RESTRUCTURING OF CHEMISTRY AND CHEMICAL CURRICULA

George S. Hammond

Division of Chemistry and Chemical Engineering,
Gates and Crellin Laboratories of Chemistry,
California Institute of Technology,
Pasadena, California 91109

These are troubled times for all educators and educational systems. Anyone who teaches must feel under attack from many directions and we are often faced with the ugly fact that an attempt to reach a reasonable rapprochement with one group of critics will infuriate another. An unfortunate consequence of the general turmoil in education is the danger that attempts to conduct new experiments of limited scope may be lost in general chaos. Our subject for discussion in this meeting is important, because the teaching of chemistry is likely to remain one of the significant functions of the university. However, nothing that we can do within chemistry can in itself save the universities from either internal decay or destruction by the most violent revisionists. I believe that our wisest course is to press for changes in the teaching of chemistry, because they are needed to increase the vitality and efficiency of the learning process. On these grounds alone we can find plenty of need for constructive change.

I will restrict my discussion to undergraduate instructional programmes, because these seem to me to have the most serious problems. This does not imply that all is well in postgraduate study. Indeed, I believe that successful revision of our undergraduate instruction may lead ultimately to focus of attention on studies leading to higher degrees.

Our principal objective must be to inform students about the field of chemistry so that they can either work in the field or gain useful appreciation of modern chemistry if they choose other professions. This learning should ideally be accomplished by some perfect combination of conventional teaching and self-teaching by the students. This is another area which we might accord intensive discussion, since the classic forms of teaching are clearly being exposed as a relatively ineffective means of education. However, I again choose the narrow path and will concentrate on subject matter. Other facets of the problem may seem more glamorous, but there is really no sense in teaching chemistry at all unless the subject matter is chosen sensibly.

Before one can lay out a programme for initial study, we must take a critical look at the field of chemistry in order to know what we propose to teach. We are rightly proud of the progress made by chemistry during the past few decades. Our understanding of structure and reactions and the capabilities of synthetic chemists have grown to levels that were, at best, vague dreams thirty years ago. Although the field is probably still in its infancy, the systematic correlation of molecular structure with microscopic properties of substances has proceeded far enough to make chemistry an important part of materials science. Finally, chemistry is beginning to be recognized as an understandable component in analysis of complex dynamic systems. The best example is probably the ambition of biological chemists to understand the chemical basis of life. There are, however, interesting examples in other fields, ranging from rocket propulsion to environmental engineering.

Our teaching should orient students and allow them to acquire skills in this changing field. I tend to become impatient with chemists who say that chemistry is a 'mature' field, lacking the glamour of fields such as astrophysics and molecular biology. This is nonsense. The only way in which chemistry is mature is that some of the objectives set forth fifty years ago have been accomplished and most of the methodology of that time has become archaic.

For several years, I have been saying that it is a mistake to describe chemistry using a conceptual organization that was created in the last century. The meanings of the words that we use—organic, inorganic, physical and 'analytical'—are for the most part obscure to anyone who has not already been thoroughly initiated in the ritual of chemistry. Organic chemistry certainly sounds like the chemistry of organs and inorganic chemistry should deal with nonorgans. Since chemistry is recognized as a physical science, the term 'physical chemistry' seems entirely redundant. Analytical chemistry is a little easier to identify, but one is confused to learn that only a minority of people who call themselves analytical chemists regard chemical analysis as their principal research interest. Furthermore, even the traditional meanings of the names known to the ingroup of educated chemists are not really good descriptions of coherent fields of reactivity. For example, good work in photochemistry is done not only by organic, inorganic, physical and analytical chemists, but also by biochemists and biophysicists. My colleague, Professor Harry Gray, is usually called an inorganic chemist, but he states that, 'Inorganic chemistry is a ridiculous field'.

The situation wreaks havoc with our attempts to communicate with a public which, at least in the U.S.A., is asking penetrating questions about the meaning and value of all science. Our students are probably the most important public audience and we owe it to them to present an instructional programme that is coherent and logical in its overall orientation. We must, however, bear in mind the fact that chemistry is a very broad field and that there must be some reasonable basis for subdivision of the field along lines that make sense in terms of the current activities of chemical scientists. The division that appeals to me is defined as three principal fields: structural chemistry, chemical dynamics, and chemical synthesis. Another suggestion, made to me by Professor Donald Cram, is that the field should be divided into two main fields, structure and dynamics. Synthesis would then become one of the fields of applied chemistry, along with other specialities such as materials science and nuclear science. I would not wish to argue the point at this juncture. If my colleagues are ready to debate the issue of how to restructure the field, I will feel that the first important step has been taken.

