratory at Cambridge, Professor A. B. Pippard discovered that most successful research students were those who have obtained the very best First Classes, but those who came next in quality were those with Upper Seconds, rather than those lower down the First Class list. The assessment at the end of the undergraduate course had not therefore provided the right assessment in respect of the ability of the students to engage in original research in the subject of their choice.

J. A. Campbell (*Harvey Mudd College, Claremont, California*)—It is indeed hard to overrate the importance of examinations and their effect in our present educational systems. At the high school level this subject has been studied in depth at a workshop on Evaluation in Chemistry held in Ceylon in 1968† and the findings would be relevant to the University level.

I suggest that we often test for the wrong accomplishments and almost never test for the full range of objectives which we hope to have achieved. It is difficult, however, to measure motivation.

On another point thermodynamics can and should be taught to first year students, but not using the non-atomistic heat engine approach of classical thermodynamics. We have 130 years of proof that this method leads very few students to a comprehension of the subject. Nor is full-scale statistical thermodynamics the only alternative. What can be successful, however, is the use of statistical inference.

† 'Evaluation in Chemistry' *Report* of International Workshop, Ceylon, 1968. IUPAC, 2-3 Pound Way, Cowley Centre, Oxford, England (price $1.5).