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Review

Learning in the laboratory; some thoughts from the literature [•]

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Introduction

Laboratory work and other forms of practical work have gained wide, but not universal acceptance as one of the most important and essential elements in the teaching and learning of science. For the purposes of this paper we concentrate on laboratory work, but many of the principles addressed apply equally to the range of practical work encountered in the sciences.

This paper provides a brief overview of the literature on laboratory work as a means of helping to answer three fundamental questions:

- What are the *purposes* of teaching in laboratories?
- What *strategies* are available for teaching in laboratories and how are they related to the purposes?
- How might we *assess* the outcomes of laboratory instruction?

Researchers at secondary school level have generated much of the literature, but their findings have importance and application at tertiary level also.

What is the purpose of laboratory work?

This could be answered superficially by saying that, "Chemistry is a practical subject and so we must do laboratory work". If pressed further, we might say that the purpose of laboratory work is to teach hand skills and to illustrate theory. But is this the end of the story? If we are going to look at the variety of strategies available for laboratory work, we shall have to be clearer about the purposes of the laboratory to enable us to decide which of these strategies lend themselves best to the achievement of our purposes. Similarly, if we are to try to match the assessment to the outcomes, we will have to be clear about the outcomes we desire to see in our students.

Such ideas have been under discussion for decades, especially in places like Britain, where a great deal of time and money has been spent on using practical activities in science teaching.[1] The important aims and objectives of practical work have been considered from as far back as the early nineteenth century.[2]

Special attention to this has been given in the post World War II period by teachers and science education researchers. The need was recognised for a list of practical aims to help laboratory teachers to think clearly about their intentions and to ensure that all the important goals of the course had been pursued. There is also an awareness of the need for a list of aims or objectives on which to base the assessment of practical work.[3] If the desired outcomes are not clearly stated how could any kind of objective assessment be applied by teachers and understood by students?

Before examining the aims and objectives, which have been produced by researchers, the terms 'aims' and 'objectives' should be defined. In the literature on practical work the two terms are often used synonymously to give a general description of the intentions of the practical work. Sutton[4] defined aims as *general statements* of what the *teacher* intends to achieve, while objectives are *specific statements* of what the *students* should be able to accomplish as a result of being taught in the laboratory. We shall adopt this useful definition and examine the *aims* of practical work in some detail because they can be generalised. The *objectives* are largely specific to given experiments and are generally so numerous that we shall not consider them in any great detail.

Aims of practical work

Kerr[5] carried out an important study of practical work in 1961. Over a two-year period he conducted a survey of practical work in England and Wales asking teachers to give information about the nature, purposes, assessment, and views

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[•] This is a revised version of the review originally posted on the Web on September 17, 2001, modified by Professor A H Johnstone following receipt of the letter from Professor D. S. Domin, (see p. 90 of this issue).

about practical work they had encountered in schools. As a result of this he compiled a list of ten aims for practical work. These were:

- To encourage accurate observations and careful recording.
- To promote simple, commonsense, scientific methods of thought.
- To develop manipulative skills.
- To give training in problem solving
- To fit the requirements of practical exam requirements
- To elucidate theoretical work so as to aid comprehension.
- To verify facts and principles already taught.
- To be an integral part of the process of finding facts by investigating and arriving at principles.
- To arouse and maintain interest in the subject.
- To make phenomena more real through actual experience.

Numerous further attempts have been made to articulate the aims of practical work. Examples are to be found in the writings of, Swain,[6] Kempa and Ward,[7] Johnstone and Wood,[8] Boud,[9] Lynch and Ndyetabura,[10] Denny and Chennell,[11] Kirschner and Meester,[12] Boyer and Tiberghien,[13] Garnett and Hackling,[14] Gunstone[15] and Wellington. [16] They are in substantial agreement with Kerr.

Attempts to specify aims have been around from the early twentieth century[17] and these aims remain almost the same today. This might suggest that the science education community has reached a consensus, but it is more likely to have been a consensus of information gathered by researchers and supported by theorists. Much of the writing has been about the situation in secondary schools, but it can equally apply to tertiary level. Similar aims are proposed by other writers such as Meester and Maskill,[18] Bennett and O'Neale[19] and Laws,[20] addressing the tertiary situation. These can be summed up in the list of principal aims produced by Buckley and Kempa.[21]

Laboratory work should aim to encourage students to gain

- manipulative skills
- observational skills
- the ability to interpret experimental data
- the ability to plan experiments

To this must be added the affective aims mentioned by Kerr and others of those listed above.

- interest in the subject
- enjoyment of the subject
- a feeling of reality for the phenomena talked about in theory

Some of these aims need further consideration.

Manipulative skills

It is true that laboratories are the only place to learn hand skills, but many of the skills depend upon the particular piece of equipment available. Not all infrared machines are the same, each having its own peculiar 'flicks of the wrist' to make it operate well. Although the student has to learn the manual skills with the apparatus available, what is important is to know how to handle and interpret the spectra from *any* machine and this can be done without a laboratory! Manipulative skills have to be encountered often if they are to be well established. A large gap between learning to operate a particular balance and using it again requires almost total relearning. Problems with facility in manipulative skills can seriously get in the way of other desirable skills (Wham[22]). A student struggling to operate a piece of equipment may fail to make important observations and gather poor data. A classical information overload can occur under these circumstances. It is essential so to establish the manipulative skills that they can 'go on auto-pilot' and free the student's attention for other things such as observation and accurate recording [23].

Observational skills

Observation is a cognitive process and it becomes scientific when it has purpose and theoretical perspective. However, what is scientific observation? Young [24] made it clear that there is a difference between 'seeing' and 'observing' when he stated that learners 'see' many things, but they do not always 'observe' them. Do learners notice every observation that could be made? Kempa and Ward[7] reported that students failed to notice or record one in every three observations. They reported that 'observability' is a function of both the nature and intensity of a stimulus and the observer's perceptual characteristics. The observational stimulus must reach a certain level below which, observation will not be made (observation threshold). They pointed out that, as the intensity or magnitude of an observational stimulus is reduced, it becomes more difficult to detect. Moreover, when there are multi-stimuli, the 'detectability' of one stimulus can be seriously affected by the presence of another; the dominant stimulus obscuring, or masking completely, the less dominant ones. This psychological factor affects learners throughout their lives. It is not enough to tell students to observe; they have to be shown how. However, some of the greatest observations in science have been made by chance, such as the discovery of polyethylene, but the observers had to have prepared minds to see the possibilities behind their observations.

In practice, by using interactive demonstration techniques Al-Shuaili[25] showed that visual observational changes, which might go unnoticed in a normal laboratory, could be made to appear well above the detection threshold. Therefore, whilst demonstrating a particular task, the instructor can highlight the kind of things learners should be looking for in order to fulfil the task's aim of focusing on 'signals' and suppressing 'noise' (Johnstone[23]). Teachers also have to ensure that 'signals' offered to students should have enough observational magnitude and intensity as to be above the threshold. They should also be aware of the dominant observation in situations of multi-stimuli and manage them accordingly. The dominant stimulus may have to be played down if it is in danger of masking other important observations. This does not imply that the teacher should give all the answers before the laboratory, but rather prepare the observational faculties for what is to come.

There may well be occasions when demonstration, rather than individual laboratory work, may be the best procedure when there is a danger of vital observations being obscured by powerful, but less important stimuli. In a demonstration the teacher has control and can focus attention on the salient observations.

According to Hodson [26], observation would appear to be more than merely seeing, and seeing would appear to be more than simply receiving sense data. Raw sense data can be 'seen' almost unconsciously, without having any significance attached to them. However, when this 'seeing' is registered and interpreted in the light of previous knowledge and expectation, it becomes an observation. This emphasises the importance of having a prepared mind before setting out in a laboratory and clearly calls for some pre-laboratory experience.

The collection of observational data can only take place within a theoretical framework. What is important in science are the ideas one has about the data, rather than the data themselves. It would be a mistake not to consider the link between observation and understanding, because what is observed depends as much on what is in the mind of the observer as on what is there to be seen. In reality scientists often have to reject sense data on theoretical grounds: the Earth is not flat, a stick, partially immersed in water, is not bent, distant stars are not red. When theory and observation conflict, nothing in the logic of the situation necessarily demands that the theory should be rejected. Rejection of observational evidence is a crucial part of scientific research. Students who lack the requisite theoretical framework will not know where to look, or how to look, in order to make observations appropriate to the task in hand, or how to interpret what they see. Consequently, much of the activity will be unproductive**.**

Hodson [26] remarked, "Knowing what to observe, knowing how to observe it, observing it and describing the observations are all theory-dependent and therefore fallible and biased".

In laboratory work, a further complication to observation is that apparatus often masks a phenomenon. Frost [27] noted that "The size and the noise of the Van der Graaf generator often masks the significance of the spark being generated. The noise from the vacuum cleaner in a linear air track can distract from the significance of the movements of the air-borne pucks". People's memories of their school science often relate more to the dramatic equipment than to its significance for scientific ideas. Because of this, it is important to take some time to explain a piece of apparatus, with the intention of making it sufficiently familiar so that the class can forget it and focus attention on the phenomenon.

Observation is carried out to check on theories, not only to collect 'facts'. However, as indicated earlier, Hodson asserted that we can reject observations, just as we can reject theories. "We may reject a theory in the light of falsifying observations or we may modify those observations in order to retain a well-loved and otherwise useful theory. The view promoted in science courses, that a change in observational evidence always brings about a change in theory, implies a simple direct relationship between observation and theory which seriously underestimates its true complexity". In everyday situations the link between observation and theory (or belief) is often tenuous. People support a team and defend its superiority despite its actual performance. The saying that "Old scientists do not change their minds: they just die off" is an illustration of the unwillingness of people to give up their held beliefs even in the face of contrary evidence. Before Lavoisier, combustion was always associated with loss of mass between reactants and products. Even when it was shown that the products of burning iron in air gave an increase in mass, the Phlogistonists failed to accept it. Facts, which did not fit the theory were manipulated or rejected. Similar defence of theories is not uncommon even in recent times.

Planning experiments

This skill is usually exercised in laboratories where there is a measure of problem solving at the bench. Conventional laboratories, with closely prescribed procedures, tend to omit any exercise of this skill.

We shall discuss this later when we consider different types of laboratory experience.

Linked to this aim are the skills of problem solving at the bench, because some forms of practical problem solving require students to plan their experiments on the way to solving problems.

Affective aims

These can be divided into two main categories; attitudes to science and scientific attitudes (Gardner and Gauld[28]). Attitudes to science include interest, enjoyment, satisfaction, confidence and motivation. Scientific attitudes apply to styles of thinking such as objectivity, critical-mindedness, scepticism and willingness to consider the evidence. (Garnett[14]) Some of the affective aims mentioned above will be discussed on the way through later parts of this paper.

Laboratory Objectives

Overall, attempts to list the objectives of the science laboratory are hindered because the stated objectives are either so detailed that they can be of use only in specific disciplines or are so general that they can include almost anything one can think of. Kirschner and Meester [12] have catalogued more than 120 different specific objectives for science practical work.

Having now looked at the purposes of laboratory work, we shall turn our attention to the variety of methods (or styles) available for laboratory work.

Types of laboratory work

What does the learning environment in the laboratory look like? Does it have different forms of instruction designed to promote the variety of aims we have considered in the earlier part of this paper?

The following section attempts to review laboratory instruction types and to relate them to the aims.

In this section we have drawn heavily upon the analysis of laboratory instructional types set out in a recent paper by Domin.[29] Sections of the paper are presented verbatim, interspersed with our own comments and observations to link Domin's analysis to the situation in UK universities. Readers are encouraged to consult Domin's original paper for the full analysis.