If we accept, even for the moment, the desirability of restructuring, we need to think in detail about the implications for undergraduate instruction. The first conclusion that I would draw is that the first year of university chemistry, often called general chemistry, is anything but general. Twenty years ago, the first year course was a jumbled mix of topics, with examples mostly drawn from inorganic chemistry. More recently, some very sophisticated courses have been developed in an attempt to introduce more fundamental principles. Unfortunately, these courses have serious imbalance. They are usually about eighty per cent structural chemistry and the small portion allocated to dynamics is badly done. One of the messages of a course in general chemistry surely should be the concept that chemical reactions are systematic and fascinating physical phenomena. After all, control of chemical dynamics offers man some of his best prospects for control of himself and his environment. We cannot give as coherent an account of the system underlying dynamic behaviour as can be done with structure, but this should not be a deterrent. After all, we want to tell students what is important in chemistry, not just those things which sound as though they are almost finished. An interesting discussion of dynamics in freshman courses was carried on three years ago under the auspices of the Advisory Council on College Chemistry and has been reported in a series of papers in the *Journal of Chemical Education*[1].

Another major responsibility of a course in general chemistry is to convey some notion of the outreach of chemical science. We take pride in the central position of chemistry among the sciences; yet we do little to acquaint our students with the facts that sustain this assertion. Such exposition is desperately needed at this time. A demand for relevance in education among students everywhere is both urgent and genuine. When we stop to think about the matter, chemistry seems like a highly relevant field. Unfortunately, weaving this concept into our instruction is not easy, largely because we have no practice in doing it. I know that my own attempts to relate my lectures to anything beyond the compact and circumscribed domain of chemistry are few and feeble. I am certain that we do not need a return to discussion of sulphuric acid manufacture, a common topic in general chemistry texts of thirty years ago. We do need sensible examples of the contributions of chemistry to biology, geology, engineering, the aesthetic life of man, and so on. I confess frankly that I do not yet know how to introduce such ideas without either seeming completely artificial or seriously diluting the inherent intellectual content of the study of chemistry itself. I even suspect that the classic style of pedantry is so ingrained in me that I will never become highly skilled in this particular teaching art. However, recognition of the problem will slowly lead to change and I suspect that ten years hence some people will be presenting lectures in chemistry more vital than any I will ever give. As an incidental note in connection with this thought, I suggest that our instructional programmes will progress faster if we give greatly increased freedom and responsibility for development of new courses to the youngest members of our faculties.

Establishment of principles on which to build a curriculum for students, who go beyond the first year of university chemistry, is even more difficult. I am convinced that immediate separation of the programme along the old divisional lines is devastating. Traditional courses in organic, inorganic and physical are all terribly stylized and artificially restricted in their scope. We must find ways of integrating presentation of organic and inorganic chemistry and much of what is usually reserved for physical chemistry must be used where it is actually needed in the integrated organic–inorganic studies.

Our present system is incoherent and redundant. Some concepts, such as the elements of theory in both structure and dynamics, appear in the syllabuses for four or five courses and are usually presented each time as though the other courses did not even exist. One reason for this sad situation is the tendency of professors to pay no attention at all to what their colleagues are teaching. For example, the elements of transition state theory are often covered rather badly in general chemistry, organic, inorganic and physical. Since the theory, at best, is not very good, students get the impression that it is just ritualistic claptrap used to disguise fundamental ignorance.

In a proposal made a few years ago[2], I suggested that preprofessional chemistry students should study structural chemistry in their second year and chemical dynamics in the third year. This suggestion has the merit of thoroughly mixing the traditional fields. However, I have come to realize that it also has some deficiencies. For example, a second year course devoted entirely to theory and physical methods for study of structure is obviously deficient, because chemical methods are also part of experimental structural chemistry and are also important. One has trouble in teaching chemical methods without spending some time on some of the systematic concepts of chemical reactivity. Thus, I conclude that there should be some overlap of instruction in dynamics and structure. The notion that considerable sophistication in structural theory should precede the most intensive study of reactivity still seems viable. After all, it is hard to conceive of any way of discussing advanced theory of chemical reactivity without heavy reliance on modern structural theory.

Another problem presented in my course outlines is their failure to introduce sufficient explicit reference to the outreach of structure and dynamics into the specialized fields of chemistry and the surrounding sciences. A good example is the deferring of synthesis for treatment in specialized courses. Two reasons lie behind this choice. First, I fail to see any way of doing a good job of treating synthesis logically without a good working background in structure and dynamics. Secondly, synthesis is probably the most sophisticated, as well as the most creative of the three areas, that I designate as principal fields of chemistry. Consideration of the large number of outstanding chemists who have no competence at all in synthesis tells us that synthesis cannot be indispensable to the life of all chemists. I think that there is real weakness in the early introduction of primitive synthetic ideas in the familiar style of many courses in elementary organic chemistry. Students are never likely to realize the difference between the uninspiring activity of preparative chemistry and the profoundly analytical field of creative synthesis. Furthermore, elementary instruction in the field is still handicapped by the outmoded notion that synthesis builds on a paper knowledge of several thousand distinct reactions, bearing names designed to immortalize chemists of yesteryear. The approach is like that familiar years ago in engineering education when instruction resembled that now associated with the field of motor mechanics.

Despite the criticisms that can be levelled at current practice in early introduction of synthetic chemistry, I am unhappy about leaving the subject untouched until late in the undergraduate programme. I feel the same way about other specialized fields, such as biochemistry and polymer chemistry. Unfortunately, I do not have a solution to the problem. Perhaps we need, in addition to core courses in structure and dynamics, a collection of lectures or readings designed to provide an overview of philosophy and prospects in frontier fields of applied chemistry. This idea usually receives short shrift from chemists since it involves two ideas, a survey course and the name 'applied chemistry', which are anathema to chemists.

Whatever we choose for a basic curriculum structure, I believe that we must go through the painful process of scrutiny of the details of everything we teach. The most popular shibboleth of scientific education is 'fundamentals'. Nearly everything that is taught in every course in chemistry is defended because it is fundamental, and fundamental principles are well known to be good for the souls of students. Obviously there is some fallacy involved. Fundamentals are supposed to be the essential elements that provide the groundwork for a system. If the basic principles of chemistry are, in fact, as numerous as implied by professors discussing their courses, the science is in a sorry state. Detailed inquiry shows that the concepts cited by chemists as fundamental principles are an unbelievable mélange of ideas and tricks of the trade. One cult follows the notion that all secrets of the universe are implied in the Schroedinger equation while another group appears to believe that quantum mechanics is pure window dressing, laid on to disguise the true sordid state of affairs in chemistry. One man's fundamental principles turn out to be intellectual garbage to another, and vice versa. Unfortunately, students are subjected to a series of unbalanced meals and challenged to use their own imaginations to extract intellectual sustenance from the entire experience.

I see chemistry as still a formative, rather than a mature, science. If so, we must expect that there will be changes in the most effective working principles. Concepts which seemed vital when I learned them as a graduate student twenty five years ago now are little more than trivial examples of today's most valuable working theories and hypotheses.

We need to question the value and motivation of everything we teach. We must always ask, 'If this is fundamental, what is it fundamental to?' Let me illustrate with thermodynamics, a subject more likely than most to gain general acceptance as a basic study. Thermodynamics does provide a consistent analytical language for dealing with the energetic characteristics of chemical changes. Unfortunately, thermodynamics is usually taught as a closed system. The beautifully unifying fundamental concepts are usually hidden behind a smoke screen of fairly trivial mathematics. Most of the rather protracted courses are then devoted to applications drawn heavily from the study of physical properties of dilute aqueous solutions, a field not commonly regarded as close to the mainstream of modern chemistry. It is little wonder that many students emerge from such courses totally confused as to what is fundamental and what is simply practice in application. My own inclination would be to make the integrated presentation of thermodynamics brief; early and careful applications should then be woven into discussion of other topics. The real problem is to find some plan for overall organization that will bind together units of study in a coherent manner, bearing an understandable relationship to the real world of chemistry as it now exists.

As you have heard at this conference, a few experiments with restructuring are being done in the U.S.A. The so-called 'Hammond Curriculum' has *not* been installed at Caltech, although Dr Harry Gray and I have done some experiments in that direction. For two years, we taught an experimental course in freshman chemistry, which included an introduction to thermodynamics and major sections devoted to what we consider to be fundamentals of structural chemistry and chemical dynamics. This last year, we have taught all of our second year students a course which we call 'structural chemistry'.