In chemistry education distinct styles of laboratory instructions have been in evidence: expository, inquiry, discovery, and more recently, problem-based. Three descriptors can differentiate these styles: *outcome, approach,* and *procedure* (Table 1[29]). The outcome of any laboratory activity is either pre-determined or undetermined.

Expository, discovery and problem-based activities all have *predetermined* outcomes. For *expository* lessons, both the students and the instructor are aware of the expected outcomes. For *discovery and problem-based activities*, usually it is only the instructor who knows the expected result.

Expository and problem-based activities typically follow a deductive approach, in which students apply a general principle to understand a specific phenomenon.

Discovery and inquiry activities are inductive. By observing particular instances, students derive the general principle. This procedure can be criticised on the grounds that students are unlikely to discover, in three hours, what the best minds took many years to find.

The procedure to be followed for any laboratory activity is either designed by the students or provided for them from an external source (the instructor, a laboratory manual, or a handout). *Inquiry and problem-based methods* require the students to develop their own procedures. In *expository and most discovery activities* the procedure is given to the students.

The Expository Laboratory

Expository instruction is the most common type in

Table 1 Descriptors of the laboratory instruction styles.

	Descriptor		
Style	**Outcome**	**Approach**	**Procedure**
Expository	Predetermined	Deductive	Given
Inquiry	Undetermined	Inductive	Student generated
Discovery	Predetermined	Inductive	Given
Problem-based	Predetermined	Deductive	Student generated

use. Within this learning environment, the instructor defines the topic, relates it to previous work, and directs students' action.

The role of the learner here is only to follow the teacher's instructions or the procedure (from the manual) that is stated in detail. The outcome is predetermined by the teacher and may also be already known to the learner. So, as Pickering[44] stated "Never are the learners asked to reconcile the result, as it is typically used only for comparison against the expected result, nor confronted with a challenge to what is naively predictable". Lagowski[30] stated that, "Within the design of this laboratory (expository), activities could be performed simultaneously by a large number of students, with minimal involvement from the instructor, at a low cost, and within a 2-3-hour time span. It has evolved into its present form from the need to minimise resources, particularly time, space, equipment, and personnel". However, this procedure, although administratively efficient, may defeat the main purposes of laboratory work, leaving the student uneducated in this area of learning.

Expository instruction has been criticised for placing little emphasis on thinking.

- Its 'cookbook' nature emphasises the following of specific procedures to collect data.
- It gives no room for the planning of an experiment
- It is an ineffective means of building concepts.
- It is unrealistic in its portrayal of scientific experimentation.

It is possible that little meaningful learning may take place in such traditional laboratory instruction.[22] Two reasons can be suggested to explain the inability of this type of laboratory to achieve good learning. Firstly, it has been designed so that students spend more time determining if they have obtained the *correct* results than they spend thinking about planning and organising the experiment. Secondly, it is designed to facilitate the development of lower-order cognitive skills such as rote learning and algorithmic problem solving. It has been reported[18] that most university laboratory experiences are of this kind.

When placed beside the aims of laboratory work already discussed, the expository laboratory seems to be incapable of helping students to achieve many of them. It may be a place for exercising manipulative and data gathering skills, but may fail to provide training in design and planning and may offer little motivation and stimulus. However, in our experience, small modifications of expository laboratories can offer the possibility of introducing some of those desirable experiences.

For example, an expository laboratory in which a copper complex is to be synthesised and characterised, can take on a new life if the task is presented in another way. If the similarities in behaviour of other metal ions in the first row of the Transition Series exist, it should be possible to synthesise the same complex of a series of metals by the same method. The students can work in groups of four to synthesise four different complexes using the method provided and compare the products for appearance, spectroscopic behaviour and other characteristics. This provides the students with freedom to allocate the tasks, generate a feeling of ownership and give a sense of responsibility to the group. The appearance of enthusiasm and co-operation is an evident bonus. It would not take too much ingenuity on the part of laboratory organisers to modify many experiments in this way and extend the range of aims achievable.

To motivate, by stimulating interest and enjoyment is one of the reasons given by teachers for engaging in practical work. Hodson [31] says that "motivation is not guaranteed by simply doing practical work; we need to provide interesting and exciting experiments, and allow learners a measure of self-directed investigation." He adds that learners need an interest in and commitment to the learning tasks that conventional laboratory work frequently does not provide. That commitment, he says, comes from personalising the experience by focusing on the conceptual aspects of the experiment, by identifying for oneself a problem that is interesting and worth investigating or by designing the procedure to be adopted.

Inquiry Laboratory (Open-Inquiry)

This is best represented by a final year research project, but it need not be confined only to final year. As shown in Table 1, inquiry-based activities are inductive. They have an undetermined outcome and require the learners to generate their own procedures. They are more student-centred, contain less direction, and give the student more responsibility for determining procedural options than the traditional format. It effectively gives students ownership of the laboratory activity, which can result in the students' showing improved attitudes towards laboratories.

Student ownership, represented in such activities, requires learners to formulate the problem, relate the investigation to previous work, state the purpose of the investigation, predict the result, identify the procedure and perform the investigation.

This type is designed to help the learner to construct thinking processes, which, if done properly, will give students the opportunity to engage in authentic investigative processes. Raths[32] lists the following higher-order thinking processes as components of inquiry: hypothesising, explaining, criticising, analysing, judging evidence, inventing and evaluating arguments. This type of practical work could be criticised for placing too much emphasis on the scientific process and not enough on science content. It can provide an environment in which many of the aims can be fostered, but it is time consuming, potentially costly and very demanding on those who have to organise large laboratory classes. However, there is a strong case for its use from time to time and at all levels. There is no reason why a short inquiry should not be attached to the end of an expository laboratory using the skills and knowledge gained in the laboratory but with no fixed instructions. An expository laboratory on acids and bases could be followed by a variety of short investigations on commercial vinegars, path cleaners, antacids and so on, using the skills gained in the laboratory. In this way it is possible to exercise the skills and knowledge gained in the laboratory and so reinforce the learning. There is an opportunity for planning, designing and interpreting and the bonus of ownership and enthusiasm. This kind of approach is already gaining acceptance, but is as yet not reported as common.[18]

Real inquiry can only come after certain knowledge of facts and practical methods have been gained. These foundations can be laid in an expository laboratory. Students must learn the language of chemistry, its symbols and nomenclature, so that they can understand the problem, plan the procedures and communicate their discoveries. Part of the training of a chemist is to learn the techniques of manipulation of materials. "When an artist knows when and how to use his brushes he can be creative. When the chemist becomes skilled in the use of his spatula, he may discover."(Jones[33])

But more than this, a student must learn that often the research chemist has a definite design in his work. He researches along a particular line of thought and he examines the literature in order not to retrace the steps of some other chemist. So we do need some method of education in chemistry, which cultivates and teaches the recognised scientific attributes of observation; the formation of a hypothesis to explain the observation; the experimentation that tests the hypothesis; and the development of the refined theory that possibly relates several hypotheses.

Berry[34] stated some factors, which contribute to such mental engagement in an inquiry laboratory: confidence in content knowledge, ownership and purpose.

***Content Knowledge*:**
To what extent do students have the content knowledge assumed by the task? For instance, if they have little or no relevant content knowledge, they will not be able to suggest why a solution has changed in colour; they simply make an 'observation'. The same thing applies for working out an appropriate procedure. Students may puzzle over the results from their procedure but lack the knowledge to tell them that their results are meaningless because their experimental design was incorrect.

Therefore, teachers have to determine how much content knowledge is necessary for learners to be able to engage mentally with a particular investigation and to what extent students have acquired this prior to beginning a task. This is the essence of what Johnstone[35] means by Pre-Laboratory work. Investigation is very knowledge dependent and cannot take place in a knowledge vacuum. Any suggestion that investigation is a free-standing skill, capable of ready transfer, is unlikely to be true.

***Ownership*:**
When learners have some input into the design of the task, they are likely to have more interest in its outcome and be more motivated to persist. Open laboratory tasks offer greater opportunity for students' ownership of the work and they are truly involved in the process, but this may be offset if they do not already have sufficient background knowledge.

For practical work to be convincing it requires that the learner becomes a 'partisan experimenter'. Solomon[36] argued that "the great experiments of the past were performed in a partisan spirit by scientists who were proving that their hunches were triumphantly right, and that students also were happiest and most successful when they were doing the same".

***Purpose and Aim*:**
As stated before, the aim refers to the scientific reason for a particular investigation and the purpose is the way in which that investigation fits into the work being covered at that time. During the laboratory session, students may ask themselves questions such as: *Why are we doing this? What should we be looking at? What do the results tell us?* Therefore awareness of the aim is important as it helps learners make sense of what they are doing while awareness of the purpose can encourage them to seek links between the activity and the rest of their science work.

Discovery laboratory (Guided inquiry)

The heuristic method taught by Armstrong in the early 20th century,[17] can be regarded as the origin of discovery laboratory teaching in which students were required to generate their own questions for investigation. No laboratory manual was used and the teacher provided minimal guidance. The student was placed in the role of discoverer.

Similar to the inquiry method, the discovery approach is inductive but differs with respect to the outcome of the instruction and to the procedure followed. Whereas in the former the outcome is unknown to both the teacher and the learner, in the latter the teacher guides learners toward discovering a desired outcome. The disadvantage of discovery learning (shared with the other non-traditional forms of instruction) is that it is more time-consuming and potentially more costly than expository learning.

Hodson[31] described discovery instruction as not only philosophically unsound, but also pedagogically unworkable. He asserted that the learner couldn’t discover something that he is conceptually unprepared for. The learner does not know where to look, how to look, or how to recognise it when he has found it. We find ourselves in agreement with this view.

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Problem-based instruction

Wright[37] stated that this type of learning is becoming a popular alternative to the other styles of laboratory instruction, not only in general chemistry but also in other chemistry courses. The teacher, in problem-based learning, adopts an active, stimulating role by posing a problem to the learners, providing the necessary reference materials and, by occasional group meetings, carefully moving the students towards a successful solution to the problem. The teacher is very much a facilitator rather than a direct provider of student learning. In this style, students are presented with a problem statement often lacking in crucial information. From this statement the students redefine the problem in their own words and devise a procedure for finding the missing information. With that in place, they then proceed with an experiment, which will lead them to a solution. The problems are ‘open-entry’ that is, they possess a clear goal, but there are several viable paths toward a solution. Wright emphasised that the problems must be designed to be conceptually simple so that students can concentrate on the methodology without being overwhelmed by the topic. Students are required to devise a solution pathway, think about what they are doing, and why they are doing it.

Like discovery and inquiry instructions, this style is time consuming and places a greater demand on both the teacher and the learner than does traditional instruction. Similar to inquiry instruction it fosters the development of higher-order cognitive skills through the implementation and evaluation of student-generated procedures. It is, however, a deductive approach. Learners must have had some exposure to the concept or principle of interest and the experimental techniques, before performing the experiment. (Domin[29]) Problem Based Learning is very commonly used in the training of medical students in North American universities and is now gaining acceptance in some British and other European centres. It demands a rethink on the part of teachers to redefine their roles. The change from expositor to facilitator is not an easy transition to make, but reports from research indicate that it is very worthwhile.[38] Interest in this kind of laboratory work in chemistry is growing in Britain. It is, of course, not confined to the laboratory and whole courses are being built around the basic principle of Problem Based Learning. An early example of this in chemistry was the ‘Eaborn Degree’ in the University of Sussex in the 1970’s.

While it is recognised that problem-solving situations are complex and variable, and they cannot be tackled by a single ‘scientific method’, science educators have come to accept that there are certain basic steps that make up a scientific process.