A marvellously courageous and enthusiastic faculty group at the State University of New York at Albany have actually installed our new curriculum as *the* curriculum for chemistry majors and have finished one year with agreeable results. A version of our freshman course has been given twice by Professor Dwaine Cowan at Johns Hopkins University. Experiments of other kinds have also been done in the past. For ten years the chemistry curriculum at Earlham College has been entirely restructured according to a plan very different from mine. Twenty years ago, a freshman course containing a mixture of organic, inorganic and physical chemistry was developed at Brown University. At UCLA, the second year courses in both lecture and laboratory have been revised to become a real mix of organic, analytical and biochemistry.

I can report in detail only about the experiments by Professor Gray and myself. The first offering was a course in general chemistry, given twice to two small groups of 16 first year students. During the academic year that has just finished, we have given a course that we called 'structural chemistry' to all of the second year students, about 60 in number, who elected chemistry. I hasten to point out that our students were not at all typical. The Caltech students are highly selected and are said to come from the top two per cent of graduates from American high schools. All have excellent secondary school backgrounds in mathematics, physics and chemistry and they are unusually intelligent and highly motivated. Consequently, we gave courses which could not in all detail be offered to most students of comparable age around the world. However, if I were to offer a first year course anywhere it would be based upon the same conceptual approach as we used, but the detailed content would be considerably modified.

GENERAL CHEMISTRY

The course began with an introduction to classical thermodynamics lasting about eight weeks. We told the students that we had no intention of giving them all of thermodynamics, but that we needed to give enough to provide a working tool during the rest of the course. The first and second laws were presented but the third law was mentioned only very briefly. The phase rule was introduced, primarily to nail down the concept of degrees of freedom of a system. We placed emphasis on the fact that definitions of most thermodynamic functions of state are arbitrary and made to suit the convenience of the scientist. For example, after having discussed the necessity of defining the entropy function as a criterion for establishment of equilibrium, we went through a nonrigorous rationalization of the form of the relationship of entropy to absolute temperature. Having done this, we then pointed out that other arbitrarily defined functions could become useful criteria for equilibrium under special conditions. This shows that the importance of the Gibbs free energy arises from the fact that most chemical systems are studied at constant pressure. The principal direction of the lectures was a drive toward development of the idea of the chemical potential. I told the students that, *to me*, this is the real essence of that part of thermodynamics which is uniquely chemical in conception and use. The concept of allocation of the total capacity of a system to do work among its various constituents is chemical because no one else cares or thinks about composition.

The second section of the course extended over twelve weeks and dealt with basic structural chemistry. We began with quantum mechanics of a fairly babyish kind, but it was real quantum mechanics. The Bohr hydrogen atom was introduced using the spectrum of the hydrogen atom as a principal experimental focus. Gray told the students how he ran gaseous emission spectra in his first technical job and gave the students tables of all the hydrogen lines. Then he discussed the Bohr atom as a solution to all man's problems, especially the relationship among the hydrogen lines. Consideration of the spectra of other atoms indicates that they are more complex, but that there is some underlying similarity to hydrogen. The Sommerfeld atom was mentioned only in passing and we jumped into quantum mechanics. The wave nature of matter was introduced as one of the brilliant *ad hoc* hypotheses of physics. We looked at the De Broglie equation and then considered writing a wave equation for the hydrogen atom. We simply asserted that one can write a suitable equation by substituting dynamic operators for the variables in Hamilton's equations of motion, which students had not seen before, but which look enough like Newton's equations of motion to be acceptable. The details of solution of the equations were described but not carried through. I pointed out to them that they would learn to solve partial differential equations of the kind involved in their mathematics course within a matter of weeks. However, we spent a good deal of time, about an hour and a half, thinking about the formulation of quantum mechanical Hamiltonians for chemical systems. The Hamiltonian *is* chemistry, not mathematics, and the frustrating problems of molecular quantum mechanics can be fairly well summarized by thinking about complete Hamiltonians and the kinds of mathematical problems that they generate.

We then stopped very briefly to describe the use of hydrogen-like orbitals for polyatomic atoms and jumped into molecular orbital theory. We did hydrogen molecules and then looked at all the symmetrical diatomic molecules from atoms of the second row of the Periodic Table (Li_2, Be_2, B_2, C_2, N_2, O_2, F_2). We decided that these were interesting but that a chemist has difficulty in doing much work with species like C_2. Consequently, we went to polyatomic molecules and discussed structures of hydrides (e.g. HF, H_2O, NH_3, CH_4, BH_3). We then went on to complex hydrocarbons and quickly got into π electron theory and reached naphthalene fairly rapidly. We showed them the simple Hückel method and tried to point out the kinds of assumptions that have to be made to keep the method simple. At this point our previous discussion of the Hamiltonians for real systems became very useful. We devoted one entire lecture to antiaromatic compounds.

Going on from the second row elements to heavier central atoms poses real problems. We chose to go directly to xenon compounds. Once this was done, the problems encountered in talking about the other heavier elements are simplified. Most of what one says about iron compounds is just a combination of the things said about carbon and xenon. We worked with qualitative ligand field theory in discussing compounds of transition elements. However, the students did a number of quantitative problems, mostly using spectral data to calculate orbital separations and energetic relationships among various species.

The last twelve weeks of the course were devoted mostly to elements of chemical dynamics. We began directly with a chemical problem, the rate of reaction of iodide ion with hypochlorite in aqueous solution. Rate laws were introduced by reference to experiment and the relationship between reaction mechanism and experiment was then built up by reference to the reaction. With this as a basis to generate a need, we talked about the concepts of rate process theory, taking the approach that there is an obvious dependence of rate on some of the chemical potentials of components of the system. I made some capital of the relationship between the chemical process in a reacting system and the flow of liquids under pressure through nozzles. The transition state concept was thus introduced in an artificial way, as is usual.

We then looked at the inferences concerning reactivity and reaction mechanism that can be obtained from the behaviour of compounds of the light elements in contact with water. One can learn a great deal by simply thinking about the extraordinary variation in hydrolytic behaviour of BF_3, CF_4 and NF_3. We spent some time on the conceptual analysis of the results of experiments with elementary reactions in molecular beams.

During the first year of the course, a month was set aside for guest lectures from some of our more charismatic colleagues and visitors. These were not connected but we did try to give our guests a clear idea of what we had taught that might relate to their subjects. Most of them did a good job of making reference to relevant material in the course. The 'frontier' lectures were very popular even though they were somewhat over the students' heads.

Gray and I worked in collaboration throughout the courses. We attended each other's lectures and participated regularly in class discussions. We also spent a good deal of time outside class talking about what we were doing. Each of us made terrible mistakes at times but the students were great in accepting these as an obvious consequence of our doing a rather new experimental course. We overstaffed the course with teaching assistants, since each year we actually had three associated with the work of our sixteen man class. During the first year, one of the assistants, Joseph Dence, taped our lectures, took notes in class, and then produced a complete set of lecture notes which were much superior in polish and completeness than the lectures themselves. These notes were typed, reproduced xerographically and given back to the students as soon as possible (never longer than a ten-day wait). We were also rather conscientious in giving students references to material to be found in the several texts which we placed on reserve for the class in the library. The combination of our own notes and the references to supporting material avoided most of the morale problems that normally arise in a new course because of the lack of a textbook. However, there is no doubt that we could have done a more thorough job if there had been a textbook tailored to the course.

During the second year, we varied the procedures but kept the format of the course essentially unchanged. We had the notes from the first year to give students straight away, so the details of the lecture presentation changed somewhat. We depended a good deal on having the students read the notes before lecture and tended to spend more time in class developing material not directly covered in the notes.

One criticism of our suggestions for curriculum revision has been the assumption of many chemists that they cannot possibly teach any branch of the subject other than their own field of specialization. In order to produce some commentary on this point, Gray and I traded assignments during the second run of our course. He gave the dynamics lectures and I gave the lectures on structure, whereas we had done the reverse the first time. Insofar as I can tell, the exchange worked well. At least Gray upgraded the dynamics section so that the lectures were better than my original version.

During the past year, three of our colleagues, Robert Bergman, Jesse Beauchamp and John Richards, decided that they would like to give their own experimental freshman course. They did so and produced a course very different from ours in detail which was highly successful. I anticipated that the experimental programme would then terminate. However, there was a good deal of comment in the department about the pity of dropping Chemistry 2, which had become something of a prestige item. However, Richards and Richard Dickerson announced that they wanted to give still another version of new freshman chemistry this year. I believe that it is instructive to look at the roster of people who will have participated in these experiments by the end of the present academic year, and to note the distribution of their specialized fields.