- Identifying a problem for investigation and putting forward a tentative hypothesis.
- Designing an experiment to test a hypothesis.
- Performing the experiment and recording the results in appropriate forms.
- Interpreting the results and evaluating the conclusions with reference to the hypothesis to be tested.

These four steps do not proceed in a linear way but rather in a cyclical manner. The conclusion of an investigation is not the end of the problem-solving process, but by raising a new problem, it becomes the starting point for another investigation. However, this model represents only a simplified outline of the scientific process. The actual problem-solving situation is usually more complex, with links and interactions across the different stages such as collecting data or recalling knowledge to predict, and evaluating the design and implementation as necessary in light of the information collected.

Many of the available published manuals are highly prescriptive and teacher-directed, offering little opportunity for students to pose problems and formulate hypotheses, or to design experiments and to work according to their own design. Students are provided with detailed instructions from the teacher or manual, and all they need to do is to follow the given procedure mechanically. This sort of recipe-type practical is primarily used as a means of verifying or demonstrating principles described in textbooks. They fail to provide experience and training in developing the skills and understanding of the scientific process. Such practicals, are concerned with investigating the *teacher's* problem and finding the *teacher's* answer. They need have little relevance to real life and so fail to promote in students a genuine interest and motivation for practical work.

Some concluding thoughts about laboratory types

This brief tour round a sample of the literature on laboratory work has found that, although many of the references have been to research in the secondary sector, there is much here for the tertiary teacher to consider. It would be naïve to imagine that all this thinking has resulted in a revolution in laboratory work in schools and that researchers on tertiary level laboratory work are unaware of it.[18, 19, 20, 39]

'Pure' discovery learning, if it ever existed, has come and gone. Guided discovery still has a place, but teachers, driven by external pressures, have little time to indulge in it. Worksheets and blow-by-blow manuals are still alive and healthy, leading to apparently efficient coverage of laboratory activities, while missing much of the point of what undergraduate laboratories have the potential to achieve.

The literature cited earlier in this paper has had useful things to say about observation, and particularly to point out that observation is largely conditioned by what we are expecting to find. The observation then either confirms our expectations or challenges us to rethink them, but this can only take place when there are expectations in mind. Otherwise, students may observe irrelevant trivialities and miss what is important, but this begs the question of what is trivial and what is important. The teacher has expectations in mind to enable this judgement to be made, but unfortunately these are not always shared with the students.

The necessity for some kind of pre-laboratory preparation is patently obvious. It applies as much to conventional laboratories as it does to more open-ended and investigative laboratories. A student entering a laboratory without some preparation is likely to spend hours in fruitless, routine handle turning and non-learning. As learning environments, laboratories are very costly in terms of specialist accommodation, consumables, breakages and staff time.[40] If they are not being used for their potential strengths and the time is spent unproductively, they are a massive sink of scarce resources.

Pre-laboratory preparation is not just "read your manual before you come to the laboratory". Many students ignore this because they know that they can survive the laboratory, quite comfortably, without doing it. The conventional laboratory may not be engaging the mind, merely exercising the ability to read and follow instructions. The kind of pre-laboratory work which is being recommended must be as carefully prepared as the laboratory manual itself. It can take many forms, but it must prepare the student to be an active participant in the laboratory. This theme is taken up in a number of publications by tertiary teachers,[40, 43, 39] the last of these being a compilation of pre-laboratory exercises from around the world

It would seem that laboratories that are totally expository miss some of the desirable aims of laboratory work. Totally inquiry laboratories are probably impracticable in the present situation in universities. A core of expository laboratories with substantial 'inserts' of inquiry will go a long way towards achieving the desirable aims of laboratory work.

Assessment of laboratory outcomes

If students are going to take laboratory work seriously, they must see some reward for their efforts. This brings us to consider the objectives set out earlier. They are, in general, a laudable compilation of desired outcomes, but how are they to be assessed?

Let us stay with the general categories set out by Kempa et.al.[21] to simplify our discussion.
The student should exhibit

- appropriate manipulative skills.
- the power to observe.
- the ability to interpret observations and results.
- the ability to plan experiments.

The conventional laboratory report, upon which the assessment is commonly based, can possibly make some kind of measurement of the second and third categories above, but is not 'designed' to handle the first and the last.[18] We might assume that the quality of the results is an indication of the manipulative skills of the student, but it is all too possible for the student to get 'good results' while knee-deep in water and broken glass! It is even possible to get satisfactory results without doing the experiment at all, provided one has good friends! For manipulative skills to be assessed, the student has to *exhibit* them to an assessor. In large laboratories, this has to be done by making demonstrators act as assessors and, for this to operate fairly, each demonstrator has to have some objective and criterion-referenced measure of the skills to be assessed. This may take the form of a set of questions for the demonstrator each of which has only a yes/no answer. In fairness these questions have to be shared with the students so that they can appreciate what is important in the manipulative part of the laboratory.[42]

The planning of experiments is a desirable skill, but how might it be assessed? This operation can take place before entering the laboratory. One possibility, from our own experience, is to give the design task to small groups and ask each group for an agreed written plan. This can be done by forming a small e-mail group and sending a copy of the practical problem to each member. Each member of the group must send the teacher (and the other members of the group) a possible design. Then each student is required to comment on the other designs (several times if need be) until a commonly agreed plan is reached. The teacher now has a written record of the contributions of all the members of the group and can make an assessment of each. This is then returned to individual students with comments. This last step then becomes part of the training in experimental design since experimental design skills are not acquired by osmosis, but need to be taught.

There still seems to be a wide gap between the ‘vision’ of the researcher and the practice in most laboratories.[18] Could it be that the practitioners view the researchers as unrealistic idealists divorced from the real business of teaching? Or do the practitioners see the arguments of the researchers as reasonable in principle, but unattainable in practice in large, busy undergraduate laboratories? Some might believe that the ideas of experimental design and open-ended projects are for final year undergraduates only because, before then, students do not know enough chemistry or have the requisite skills. This means that many undergraduates will never be exposed to ‘real’ investigative work at any time in their studies and be denied the excitement experienced by students who have tasted this freedom. How many students confess to never having enjoyed laboratory work till their final year project?

It should not be beyond the ingenuity of tertiary teachers to find ways of giving students, at all levels, the joy of experiencing laboratory work to the full. It is achievable at secondary level[41] and so must be possible at tertiary level.

References

1. B.E. Woolnough, *Towards a rationale for practical work in school science: Implications for training teachers* in: *Pre-service and in-service Education for science teachers*; Eds. Pinchas Tamir; Avi Hofstein and Miriam Ben-Peretz Balaban, International Science Services, Philadelphia, 1983.
2. M. Faraday, *Chemical Manipulation*; W Phillips, London, 1827.
3. F. Vianna, *Using Information Processing Theory to design an undergraduate practical course in chemis*try, Ph.D. Thesis, University of Glasgow, 1991.
4. A. Sutton. *An introduction to assessment and evaluation processes and procedures*, University College, Cardiff, 1985.
5. J.F.Kerr, *Practical work in school science: An account of an inquiry into the nature and purpose of practical work in school science teaching in England and Wales*, Leicester University Press, Leicester.1963.
6. J. Swain, *Educ. Chem.*, 1974, **11**, 152.
7. R.F. Kempa and J.E. Ward, *Intern. J. Sci. Ed.*, 1988, **10** (3), 275.
8. A.H. Johnstone and C.A. Wood, *Educ. Chem.*, 1977, **14**, 11.
9. D.J. Boud, *Higher Education* 1973, **2**, 81.
10. P.P. Lynch and V.L. Ndyetabura, *Journal of Research in Science Teaching*, 1983, **20** (7), 663.
11. M. Denny and F. Chennell, *European Journal of Science Education*, 1986, **8** (3), 325.
12. P.A.Kirschner and M.A.M. Meester, *Higher Education*, 1988, **17**, 81.
13. R. Boyer and A. Tiberghien, *Intern. J. Sci. Ed.*, 1989, **11** (3), 297.
14. P.J. Garnett and M.W. Hackling, *Australian Science Teachers’ Journal*, 1995, **41**(2), 26.
15. R.F. Gunstone, *Reconstructing science from practical experience* in: *Practical Science*, ed. B. Woolnough, Open University Press, Milton Keynes, 1991.
16. J. Wellington, *Practical work in school science: which way now*? Routledge, London, 1998.
17. W.H. Brock, *H.E. Armstrong and the teaching of Science 1880-1930*, Cambridge University Press, London, 1973.
18. M.A.M. Meester and R. Maskill, *Second Year Practical Classes in Undergraduate Chemistry Courses in England and Wales*, The Royal Society of Chemistry, London, 1994.
19. S.W. Bennett and K. O’Neale ,*U. Chem. Ed.*, 1998, **2**(2), 58.

20. P.M. Laws, *Studies in Science Education*, 1996, **28**, 1.
21. J.G.Buckley and R.F. Kempa, *School Science Review*, 1971, **53**(182), 24.
22. A.H.Johnstone and A.J.B.Wham, *Educ. Chem.*, 1982, **19**(3), 71.
23. A. H. Johnstone and K. M. Letton, *Educ. Chem.*, 1990, **27**(1), 9.
24. B. Young, *Teaching primary science*, Longman Group, Harlow, 1979.
25. A. Al-Shuaili, *A study of interactive projected demonstration techniques for school science in Oman*, PhD thesis, University of Glasgow, 2000.
26. D. Hodson, *School Science Review*, 1986, **68** (242), 17.
27. J. Frost, in: Teaching Science, eds Jenny Frost, Arthur Jennings, Tony Turner, Sheila Turner and Leslie Beckett, The Woburn Press, London, 1995.
28. P. Gardner and C. Gauld, in: *The student laboratory and the science curriculum*, Ed: E. Hegarty-Hazel, Routledge, London, 1990.
29. D.S. Domin, *J. Chem. Ed.*, 1999, **76** (4), 543.
30. J.J. Lagowski, *J. Chem. Ed.*, 1990, **67** (7), 541.
31. D. Hodson, *Journal of Curriculum Studies*, 1996, **82** (2), 115.
32. L.E. Raths, S.Wassermann, A. Jonas and A. Rothstein, *Teaching of thinking: theories, strategies and activities for the classroom*, Teacher College, Columbia University, New York, 1986.
33. C.E. Jones, *School Science Review*, 1970, **52** (178), 178.
34. A.Berry, P. Mulhall, R. Gunstone and J. Loughran, *Australian Science Teachers Journal*, 1999, **45** (1), 27.
35. A.H. Johnstone, *J. Chem. Ed.*, 1997, **74**(3), 262.
36. J. Solomon, *Studies in Science Education*, 1988, **15**, 103.
37. J.C. Wright, *J. Chem. Ed.*, 1996, **73** (9), 827.
38. A.M. Mackenzie, *Prescription for change: medical undergraduates' perceptions of learning in traditional and problem-based courses*. PhD thesis, University of Glasgow. 1999.
39. J. Carnduff and N. Reid *Enhancing Undergraduate Chemistry Laboratories: Pre- and post- laboratory exercises*, The Royal Society of Chemistry, London, 2001.
40. C.J. Garratt, *U. Chem. Ed.*, 1997, **1**,19.
41. *Scottish Certificate of Sixth Year Studies-Chemistry*. Scottish Examination Board (now Scottish Qualifications Authority), Dalkeith, 1970.
42. A.H. Johnstone and K M Letton, *Educ. Chem.*, 1991, **28** (3), 81.
43. B. Nicholls, *U. Chem. Ed.*, 1999, **3**, 22.
44. M. Pickering, *J. Chem. Ed.*, 1987, **64**, 521.