Teacher	*Field*
Beauchamp	Chemical Physics
Bergman	Theoretical Organic
Dickerson	Protein Crystallography
Gray	Inorganic
Hammond	Photochemistry
Richards	Enzyme chemistry

Apparently, there is no unique correlation between field of specialization and ability to teach first year students. It is also evident that interest in such teaching is more widespread than many people imagine.

STRUCTURAL CHEMISTRY

During the past year, Gray and I have given a course called 'structural chemistry' and we will repeat the exercise during the coming year. It was our intention to include both theory and experiment and to put in chemical as well as physical experimental methods.

During the first two weeks of the course, Gray gave an introduction to group theory. This was done for two reasons. First the subject was new to all of the students and, secondly, classification of molecules in point groups is a good way to focus on the three-dimensional aspects of molecular structure. These considerations are still valid, but we discovered as the course developed that putting group theory first was a mistake since several months passed before we started real applications.

The second long section of the course dealt with characteristic reactions of compounds. I took the students on a complete tour of the periodic table, building the whole scheme around the simple question, 'What does it do in water?'. We ended up with three weeks of concentrated lectures on organic reactions. In my own conscience, I am not sure whether or not this is structural chemistry. However, we put it in because students must realize that chemical methods for adducing structure exist, and because most of our students knew next to nothing about chemical reactions and had never heard that reactions are reasonably systematic phenomena. We used the concept of hard and soft acids and bases more than anything else as a correlating theme. We were handicapped by a complete dearth of reading material, since the subject is not covered in conventional texts. The fact that we had sixty students also made it difficult to achieve the kind of small group interaction that we had used in the small freshman classes. Later in the year, some of this was recaptured by breaking the class up for sessions with teaching assistants about once every two weeks.

The characteristic reactions section covered twelve weeks *in toto*. We then began physical methods and in ten weeks went through infra-red and Raman spectroscopy, x-ray crystallography, and nuclear magnetic resonance. Obviously, none of the topics was treated exhaustively. The i.r. and Raman part went very well and Gray put group theory to work. He also gave an excellent introduction to use of group frequencies for identification purposes, including showing the relationship between group frequencies and normal modes in some small molecules.

The x-ray crystallography was a *tour de force* which was not successful. Our colleague, Richard Marsh, gave two weeks of lectures in which he began with basic concepts and brought the class to the point of being able to construct a Patterson map. However, the homework assignment given to demonstrate the competence required many hours of work by even the best students. A few students who actually finished the job learned a fantastic amount in a short time. For the majority, the whole magnificent effort was a failure. They did not or could not invest the time needed and the majority lost the chain of logic.

Nuclear magnetic resonance was intermediate in success. I gave the lectures and built it all around the use of quantum mechanics to formulate spin coupling problems in exact form. I think that this can be useful as an especially simple kind of quantum mechanical problem having immediate and obvious utility in problems of practical interest. I had never before given lectures on the subject and misjudged the time required to complete my objectives. Consequently, we did not work with real spectra nearly as much as had been planned. Based on one year's experience I would guess that I could do a much neater and more complete job next year.

The last unit of the course, eleven weeks, was devoted to molecular structural theory. Gray developed an approach based upon electronic spectra of both organic and inorganic molecules which seemed effective in keeping theory in touch with the physical world. His review of basic quantum mechanics, which all the students had seen in freshman chemistry and studied concurrently in sophomore physics, was compacted into two lectures. Specific reading references to more detailed presentations were given for the use of those who needed or desired supplementary material. The problems of electronic structure were then treated moderately rigorously, using formal quantum mechanics, group theory, and approximation methods for calculations.

MISCELLANEOUS COMMENTS

The two legitimate barriers to such experimental teaching are fear and the work involved. At the beginning of the first freshman course, I was stricken with fear. I had never taught thermodynamics and had studied a postgraduate course in the subject more than twenty years earlier. Yet here I was proposing to select and drive home the essential elements of the subject for an extraordinarily bright group of first year students. I was afraid that I would fail, and if I did it would be no private matter because our experiment was carried on in full view of a considerable, critical audience of my colleagues at Caltech and elsewhere. I can see no way to avoid such fear; one can only accept it and live through it.

The labour has been considerable. To give a really new course requires hours and hours of rethinking and reformulating old concepts. New information must also be gathered but this is the lesser job. I frequently wrote and rewrote notes two or more times, always compacting the presentation with every reworking. I believe that this shows that the more one thinks about a subject, the more concisely the subject can be put.

The courses have been successful, but might not have achieved an acceptable standard except for the great help we have received from some of our graduate teaching assistants. These assistants have been doctoral candidates who were simultaneously deeply involved in thesis research. They have been caught up in the spirit of adventure and have performed unbelievably well in assuming responsibility and increasing direct communication with students in tutorial contacts. At the same time none has suffered badly in their research programmes. I am convinced that the usual style for utilizing graduate teaching assistants in the U.S.A. can be rethought and revised so as to make such young people very much more effective in our educational process than has usually been the case. Incidentally, as a byproduct of the experiments, we now have a number of young men who are not only dedicated but better prepared to teach new chemistry courses than most American senior faculty members.

REFERENCES

[1] This collection of papers is the result of the Advisory Council on College Chemistry Conference on Chemical Dynamics held at San Clemente, California, December 1966, serial publication No. 37 of the Advisory Council, reprinted from *J. Chem. Educ.*, **45**, Nos. 6 and 7 (1968).

[2] *Chem. Eng. News*, p 48, 14 November 1966.

DISCUSSION

R. S. Nyholm (*University College, London*)—Professor Hammond has given this conference a superb start with a most challenging paper. I agree wholeheartedly with his proposal that chemistry be taught under the three headings of Synthesis, Structure and Dynamics. Indeed these three headings have even been proposed by some members of the Publications Board of the Chemical Society for the subdivision of the *Journal of the Chemical Society* in place of the traditional divisions: organic, inorganic, physical.

I see two main problems, however, in implementing his scheme and these must be overcome in due course. First, to persuade one's colleagues to adopt the scheme. Secondly, for those who do wish to adopt the scheme to agree upon the division of particular topics between the three areas, e.g. many subjects such as nuclear magnetic resonance are important in both structure and dynamics.

Chemists are concerned with chemicals and the role of synthesis warrants some serious treatment at the undergraduate level for all students. By synthesis I mean preparation or isolation followed by purification. One cannot undertake structural or dynamic work unless one has the compound in a pure form.

M. Cais (*Israel Institute of Technology*)—I find myself in agreement with most of the statements made by Professor Hammond. However, we have to remember that the problem of restructuring a curriculum cannot be solved merely by a change in nomenclature. It does not make much difference what one calls a course if the person teaching that course does not change his personal attitude to it. If someone teaches, say, organic chemistry in a certain way, he may go on teaching in the same way irrespective of whether this course is called 'organic chemistry' or 'structural chemistry' unless he has changed his attitude and agrees with the philosphy of the new curriculum.

The second point, which I regard as extremely important for the success of any restructuring of a curriculum, is the problem of self-teaching by the undergraduate students. It is unfortunately true of most universities that the undergraduate chemistry curriculum is heavily overloaded with both lectures and laboratory work. I suggest that in any thinking about curriculum structure we should pay special attention to the problem of providing sufficient time for a student to make as much use as possible of the library and to use self-teaching as a major educational tool.

J. W. Linnett (*University of Cambridge*)—In many of the new universities in the U.K. a tutorial system has been adopted and this has been used also in a number of older chemistry departments. By a tutorial system is meant the regular meeting (probably weekly) of small groups of students with a staff member. This method of teaching has been known at Oxford and Cambridge for many years. However, I believe that most universities in the U.K. have missed the most important feature of the system, which is conducted particularly successfully at Oxford.

One advantage of the tutorial periods is, of course, that they provide direct contact between staff and undergraduates. During these contacts, questions can be asked, discussion can take place and problems can be solved either by joint effort or through the guidance of the tutor. Valuable though this aspect is, I believe that it is not the most valuable feature of the tutorial system. More important is that during the week between one tutorial and the next, the student spends ten or fifteen hours, working on his own, developing an essay on some particular set topic. This fosters individuality, initiative and self-reliance besides providing a scheme for guided self-education; and that is the best type of education. Some universities in the U.K. have omitted this most important feature of the tutorial system: they seem to believe that all such a system provides is an opportunity for the student to obtain answers to his problems.