Preparing the Mind of the Learner – Part 2

Paper

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The effectiveness of pre-lectures has already been described in this journal.[1] This paper completes the story by describing the effect of new teaching materials for first year undergraduates, which were designed to mimic the pre-lecture. It is shown that these materials are able to enhance the performance of the less well-qualified students so that their performance in formal examinations does not differ from that of their more qualified colleagues.

Introduction

In 1968, Ausubel[2] made the comment: "*If I had to reduce all of educational psychology to just one principle, I would say this: the most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly.*" In a previous paper,[1] it was noted that this bold assertion was supported by several studies (Johnstone and Su,[3] Johnstone [4, 5]). In particular, a study that looked at pre-lectures has described in some detail the effects of pre-learning.[1]

A pre-lecture can be described as an activity carried out before a block of lectures, designed to ensure that the essential background knowledge is established and is accessible so that new learning can be built up on a sound foundation. A decision in the University of Glasgow to develop a new introductory course in chemistry provided an opportunity to introduce pre-lectures. These were subsequently discontinued. The effects of the pre-lectures have already been described in detail.[1] and later the opportunity arose to develop teaching materials that sought to mimic pre-lectures in many ways. The effect of the use of these materials is described here.

Students will come to lectures with a wide variety of background knowledge. In some cases, previous learning in chemistry may have led to an incomplete or incorrect grasp of concepts. For other students, ideas once known and understood may not have been used for many months, making it difficult to retrieve them from long-term memory. In order to allow effective learning, it is important to ensure that the background knowledge and understanding is not only present but stored in such a way that it is accessible and understood correctly. This is the basis for the idea of the pre-lecture.

The General Chemistry course

In 1993-94, a new course was introduced at the University of Glasgow. Previously, students studying chemistry at level 1 (of a Scottish four year degree) all followed the same course. With increasing numbers (typically between 600-800 every year over the past few years) and more diverse entry qualifications, two chemistry classes were formed. The mainstream class (Chemistry-1) continued to operate, while the smaller class (General Chemistry) was offered a course with a slight reduction of content. General Chemistry was aimed to meet the needs of students with a wide range of entry qualifications in chemistry. Success in either course allowed students to proceed on to Chemistry at level 2.

Students take three subjects in the first year and both classes, therefore, took about a third of the time-commitment of a first year student. The level of both courses was appropriate for students who had obtained a pass in Chemistry at Higher Grade in the Scottish Certificate of Education. However, the entry qualifications of the students in General Chemistry ranged from those who have passed Chemistry at the Scottish Higher Grade (occasionally, with a pass at the Scottish Certificate of Sixth Year Studies as well) to those who had indicated no formal chemistry qualification at all, their entry to the university being based on qualifications in other subjects. Surveys of students showed low levels of commitment and motivation because the majority were taking the course merely to fulfil Faculty requirements.

Pre-lectures operated for the first two years (1993-94, 1994-95) of the General Chemistry course. A pre-lecture can take many forms (see, for example, Kristine[6]). In the General Chemistry course, pre-lectures took the following form. Working in an ordinary lecture theatre, it involved a short multiple-choice test that sought to check on necessary background knowledge. The students marked this for themselves. The results provided them with some evidence about the level of their background knowledge and understanding. They were invited to see themselves as ‘needing help’ or ‘willing to offer help’; the latter group assisted the former to complete various tasks, working in pairs or trios.

In this way, support was available for the students in need of help to understand the background knowledge that would enable them to make sense of the lecture course to follow. Those able to offer help assisted in this process of teaching, and, by the very act of teaching others, they themselves were assisted in ensuring that ideas were grasped clearly and correctly. The lecturer, supported by demonstrators, was on hand to offer assistance as required.

After two years the pre-lectures, as described here, were discontinued but, as has already been shown,[1] the pre-lectures of this form had the effect of supporting selectively the less well qualified students so that final performance did not relate to entry qualification. Many other alternative explanations were explored but none was shown to account for this effect.

Performance and entry qualifications
Usually, performance in formal assessments reflects the quality of entry qualifications. This typical pattern can be illustrated (see Table 1) by looking at the Chemistry-1 class (the mainstream class). Students enter with qualifications at Higher Grade or Higher Grade along with the Certificate of Sixth Year Studies (CSYS).

Taking any of the five years, it is easily seen that performance in examinations (either in January or in June) relates very closely to entry qualification. The Chemistry-1 class never has had pre-lectures as described for the General Chemistry Class. It has already been demonstrated that the presence of pre-lectures with the General Chemistry class (1993-94 and 1994-95) removed this relationship between examination performance and entry qualification while, on the removal of the pre-lectures (1995-96, 1996-97, 1997-98), the relationship was re-established.1

The Chemorganisers
In session 1998-99, the opportunity arose to develop and test teaching materials that sought to copy the pre-lecture idea. These materials were called 'Chemorganisers’. The materials were designed to provide bridges between what the learner already knows and what is to be learned. They were designed to help the learner organise and retrieve material that had already been learned. They also sought to teach by filling the gaps and clearing areas of misconception.

The Chemorganisers were based particularly on ideas developed by Ausubel[2] in 1968 (preparing the mind for learning) and Johnstone[7] in 1993 (the information processing model with its overall insight into learning). The Chemorganisers were designed to fulfil three broad aims:

1) Enhancing the preparation of the mind for new learning by:
   (a) assisting students to recall important background information.
   (b) helping students to organise and relate new information to their previous knowledge.
   (c) clearing up misconceptions.
   (d) filling gaps.

2) Easing the load on the working memory space by:
   (a) presenting material in such a way as to minimise demands on working memory space.
   (b) teaching students how to break down complex areas into manageable amounts.
   (c) enabling students to see interconnections so that knowledge can be ’chunked'.[8]

Table 1: Chemistry-1 Students’ Performance with Entry Qualifications

Entry Qualification	Pass Grade	Average Mark for sessions									
		94/95		95/96		96/97		97/98		98/99	
		Jan	June	Jan	June	Jan	June	Jan	June	Jan	June
Certificate of Sixth Year Studies (CSYS)	A	77	77	81	82	84	81	87	89	90	85
	B	55	55	69	70	72	73	76	76	84	76
	C	38	40	59	64	65	60	68	66	68	62
	D	28	33	45	54	56	50	64	59	60	53
Scottish Higher Grade (H)	A	50	53	63	66	68	65	72	71	76	68
	B	31	38	48	54	51	51	59	55	63	55
	C	23	28	51	56	54	55	58	52	55	46

3 Changing attitudes towards learning by:
  (a) giving students the opportunity to reinforce understanding and increase their confidence.
  (b) enhancing motivation by providing students with summaries, related diagrams, and tables to be used for examination revision.
  (c) encouraging students to become aware of their own learning processes, and as far as possible, to be in control of them.

Some sixty Chemorganisers were developed, covering those topics that had been found previously (by means of scrutiny of examination scripts as well as extensive use of questionnaires) to be causing difficulties for students. Although apparently very different from pre-lectures, their underlying aim was to mimic pre-lectures in preparing the minds of learners.

Each Chemorganiser was designed to fit on to one A4 page in landscape orientation, making it easier for the students to see all the parts of the presentation at one time. The style, language and terminology were made consistent with the way individual lecturers presented the topics. Extensive use of variable typescript formats and shading was introduced to aid ease-of-use and to emphasise key points.

Each Chemorganiser started by introducing the topic or presenting the problem, followed by a list of the background information that the student would need (entitled: “Before You Start”). The topic was explained, often using an example, a general strategy was outlined and students were given opportunities to try out their skills, with answers provided. Although each Chemorganiser covered a single topic or idea, links between Chemorganisers were provided so that students could move from one to another logically or could move back to a previous one to clarify underlying ideas.

Each Chemorganiser was constructed with a clear single focus in mind. The aim was to reduce demands on “Working Memory Space” by minimising unnecessary ’noise’.[9] They also aimed to develop an idea and then allow students to apply it in an unthreatening way to build confidence and provide useful feedback. The format of the Chemorganisers is shown in Figure 1 with a complete example being shown in the Appendix. In the set of Chemorganisers, many covered very basic background knowledge, including mathematical knowledge, with ten in inorganic, twelve in physical, and twelve in organic chemistry. Five dealt with the mole and four with acids, bases and pH, all known areas of difficulty.

The Chemorganisers in use

The Chemorganisers were used by the General Chemistry students in two main ways:
Twelve of the Chemorganisers (mainly those with fundamental mathematical emphases such as logarithms) were used at the beginning of the academic year 1998/99. These twelve were used on three occasions, the classes being optional for students. At the beginning of each class, the appropriate Chemorganiser sheets were distributed by the staff member who asked the students to look at each sheet. A discussion session was then started by explaining the theoretical background behind each problem, ’Before you start‘, and then the worked example was worked through step by step. When students were satisfied that they understood the process, they were asked to try on their own (or with a partner) to solve the self-assessment question(s). In many ways, this use of the Chemorganisers directly reflects the way the former pre-lectures operated. The atmosphere was

Figure 1: The Chemorganisers

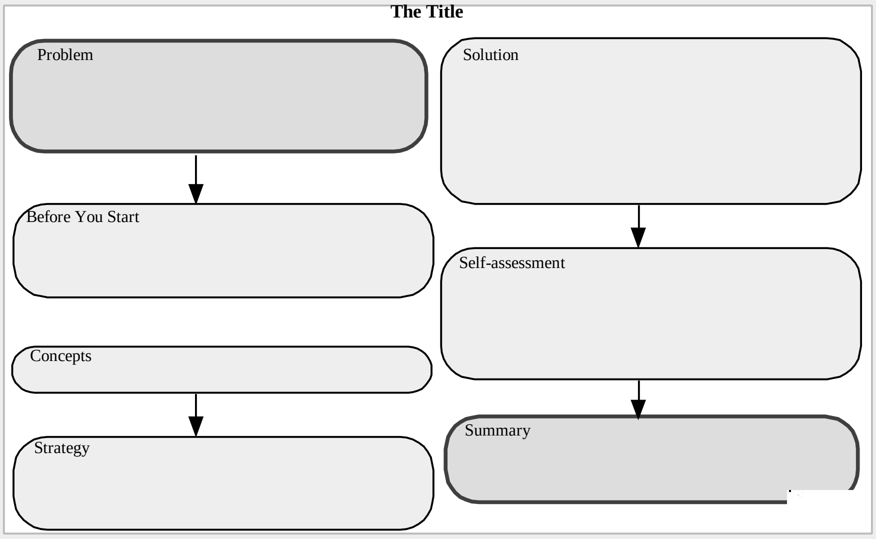

Table 2: **Results of Statistical Analysis of General Chemistry Students' Examination Performances Based on Chemistry Entry Qualifications**

Year	N	Exam	Average Marks			t-test	Mann-Whitney test
			Class	Upper	Lower		
1993/94	110	January	53.3	54.4	51.3	not sig.	not sig.
		June	47.3	47.4	46.3	not sig.	not sig.
1994/95	180	January	48.7	49.5	49.3	not sig.	not sig.
		June	48.6	48.8	48.6	not sig.	not sig.
1995/96	169	January	41.0	44.3	37.1	sig. at 0.1%	sig. at 1%
		June	45.2	49.4	40.3	sig. at 0.1%	sig. at 1%
1996/97	163	January	45.8	50.3	42.0	sig. at 1%	sig. at 1%
		June	43.4	46.1	41.9	not sig.	not sig.
1997/98	229	January	45.1	46.8	43.9	not sig.	not sig.
		June	43.2	46.6	38.7	sig. at 0.1%	sig. at 0.1%
1998/99	192	January	47.4	48.6	46.7	not sig.	not sig.
		June	49.4	50.9	48.6	not sig.	not sig.

unthreatening, involved no assessment and allowed students to be involved in cooperative learning.