It is true that this tutorial system demands a good deal of staff time but it is an excellent method which I believe universities should think seriously of using, at any rate during part of the student's course.

G. A. Olah (*Case Western Reserve University*)—I feel that we are dealing in general not only with alpha plus students and teachers, but also with the average student and teacher. What works well with a small selected group of students may be difficult to adapt to a larger group of average students. I would also like to stress the importance of motivating the freshman toward chemistry as a live and fascinating field. If we succeed here, if we can initiate a lasting 'love affair' with chemistry, the student will develop successfully, including the ever-important self-study or self-teaching aspect.

J.-E. Dubois (*University of Paris*)—Starting from an analysis of the Westheimer report it is interesting that you share its views on the value of describing the aims and activities of large groups of chemists. But this has been achieved in this report by definition of three fields: 'structural chemistry', 'chemical dynamics' and 'chemical synthesis'.

Now, in your very interesting proposals you retain the two most abstract of these fields for basic courses but you drop 'chemical synthesis'. Furthermore, by introducing 'general chemistry' you really develop a structure of chemistry which is no longer of appeal for most of the actual chemistry students.

In other words, I wonder whether your proposed restructuring of chemistry is not leading to an emphasis on physical chemistry. Future students attracted by such chemical curricula will have to be better in mathematics than the actual students in chemistry today. In fact, are you not expecting to attract some physicists as your chemistry students?

At the present time, those students who could follow such courses take physics for the very special reason that physics has found a way of appealing to people outside the university. Physicists tend to become astronomers, space researchers, engineers or oceanographers, which are recognized professions linked to glamorous programmes.

Do you not think that restructuring of chemistry courses should take account of prospective interests in which chemists would be more understood by the outside world and associated with well-known national programmes?

H. Zollinger (*ETH, Zürich*)—The research interests of each professor are, and should be, reflected in some way in his teaching methods, even on a very elementary basis. Having similar interests with Professor Hammond, I agree with his ideas about replacing the traditional division of chemistry with a more modern one and, in particular, teaching dynamics in a more systematic and generalized way. But it may be relevant to enquire how should the 'facts' of chemistry be presented and how does one overcome the problem of teaching superficially simple ideas, such as reactions in aqueous solutions, which are really quite complicated from the point of view of chemical principles.

M. Oki (*University of Tokyo*) (written communication)—When we are talking about the facts and the theory of chemistry, it is frequently said that they are like the words and grammar of a sentence. Since no one can write a good sentence without having sufficient vocabulary and a knowledge of grammar, it is rather dangerous to overstress the deductive way of teaching chemistry. Weaving the facts and the theory together is most important.

T. Urbanski (*Politechnika, Warsaw*)—It is my view that teaching chemical analysis along classical lines should *not* be discontinued at freshman level. It introduces students to laboratory techniques and helps to explain the basis of elementary processes, such as oxidation, reduction, hydrolysis, etc. The premature introduction of instrumental analysis can be dangerous.

At the M.Sc. level there is much to be said for introducing special courses in chemical technology, as for instance in many universities, particularly the technological universities, in central and eastern Europe. Such courses should not be limited to chemical engineering departments.

G. Illuminati (*University of Rome*)—In my opinion, there are two distinct aspects concerning Professor Hammond's approach to chemical education: (a) the need for profound changes in the way chemistry is presented; (b) the ways such changes should be carried out.

Most criticisms and discussions have been concerned with (b). However, apart from the objective difficulties in the realization of restructuring chemical curricula on the basis of integrated courses, I wish to point out, as a supporter of Hammond's approach, that we should not miss the fundamental importance of point (a). To the extent that there exists such a thing as chemistry itself, all internal branches of chemistry have developed because of an artificial classification of Nature due to a first approximation process in our knowledge of science. Objectively, there are no such things as inorganic, organic or physical chemistry except in our minds. By classifying science in this way we introduce a distortion of Nature. The more we know about chemistry the more we do not need to divide it in what has been called the traditional way. So not only ought we to make every effort to update our teaching by presenting chemistry as we see it *today*, but also we should make it clear to ourselves and to the students that the most honest presentation of science is fundamentally motivated by the present objectives of studies as indicated by the trends of interests which are bound to change, as they should, from time to time.