The other Chemorganisers (the majority) were distributed at the beginning of the appropriate blocks of lectures. These contained relevant themes from inorganic, physical, and organic chemistry. They were offered to students throughout the course, but there was no pressure on students to take them, to use them, or to use them in a specific way.

Numerous observations were made throughout the course by means of questionnaires, sample interviews as well as informal communications with students during problem solving and laboratory sessions. These all indicated that the Chemorganisers were being used and were appreciated. However, in this paper, only the possible relationship between the use of the Chemorganisers and the performance in formal examinations is discussed in detail.

Examination performance

Students sit formal examinations in January and June as well as undertaking class tests at various stages throughout the year. The performance in the formal examinations is considered here. The General Chemistry class cannot be divided up into groups according to exact entry qualification because the diversity of entry qualification would make the groups too small for comparison purposes in any one year-group. Instead, following the analysis described previously,[1] the General Chemistry class was divided up into two groups.

Group 1: those with an upper level of qualification in chemistry (a pass at Scottish Higher Grade at "C" or better)

Group 2: those with a lower entry qualification in chemistry (less than a Scottish Higher Grade pass at "C").

The pattern of examination results is shown in Table 2. To check if the difference in performance between the upper and lower groups is statistically significant, two statistical tests were employed. The t-test assumes an approximation to normal distribution while the Mann-Whitney makes no such assumption. Both tests were employed since the actual mark distributions only roughly approximated to a normal distribution. However, the conclusions from both tests are identical. This shows that, in the first two years (when there were pre-lectures), there are no statistically significant differences between the two groups while, in the next three years (when such pre-lectures did not operate), the performance of the two groups was frequently different. In the final year when Chemorganisers were in use, the significant differences again disappeared.

Another way of looking at the data is to explore the *differences* in average performance between the two groups. This is shown in Table 3. This shows even more clearly that, in the middle three years when the pre-lectures were NOT operating, the differences in performance between the two groups are significant. The first two years (with pre-lectures) and the final year (with Chemorganisers) show no significant differences.

Finally, it is possible to explore subgroups by bringing together numbers from several years (to make comparisons possible). This is shown is Table 4. An inspection of the data again illustrates the way the pre-lectures (the first two years) and

Table 3: General Chemistry Main Groups Performances (Upper and Lower)

Year	Number of pre-lectures	% of Students		January			June			Average differences between Upper and Lower in January and June Exams
				Average Marks		Differences	Average Marks		Differences	
		Upper	Lower	Upper	Lower	Upper - Lower	Upper	Lower	Upper - Lower	
93/94	8	50.9	42.7	54.4	51.3	3.1	47.4	46.3	1.1	2.1
94/95	6	50.0	40.0	49.5	49.3	0.2	48.8	48.7	0.2	0.2
95/96	0	50.9	40.8	44.3	37.1	7.2*	49.4	40.3	9.2*	8.2*
96/97	0	43.2	48.4	50.3	47.0	8.3*	46.1	41.9	4.2	6.3¶
97/98	0	52	41.4	46.8	43.9	2.9	46.6	38.7	7.9*	5.4#
98/99	0	39.6	56.8	48.6	46.7	1.9	50.9	48.6	2.3	2.1

* These differences are significantly different (t-test, two-tailed, unrelated): $p<0.001$

¶ These differences are significantly different (t-test, two-tailed, unrelated): $p<0.01$

\# These differences are significantly different (t-test, two-tailed, unrelated): $p<0.05$

the Chemorganisers (the last year) bring about a different pattern of examination results when compared to the middle three years. The pattern of performance for the students who had entered with a Standard Grade pass is particularly interesting. These are students who had passed at Standard Grade (at about age 15-16) and had not taken Chemistry at the Higher Grade. It is clear that the pre-lectures and the Chemorganisers were working extremely effectively in 're-awakening' the chemistry of two years before and, perhaps, filling some of the gaps between what they had learned and what was needed to make sense of the university course. In this way, they were able to perform just as well as their better qualified peers in the examinations.

Conclusions

It is frequently an observation that curriculum interventions can affect most learners, with the favoured groups (usually the more able) gaining most. In this case, the less well qualified gained most. It can be argued that the better qualified had less need for the mind preparation that was offered through the Chemorganisers and, therefore, derived less benefit. Other observations did not suggest that any particular segment of the class was not using the Chemorganisers. Nonetheless, the observation of the less favoured group benefiting specifically from a curriculum intervention is unusual.

The importance of the idea of preparing the mind of the learner was first laid down by Ausubel.[2] Later, Johnstone[9] developed a predictive model in the specific context of science education. In applying this, it is clear that, in the idea of preparing the mind of the learner, there is a fundamental principle which can be turned into a practical reality: this brings benefits to those who are disadvantaged by their lack of previous experience of chemistry. The pre-lecture can be used in any course in Higher Education while the set of Chemorganisers may prove to be a useful resource to assist the hard-pressed university teacher when faced with classes where the background experience may be inadequate as a basis for success.

Acknowledgements

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Table 4: General Chemistry Sub-Groups' Performances

(a) The first two years (The presence of pre-lectures)

Group	1993/9			1994/9				Two years			
	N	January	June	N	January	June		N	January	June	Average
Higher	52	53.5	47.2	85	48.4	49.2		137	50.3	48.4	49.4
Standard	21	55.2	50.2	23	50.8	49.3		44	52.9	49.7	51.3
Alternative	16	50.3	42.7	28	50.5	50.7		44	50.4	47.3	48.9
None	10	44.5	44.1	21	46.1	45.2		31	45.6	44.9	45.2

(b) The intermediate three years (No pre-lectures)

Group	1995/9			1996/9			1997/9			Three years			
	N	January	June	N	January	June	N	January	June	N	January	June	Average
Higher	77	44.4	49.6	58	49.4	45.0	109	46.6	47.1	244	46.6	47.4	47.0
Standard	19	36.2	38.1	25	42.9	41.2	26	35.7	30.5	70	38.4	36.4	37.4
Alternative	22	37.6	42.0	23	41.0	40.0	18	49.8	42.2	63	43.1	41.4	42.3
None	13	31.4	39.7	17	42.3	47.3	26	44.5	41.2	56	40.8	42.9	41.9

(c) The last year (Introducing the Chemorganisers)

Group	1998/9					One year			
	N	January	June			N	January	June	Average
Higher	73	48.8	51.0			73	48.8	51.0	49.9
Standard	22	50.7	51.3			22	50.7	51.3	51.0
Alternative	37	43.3	48.6			37	43.3	48.6	46.0
None	19	45.0	50.8			19	45.0	50.8	47.9

Groups:

Higher:	The Higher Grade of the Scottish Qualifications Authority
Standard:	The Standard Grade of the Scottish Qualifications Authority
Alternative:	Qualifications based on SCOTVEC modules or Wider Access courses
None:	No formal chemistry qualification at all

References

1 G. Sirhan, C. Gray, A.H. Johnstone and N Reid, *U.Chem.Ed.*, 1999, **3**, 43.

2 D. Ausubel, *Educational Psychology: A Cognitive View*, Holt, Rinehart and Winston, New York, 1968.

3 A.H. Johnstone and W.Y. Su, *Educ.Chem.*, 1994, **81,** 75.

4 A.H. Johnstone, *J.Chem.Ed.*, 1984, **61,** 847.

5 A.H. Johnstone, *U.Chem.Ed.*, 1997, **1**, 8.

6 F.J. Kristine, *J.Chem.Ed.*, 1985, **62**, 509.

7 A.H. Johnstone, *J.Chem.Ed.*, 1993, **70**, 701.

8 G.D. Miller, *Psy.Rev.*, 1956, **63**, 81.

9 A.H. Johnstone and H. El-Banna, *Educ.Chem.*, 1986, **23**, 80.

Chemorganiser

The Mole and solutions

Problem

How many mL of 2 M H_2SO_4 will be required to neutralise 25 mL of 1 M NaOH?

Before you start

- * The millilitre (mL) is one thousandth of a litre: 1000mL = 1 litre
  If a solution contains 1 mole of dissolved material per litre it is said to be **Molar** solution and the symbol used is **M**. Thus a 2 M solution contains 2 moles per litre.
- * Neutralisation is complete when all the H^+(aq) of an acid have joined with exactly the same number of OH^-(aq) of an alkali:

$$2\ H^+\ (aq) + 2\ OH^-\ (aq) \longrightarrow 2\ H_2O\ (l)$$

- * The reaction of a strong acid with strong alkali (base) gives new material called a **salt**:

$$\underset{\text{acid}}{H_2SO_4} + \underset{\text{alkali (base)}}{2\ NaOH} \longrightarrow \underset{\textbf{a salt}}{Na_2SO_4} + \underset{\text{water}}{2\ H_2O}$$

Concepts

Strong acid, strong alkali (base), concentration, mole, neutralisation, salt, molar solution, molarity, neutralisation point

Strategy

(1) Imagine the alkali in a beaker: How many moles of OH^- in the beaker?
Number of moles OH^- = Volume (in litres) x Molarity x Number of OH^- in the formula

(2) Imagine the acid in a beaker: How many moles of H^+ in the beaker?
Number of moles H^+ = Volume (in litres) x Molarity x Number of H^+ in the formula

(3) When an acid neutralises an alkali. The number of H^+ = the number of OH^-

Solution

(1) Number of moles OH^- = Volume in litres x Molarity x Number of OH^- in the formula
= 25 ÷ 1000 L x 1 x 1 (i.e. 1 OH^- in NaOH)
= 0.025 moles OH^-

(2) Number of moles H^+ = Volume in litres x Molarity x Number of H^+ in the formula
Suppose that the volume of the acid is **V**
= (**V** ÷ 1000 L) x 2 x 2 (i.e. 2 H^+ in H_2SO_4)
= (0.004 **V**) Litres

(3) The number of H^+ = the number of OH^-
0.004 **V** = 0.025
V = 0.025 ÷ 0.004 = 0.00625 Litres = 6.25 mL

Thus: 6.25 mL volume of H_2SO_4 is needed.

Self-assessment

(a) What is the molarity of $Ca(OH)_2$ when 100 mL of it can be exactly neutralised by 12.5 mL of 0.50 M HCl ?

(b) 100 mL of 0.20 M HCl are placed in a flask. How many millilitres of 0.40 M NaOH are required to bring the solution to the neutralisation point

Summary

- * Number of Moles OH^- = Volume (L) x Molarity (mol L^{-1}) x Number of OH^-
- * Number of Moles H^+ = Volume (L) x Molarity (mol L^{-1}) x Number of H^+
- * In our problem above:

At neutralisation point,
Number of moles OH^- (alkali) = Number of moles H^+ (acid)
Therefore, V x M x number of OH^- = V x M x Number of H^+

Or, $\mathbf{V_1 \times M_1 \times P_1}$ **(alkali)** = $\mathbf{V_2 \times M_2 \times P_2}$ **(acid)**
[P stands for ***power*** (H^+ or OH^- per formula)]

Answers: (a) 0.031 M, (b) 50 mL

Proceedings

Who is asking the question?

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The perceived problem

To introduce the symposium, it is helpful to set the scene for the subsequent discussions of the main topic. Our theme is prompted in part by criticism aired in the press, Research Councils and learned societies that the skills of graduates in general, but here confined to chemists, may not match the expectations of employers. For example, in a recent DTI document,[1] the statements are made that "Companies we have consulted have said that our universities are failing to produce people with the right understanding of the fundamentals of chemistry, relevant practical experience, and basic skills upon which they can build."
"UK universities are not addressing the deficiencies of their intake."
"… an absence of 'core-skills' – communication, IT, numeracy/maths, and basic chemistry was a real concern across the [chemicals] industry, and needed to be addressed."

The changing scene

For the most part, such statements are anecdotal, and are often offered in ignorance of the profound changes which have taken place in secondary and tertiary education in the past two decades, which has seen the tertiary sector move from elitist to mass education. Some of the differences are summarised in Table I, where the situation in the 1960s is compared with that of the present day.

Against this background, it must be said that (again quoting from the DTI Chemicals Directorate),
"Employers now expect their new recruits to have higher levels of skills than their predecessors."
"There is an increasing demand from industry for graduates to have experience of a broader range of multidisciplinary skills. These are needed for problem-orientated team working which is becoming common in the workplace."
So, expectations are higher, resources lower, and entry qualifications probably poorer.

Given this move to a mass education, it is not surprising perhaps that the direct comparison between current graduates and those of yesteryear is difficult. We would be better engaged upon a definition of what skills we would see to be essential or desirable in today's chemistry graduates, recognising the breadth of provision within the university sector. This poses an immediate problem, since there seems to be little consensus about what these essential skills are; hence the title of this short piece.

Table 1 Changes in Higher Education Institutions

	1960s	**Present**
School qualification	GCE 'O' and 'A' level (elitist)	GCSE, A and AS level (wider participation)
Participation level	10% of age cohort	35% and rising
Number of universities	50 plus 45 polytechnics	95 universities
Alternatives	Good apprenticeship training, technician training	Technician training now replaced by graduate training
Outcome	40% Good degrees in Chemistry. Full employment, vigorous chemical industry, jobs for life	75% Good degrees in chemistry, changing pattern of employment, less security, changing chemical industry, rise of SMEs
Funding	Adequate	40% reduction in annual spend per capita in the last decade

Table 2 Employment destinations for chemistry graduates

Research (leading to a higher degree)	Academia Industry School teaching Other (government, finance, consulting)
Education	School teaching Other education
Technical	Production Sales Laboratory management
Non-specialist scientific	Management Sales Consulting
Non-scientific	Finance Communications IT Management Accountancy

What are the required skills?

To begin, we should consider who might be asking the question. The answer must include future employers, those professionals responsible for HEI provision and, importantly, the 'customer' students themselves. From a consideration of these, we may be able to distil 'core' skills that all graduates should have. Some major employment destinations for chemistry graduates are listed in Table 2.

It would not be surprising if different types of employment required a different balance of skills. What does the employment market want?

An 'ideal' chemistry graduate might have the following accomplishments:

- Superb academic understanding of all branches of the subject
- Ability to apply knowledge in problem solving; flexibility in problems to be tackled
- Very high competence in the laboratory
- Articulacy, excellence in verbal communication
- Numeracy, good IT skills
- Ability to write correct, precise English
- Foreign language skills
- Familiarity with 'team-working'

While all of these must be present to some extent, different employers will of course place different emphasis on various components of the mix. Thus, academics seeking research staff might emphasise the first three; industrial employers may place great emphasis on problem-solving and communication skills; SMEs might emphasise versatility; non-scientific employers would certainly emphasise problem-solving skills, literacy, numeracy and IT.

Core skills

All graduates in chemistry should have

- Academic competence; but this might be at a level different for a research market than for a non-research market or non-scientific market
- Laboratory skills
- Communication, IT skills
- Problem-solving abilities
- Numeracy, literacy

It is not my purpose here to debate what scientific material should be included in a 'core' chemistry course; this is for individual Departments and accreditation agencies, such as I.Chem.E. and RSC to determine. I would make the observation, however, that in my view we almost invariably include too much material. All HEIs now pay attention to 'transferable skills'; some do it in a diffuse manner by embedding them in teaching modules. It will be argued elsewhere[2] that explicit, dedicated provision should become the norm and at a level significantly higher than is currently the case in most institutions.

All the attributes of the 'ideal' graduate can be fostered to varying degrees in HEIs with, in my view, the exceptions of numeracy or mathematical ability and literacy, which ideally should have been acquired during secondary education. However, what is required at national level is the supply of a broad 'range' of employable chemistry graduates with a diversity of skills in recognition of their different employment destinations.

However, we must emphasise that whatever the prospects of employment for chemistry graduates, student motivation to study chemistry may be for quite other reasons, including genuine interest, even passion, for the subject. In identifying what any employer may want to see in graduates, we must never lose sight of the need to satisfy student client expectations in this regard, and also to recognise the opportunity a chemistry course offers of providing a general, sound education. The best of students wish to be ‘stretched’; the poorest want to learn how to achieve a qualification with least effort; the vast majority want stimulation and enhanced employment prospects.

Which way forward?

The nation must decide how best to produce this range of graduates. There are several possible models. At one extreme, individual HEIs may seek to supply one type of graduate aimed, say, at the research ‘market’, with others providing a different training. This diversity by institution may happen to some extent *de facto*, but the UK HE funding models do not promote it since financially all Departments are dependent upon relatively high-volume undergraduate teaching and research for survival. Given this situation, individual HEIs may satisfy student client requirements by offering a diversity of courses; and this necessarily leads to debate about the content, duration, and qualifications achieved. Most Departments now offer, some exclusively, an ‘enhanced’ degree course of four (sometimes five) years’ duration, leading to an M.Chem./M.Sc. qualification. While this is satisfying academically to many undergraduates, the courses are largely research oriented. Such courses may well become a requirement for graduates wishing to pursue a Ph.D. Given the large number of successful three-year B.Sc. degrees, some provision will be required for well-qualified B.Sc. graduates to progress to Ph.D., probably via M.Res. type courses. There has long been debate about the various options such as ‘2+2’and ‘3+1’ schemes. Suffice to say that there has not yet been a serious attempt by QAA or accreditation agencies to standardise qualifications, or by research councils to establish requirements for entry to higher degree programmes; nor have the Funding Councils really provided the financial framework for diversity of provision to be explored widely.

The changing markets for graduates, the financial pressures on student consumers of our courses, the decline in percentage terms of student numbers seeking entry to chemistry courses will all conspire to ensure that the nature of what we offer, and the methods used, will be constantly reviewed in coming years. Whatever changes are made at national or institutional level, we must never lose sight of the goal of providing our students with a challenging, enjoyable, rewarding experience which will be recognised as such by them, by future employers, and by ourselves.

References

1. *Learning and Skills Issues in the UK Chemicals Industry-A Competitiveness Study Report 1-Education-related issues (up to and including post-16students),* Chemicals Directorate, DTI [This is a recent internal DTI document with some limited external circulation, but it reflects views widely expressed in industry and elsewhere.]
2. P.D. Bailey, *U. Chem. Ed.*, 2001, **5**, 80 (the Nyholm Lecture).

Teaching chemists to think: from parrots to professionals

Proceedings

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There is a need in chemical education to provide students with open ended, creative problem solving activities. Problem solving case studies are being developed in order to provide students with a ‘real’ context to extend their knowledge of chemistry, to develop intellectual or ‘thinking’ skills and to practise a range of transferable skills. The case study described here is set within an environmental investigation of a river and the mechanics of delivery have been designed to be flexible, allowing it to be tailored to a particular course and lecturer. There may be no right or wrong answers and it has been designed to highlight a number of issues. The nature of the activities involved ensures that, in order to complete the case study, students must use a variety of subject specific and transferable skills.

Introduction

Employers have long been urging the Higher Education sector to produce graduates with a range of key skills that would make them more immediately effective in the world of work. Several reports[1, 2] have highlighted particularly communication skills, team working, numeracy, use of IT and learning to learn as highly desirable qualities in a graduate. This view has also been highlighted as being particularly important in a recent report by the LGC.[3] Following a comprehensive survey carried out by the LGC,[4] the report states that employers’ overwhelming concern was with the graduates’ ability to apply appropriate theory and laboratory techniques to practical problems. In particular, graduates should be able to evaluate a specific problem, identify appropriate theory, methods and techniques that can provide a cost-effective and reliable solution, and ensure that this solution is implemented in accordance with rigorous quality or regulatory regimes. Good interpersonal skills were identified as being crucial to allow analysts to work effectively in a team and to evaluate problems jointly with clients. Most if not all of these qualities would be highly regarded by any employer of science graduates; but, unfortunately, those employers questioned in the survey felt that very few graduates had them.

The Quality Assurance Agency’s recent initiatives all place an emphasis on these broader skills and capabilities. The subject benchmark statement for chemistry[5] quite specifically mentions transferable skills such as numeracy, team working, communication, and cognitive skills such as solving novel problems. Programme Specifications[6] also require academics to make the outcomes of programmes explicit in terms of what students should be able to do, rather than what they should know. The National Qualifications Framework[7] level descriptors for B.Sc. and M.Chem. emphasise problem solving and analytical evaluative skills. The evolution of Personal Development Plans and Progress Files[8] may make students more aware of their own skills profile and staff will have to integrate explicit skills-development opportunities within their courses.

So, in order to produce graduates who can operate in the workplace as professionals, we need to go much further than just ensuring that they have a sound knowledge of chemistry. We must produce graduates who can think critically, have an analytical approach, can interpret data and information, tackle unfamiliar and open-ended problems and apply all the chemical knowledge that they have acquired. In addition, the modern graduate must master a range of ‘professional’ or key skills. These include communication, team working skills, time management, information management, independent learning.

These requirements increase pressure on both academics and students. The expansion in the higher education system in recent years has not been matched by a similar increase in the numbers of prospective students applying to science departments. Whilst numbers in chemistry barely hold steady, the nature of the chemistry undergraduate intake has changed. The undergraduate population is not the homogeneous body it once was. As science becomes less attractive to students, a lower proportion of the more able ones enter our departments. As well as generally lower entry grades, students now choose more diverse A-level combinations, choose from a wide range of optional modules, and enter higher education via non-traditional routes. All this means that it is increasingly difficult to predict the starting level of any of our students at a time when, it might be argued, we expect them to learn much more.

The belief held by many chemistry academics, that students acquire intellectual and personal skills by a process of diffusion whilst 'doing' chemistry, is no longer sustainable. It may have been true in the past; but today's students, employers and regulatory bodies require such skills to be explicitly developed in an attempt to ensure that all graduates have them.

The Challenge

What is missing from the traditional approach to the chemistry curriculum that would enable students to develop these intellectual and personal skills and capabilities? We produce students with a sound knowledge base in chemistry, adequate laboratory skills and rudimentary problem solving skills. In order to enhance the qualities of the chemistry graduate we need to provide opportunities to develop advanced problem solving skills, a range of key skills, and an appreciation of the range of applications within which the professional chemist works.

Problem solving activities can provide the vehicle for achieving this. Students should begin to tackle unfamiliar and open-ended activities that allow some degree of flexibility and creativity.

Table 1 Classification of problems

TYPE	DATA	METHOD	GOAL
1	Complete	Familiar	Clear
2	Complete	Unfamiliar	Clear
3	Incomplete	Familiar	Clear
4	Complete	Familiar	Unclear
5	Incomplete	Unfamiliar	Clear
6	Complete	Unfamiliar	Unclear
7	Incomplete	Familiar	Unclear
8	Incomplete	Unfamiliar	Unclear

Johnstone[9] has categorised problem solving activities and identified their characteristics according to whether the problem is familiar, has well defined aims and has a complete data set. This is shown in Table 1. Most of the problems that students encounter during traditional chemistry teaching and learning activities are firmly rooted in Type 1 or Type 2. Consider for example questions of the kind: "Calculate the concentration of…", "Identify the compound from the following spectra…","Determine the order of the reaction of…" etc. There is a distinct lack of problems of the type that require students to do more than manipulate previously practised algorithms and methods.

An attempt was made to produce novel problems for chemistry undergraduates in the 1999 publication *A Question of Chemistry*.[10] In this book problems of several different types were presented. The categories used were: 'understanding argument', 'constructing argument', 'critical reading', 'using judgement', and 'reference trails'. The aim of the book was to develop critical thinking skills in students. The nature of the problems meant that their styles would be unfamiliar to most students as they were generally non-numerical, open-ended, and without a single correct solution. This approach means that students gain most benefit from using them when they work in small groups, and share opinions and ideas and develop strategies co-operatively.

An example of a problem from the 'using judgement' chapter is given here. It is based on the requirement to carry out a 'back of the envelope' calculation in order to obtain a rough answer that gives the student some insight into analytical processes and scale of analyses.

The proverbial expression 'looking for a needle in a haystack' might be used by scientists trying to detect or identify traces of compounds.

If there is one needle in a haystack, estimate its concentration in parts per 10^n *on a weight or volume basis.*

Suppose you made up a solution with a concentration of 'one needle per haystack'. What volume of the solution would contain a single molecule of solute?

Is the task of looking for a needle in a haystack comparable with using atomic absorption spectroscopy to detect a metal ion at a concentration below 1 ppb?

When problems of this type are used in classes of students, in addition to developing their range of thinking and problem solving skills, it is immediately obvious that other 'key' skills and competencies are being developed. The students have to formulate and defend ideas, communicate their ideas to each other clearly, and they have something to discuss for which they are entitled to hold and defend an opinion that may differ from that of the tutor. There is no longer a single correct answer, so students have to realise that answers are not always right or wrong.

Through using these problems from *A Question of Chemistry* for several years in many different situations and observing the students' responses, I have become convinced that the best way to address the skills development agenda is through problem solving activities. Those in *A Question of Chemistry* are fairly short, so they can be worked on within a tutorial session. If the problem-solving activities were extended so that they required students to learn some chemistry content in order to make progress and, if the problems were carefully developed, these should then stimulate students to expand their knowledge and develop a wide range of professional skills. If these problems are also set within a realistic context then they should also enable students to appreciate the range of applications of chemistry and enhance motivation and enthusiasm.

This reasoning has led to the development of problem solving case studies. Our model provides real problems that cannot be described as exercises. They are related to applications or real contexts, provide incomplete or excessive data, require independent learning, evaluation of data and information, and do not lead to a single 'correct' answer.

Case studies have a long history in many subject areas and their value within chemistry has long been recognised.[11, 12, 13]

A case study should:

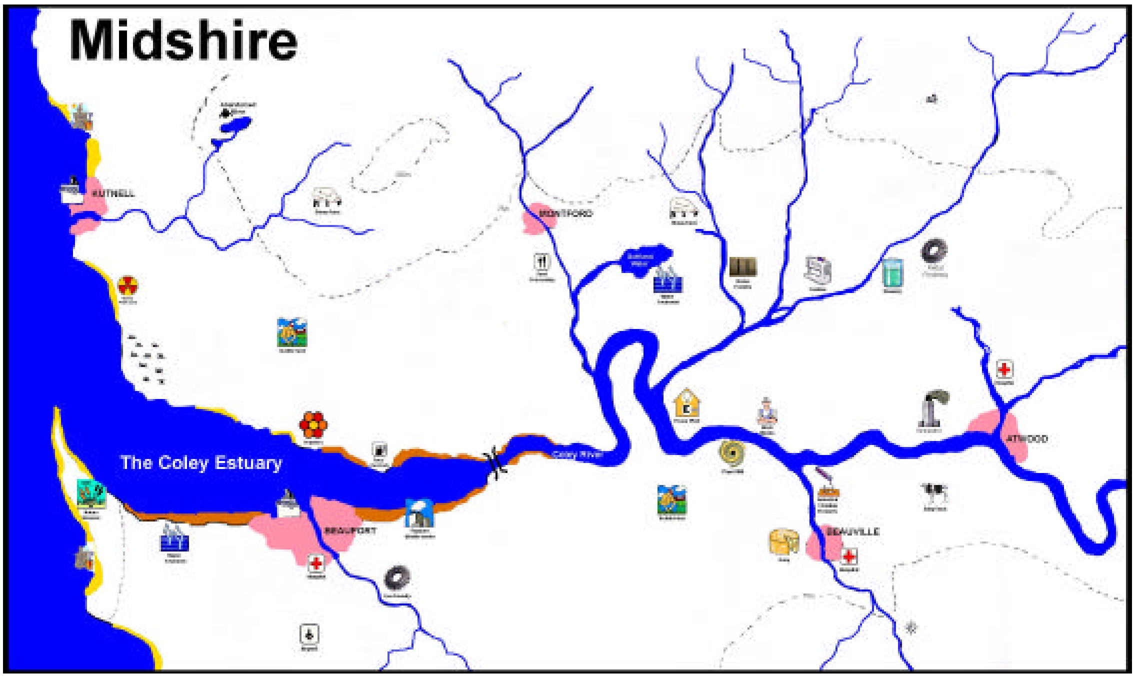
- involve the learning of chemistry either by building on and showing the relevance of prior learning, or by requiring students to learn independently in order to tackle the case
- be active in style
- involve a work-related context
- involve the development of personal skills
- encourage reflective learning
- have clear learning objectives for students

Chemistry is a discipline that provides many contexts for developing teaching and learning activities. We have chosen contexts within environmental, industrial, forensic, analytical and pharmaceutical chemistry to provide 'real' scenarios or case studies. Each requires students to work both individually and as part of a team to solve an extended problem. Each case study is flexible enough to be used in a variety of different teaching situations and each has been designed to encourage the development of different transferable skills. One such is described here.

Tales of the River Bank

This case study is set within the Coley River system in the fictitious county of Midshire (Figure 1). The river rises from springs in the limestone hills. The water in the upper reaches is clear; not until the tidal reach does the water become turbid. The river is navigable to just beyond the town of Atwood. The River Authority and the County Council led the clean-up of the previously heavily polluted river. The dumping of untreated industrial waste and sewage has been stopped. The building of new sewers and treatment works has meant that raw sewage should no longer get into the River Coley. It has in the last couple of decades once again become renowned for trout fishing.

Figure 1 Map of Midshire



The purpose of this case study is to produce a multi-layered problem that becomes more complex as the students proceed. To introduce it students are provided with copies of two letters: one from the chairman of the local angling club to the Environmental Agency complaining about his members' perception of a lack of fish in the river, and a copy of the reply from the Agency. The students are provided with a map of the area (Figure 1) and have to decide whether an investigation is required and, if so, how to proceed with it. The results of analyses of river water samples are provided or can be requested at various stages. Additionally, assistance is provided along the way in the form of briefing papers and exercises

The industries and land use are simplified compared with the complexity that would be found along a real river. If there is a problem with the water quality and fish stocks, the cause may or may not be identified, but the students should be able to consider all possible causes and suggest methods of remediation or preventative action.

Initially, students should identify a seasonal variation associated with nutrient runoff from the land that could cause problems. Further investigation should show a recent increase of conductivity due to an industrial effluent, and finally the presence of estrogens / phthalates should be considered. The students will have to consider whether any or all of these factors could have influenced fish stocks.

Table 2 Summary of chemical skills developed

Subject Specific Skills	
Technical Approach	Selecting appropriate analytical methods.
Knowledge	Environmental classification, chemical and biological indicators, water quality, sampling, pollution, toxicity, spectrophotometry, electrochemical testing.
Independent study	Background to analytical techniques, environmental science and remediation. Study of industrial processes and effluent streams.
Interdisciplinary skills	Analytical chemistry, environmental science, toxicology, ecology, geography, hydrology, etc.
Interpretative skills	Manipulation and evaluation of information and data to make realistic decisions on the evidence available.
Practical skills (Optional)	Instrumental manipulation, observation and recording.

Table 3 Summary of transferable skills developed

Key Transferable Skills	
Communication	Oral presentations to scientists and to other interested parties, report writing for different audiences.
Information retrieval	Collection and classification of information.
Personal	Individual judgement, taking responsibility for decision making, time management, working to deadlines.
Problem Solving	Tackling unfamiliar problems, using judgement, evaluating information, formulating hypotheses, analytical and critical thinking.
Team working	Brainstorming, discussion, division of tasks and reporting back to the group.

Tackling the problem

The students take the role of the investigation team. They must consider:

- Whether there is a problem
- What factors could cause the reduction in the fish stocks
- Where they should sample along the river
- What analyses should be carried out
- Whether the problem is due to organic or inorganic effluent
- Whether the problem is continuing, seasonal or recent
- Sources of the problem
- Possible remedial action

The class is organised into groups of three to six, with four being the optimum number. The groups are gradually supplied with information in the form of reports and briefing papers, and at various stages are invited to request analyses or carry out independent investigations. After gathering the final pieces of evidence and completing the required independent study, the students are expected to have identified what had caused the reduction in fish stocks.

The chemical topics and issues that the students have to cover are given in Table 2. In addition, the professional skills that should be used in order to complete the case study successfully are outlined in Table 3.

The case study can be tackled over two 2-hour workshops or over four one-hour sessions with about eight hours of additional student study time. The project comprises several short tasks so it is inherently flexible. Its background material includes a number of briefing papers and exercises that can be used to help students with varying backgrounds. The overall structure for two teaching sessions is shown in Table 4.

Students are provided with information from Environmental Agency monitoring stations along the river. This includes longitudinal data on COD, BOD (which indicate the amount of organic matter present), dissolved oxygen and ammonia. This information, together with the relevant briefing paper, allows them to consider the quality of the water along the river. They should be able to identify a seasonal variation between two sampling points, indicating agricultural runoff. Students can request more recent data that indicates that there is currently no problem with dissolved oxygen and nitrogen levels but that there is high conductivity, indicating inorganic pollutants and the possibility of a problem originating at one of the industrial or

Table 4 Timetable for two 2-hour workshops

Session 1a	Overall aims of the case study are described. Students are divided into groups. The letters from the Angling Association and the Midshire River Authority are given out. The Midshire map with the accompanying information about the ColeyValley describes the area and associated industries. The briefing paper on river quality is given out.
Task 1	To consider the industries and other potential sources of pollution down the Coley Valley. The water quality exercise is used to bring the students' attention to the aspects of water quality.
Session 1b	Students are given analytical data from four Environmental Agency sampling points.
Task 2	Discuss whether there is a real problem. (If they decide that there isn't one, they have to justify that decision.) Decide how they would narrow down their search. Discuss possible sources of the problem. Plan sampling exercise to highlight issues related to sampling in various conditions.
Session 2a	Students are handed larger scale map of area between Coley Bridge and Atwood with possible additional sampling points marked.
Task 3	Choose two additional sampling points, request analysis. Given the results on result cards. After discussion, request analysis from two further points along river. Consider the industrial and commercial activities along the river and identify potential sources of pollution.
Session 2b	Groups may request analysis of fish and are given the fish autopsy results. Students given briefing paper on toxic substances.
Task 4	Request further chemical analysis; receive results. Decide on source of problem. Discuss remediation, prevention. Prepare an oral presentation and / or reports.

commercial enterprises along the riverbank. Careful further sampling should enable them to narrow down the problem area. Students must then survey all the relevant industries and activities to ascertain the nature and source of possible effluents. They may then request chemical analyses from their chosen sampling points. The number of allowed sample points and analyses is strictly limited in order to encourage the students to think carefully and critically about the requests they make. This restriction may be justified to the students on grounds of ‘cost’. If they request the correct analyte and method they will receive meaningful results, which should enable them to identify the source of the second problem. If students are unsuccessful at this stage they may be prompted by the tutor or allowed to make additional requests.

Additional support on specialised areas such as water quality is provided in the form of briefing papers. Additional exercises can be run within the case study to emphasise particular topics, such as sampling.

Assessment

A case study may be assessed in a variety of ways and the chosen method may depend upon how the it is being used. The activity has been trialled with students on analytical chemistry, environmental science and professional skills modules; and the assessment focus differed in each case. For example, for an analytical module the focus may be on using the correct analytical technique and solving the problem effectively. For a skills-based module the focus may be on effective group work and the quality of oral presentations. Assessment tools which have been successfully used include oral presentations to other scientists, oral presentations to a lay audience, written reports, summaries of data collected, peer assessment of group participation, and individual reflection on skills development.

Observations

The case study has been piloted with students on analytical chemistry and environmental science modules at three institutions. Student feedback on these activities has been very positive. Feedback questionnaires provided evidence that the students realised that they had developed a range of skills during the activity (Table 5)

Table 5 Feedback from Students

Do you feel you have developed any of the following skills? (scale: 1 = not at all, 5 = a lot)	Score
solving unfamiliar problems	3.8
working with others	4.0
thinking logically/critically	4.0
using judgement	4.0
forming and defending arguments	4.0
communicating your ideas	3.9
link between theory & practice	3.7

The case study presented a very new and different way of working for all these students and they required some support to encourage them to take the activity seriously. They showed a tendency to believe that they would be given meaningful results even if they had not asked the right questions. They also had to be encouraged to take the independent learning aspect seriously and accept that it was an integral part of the exercise. The students recognised that the outcome of the study was that they had practised a range of skills and had gained a grasp of analytical and environmental science. Their enthusiasm increased throughout the project as they became more involved in the decision-making processes. Ensuring that the exercise is properly assessed and counts toward the module helps in overcoming the students’ initial reluctance to work outside the classroom sessions.

The case study achieved the initial objective of using problem solving to develop knowledge and skills. The study presented students with an open-ended, unfamiliar problem for which there was no single correct solution. They had to use a range of skills in order to achieve a satisfactory outcome, and the applied, realistic context engendered enthusiasm and engagement with the problem.

Other case studies

We are currently developing a suite of problem solving case studies, each with a focus on analytical science whilst utilising contexts within environmental, forensic, industrial and pharmaceutical chemistry. They will be suitable for use at levels 1, 2 and 3 and will cover a range of analytical science and a broad range of transferable skills. Those currently being developed include scenarios such as a suspicious death, smuggling of illicit drugs, pharmaceutical preparation, industrial processes, validation of analytical measurements, setting up a laboratory, and land reclamation.

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References

1. *Skills for Graduates in the 21st Century*, The Association of Graduate Employers, Cambridge, 1995.
2. E. Finer, *Chemistry in Britain*, 1996, **32** (10), 3.
3. J. Fleming, M. Sargent and V. Singleton, *Chemistry in Britain*, 1994, **30**, (1) 29.
4. L. Milgrom, *Chemistry in Britain*, 1993, **29**, 949.
5. http://www.qaa.ac.uk/crntwork/benchmark/chemistry.pdf
6. http://www.qaa.ac.uk/crntwork/progspec/contents.htm
7. http://www.qaa.ac.uk/crntwork/nqf/nqf.htm
8. http://www.qaa.ac.uk/crntwork/progfileHE/contents.htm
9. A.H. Johnstone in C.A. Wood (ed.), *Creative Problem Solving in Chemistry*, Royal Society of Chemistry, London, 1993.
10. J. Garratt, T. Overton and T. Threlfall, *A Question of Chemistry*, Pearson Education, Harlow, 1999.
11. C.J. Garratt and B.J.H. Mattinson, *Education, Industry and Technology*, Pergamon Press, 1987.
12. J.A. Pontin, E. Arico, J. Pitoscio Filo, P.W. Tiedeman, R. Isuyama and G.C. Fettis, *J. Chem. Ed.*, 1993, **72**, 525.
13. S.T. Belt and L Phipps, *U. Chem. Ed.*, 1998, **2**, 16.

Can problem solving be taught?

Proceedings

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Introduction

There has been a strong movement over the past few years to consider Transferable Skills as part of the education process at all levels. Among these skills Problem Solving has had a prominent part; but is Problem Solving a Transferable Skill and can it be taught?

It could be argued that all human beings exist because they are already competent problem solvers. Daily we solve quite complex problems such as crossing a busy road, driving a car, feeding a family and maintaining a home with all its interpersonal and practical needs. From time to time we deal with difficult problems such as buying a house, moving house, planning a vacation, changing career or choosing a course of study. Despite occasional mistakes, people on the whole are pretty good problem solvers and survivors. The range of problems we can tackle is remarkably wide.

However, in the academic sphere, we complain that our students are poor problem solvers. Presumably we mean that they are not good at solving *our* kind of problems. This points up the fact that problem solving is very context dependent. A person who can solve complex everyday problems may seem to be hopeless when confronted with a chemistry problem even though the basic thinking processes may be very similar.

The nature of problems

Before we go any further in our attempt to answer the question that is the title for this paper, we need to look more closely at the nature of problems. They can be thought of as having three parts: some starting information, a goal or desired outcome, and a method of getting from where we are to where we want to be. If one or more of these three components is missing or incomplete or fuzzy, we have a problem. To clear our minds, we can set up a classification of problems as shown in Table 1.[1] There are eight possible permutations of the three components of a problem, but the first of these is not really a problem if we accept the definition above, that one component must be missing or incomplete to constitute a problem.

Table 1 Classification of problems

TYPE	DATA	METHOD	GOAL
1	Complete	Familiar	Clear
2	Complete	Unfamiliar	Clear
3	Incomplete	Familiar	Clear
4	Complete	Familiar	Unclear
5	Incomplete	Unfamiliar	Clear
6	Complete	Unfamiliar	Unclear
7	Incomplete	Familiar	Unclear
8	Incomplete	Unfamiliar	Unclear

However, the situation designated as Type 1 is what **we** commonly call a problem. Many academic ‘problems’ are of this kind: all the necessary data is given, the method is familiar, and the goal is explicitly stated. Standard stoichiometric problems, physical chemistry exercises in thermodynamics and kinetics, synthetic pathways in organic and inorganic chemistry and general spectroscopic questions tend to be of Type 1. They are algorithmic, following well-trodden paths, using familiar formulae and common mathematical techniques. Students, with practice, should be able to solve these, but often fail to do so. In almost every case an explanation for this failure can be found in information overload, which has been discussed elsewhere.[2]

Let us return to the other seven types of problem set out in Table 1. In each case something is missing or incomplete and the solver is obliged to recognise what is missing and to find some way of supplying it. This involves skills that require insight and an ability to see things in new ways. A degree of creativity is needed to tackle these successfully.

Problem-solving strategies

Coming back to the title of this paper, it is recognised that problem solving as applied to Type 1 situations can indeed be taught by routines repeated many times. However, for the other seven types, the answer to the question is much less clear. When we move into the realm of insight and creativity, we are unable to reduce the problem solving process to any kind of routine. There are general principles that can be applied to turn the problems into a form which make the application of insight easier, but which do not, in themselves, provide the solutions.

Here is an example of the advice given by an examination board to its high school chemistry pupils who are about to do a practical project.

> Make sure you understand what is wanted
> Plan the route
> Carry out the plan
> Check that the result is reasonable

This is all good advice for tackling the problem, but it does not really provide the solution! Problem solving can be thought of as filling gaps between 'certainties'. We can teach ways of narrowing the gap, but I am sure that we cannot teach the last step: the bridging of the gap. This last step needs knowledge (both know-what and know-how), experience, confidence, and the mental flexibility to 'see' new things.

Let us look at the gap-reducing techniques that are teachable.

Knowledge has to be in place because problem solving is very context dependent.

Let the mind 'hang loose'. If you are getting nowhere in one channel, take a break and look for another approach. Brainstorming in a group is just this.

Break down the field that may lead you into a fixed way of thinking by pulling the problem apart. This removes distracting things and reduces the load on mental Working Space.[3]

If possible make your problem visible by converting words into pictures, diagrams or graphs. (This is recognising that most of us are visual thinkers.)

Work *backwards* from the goal, if need be. At the end, go back over how you did it to establish and reinforce any new technique you may have 'invented'. This will also confirm new linkages you have made in your mind. It is possible to illustrate these guidelines by use of crossword clues. The structure of cryptic clues is that they have two parts, each of which supports or confirms the other. With that in mind, let us look at some mini-problems provided by crossword clues.

Find rare new frequencies below the visible range (8 letters)

Since clues have two complementary parts, it is necessary to find where the clue splits. This one divides into 'find rare new' and 'frequencies below the visible range'. Chemists will *know* (importance of knowledge in problem solving) that frequencies below the visible are infrared or below. Can the other half of the clue clinch the answer? 'Find rare' can be rearranged to give INFRARED and so the problem is solved. Finding an anagram is made easier if the present order of the letters (the field) is broken down to help new associations to be formed. For example,

FIND RARE written as
F I
N R
A R
E D

makes it easier to see new arrangements because the original sense has been removed.
This simple example has illustrated three principles of problem solving: break the problem down; break the 'linear field' to allow for new associations; apply existing knowledge.

Let us look at a few more clues to illustrate other points.

Hide from an aquatic creature (8 letters)

The way it is presented is trying to mislead with the word 'hide'. The mind has to explore possible meanings: 'hide' to 'conceal' or 'hide' is 'skin'. The solution of this one depends upon other cross clues and the fact that 8 letters are required. In other words, data is missing and has to be found in other ways. This involves working backwards from the requirement of 8 letters. The answer is SEALSKIN.

Follows orders, orders about the end of day (5 letters)
This breaks at the comma. ‘Follows orders’ can be OBEYS. Is this confirmed by the second part of the clue, ‘orders about the end of day’? Here we have to let the mind ‘hang loose’ to explore the word ‘orders’. Orders can be decorations, medals, etc. The end of ‘day’ can be ‘night’ or just the letter ‘y’. Decorations can be O.B.E.-s, and adding in ‘y’ we get OBEYS. This confirms our previous deduction from the first half of the clue and fits the requirement for 5 letters.

Again basic problem solving techniques are illustrated: divide the information, use knowledge, look for the unusual, and finally use the evidence to corroborate.

One last clue shows how easily the mind can become stuck in one channel.

Man on board has right to consume seafood (5 letters)
‘Seafood’ and ‘on board’ have a nautical link, which may be misleading. What seafoods do we know with 5 letters? ‘Prawn’ is a possibility. Does it fit with the first part of the clue ‘man on board has right’? Is there any other way of thinking of ‘man on board’? It could be a ‘piece in a board game’: a PAWN. Include R to stand for ‘right’ and we have PRAWN. This solution has drawn on knowledge, on the ability to think laterally and on breaking out of the obvious association and looking for something new.

Now let us apply these ideas to some chemical examples.

Given that it shows two signals in NMR, what is the structure of SF_4?
What additional information would you need to be able to decide between the various possibilities?

This is a problem of Type 3, in which the data are incomplete. Students seeing the formula SF_4 might be misled into thinking of tetrahedral, square planar or square pyramidal structures. However, the other part of the clue (two NMR signals) does not fit with any of these. This needs a new thought. Does a Gillespie-Nyholm (VSEPR) approach help? Sulfur has six outer electrons and each fluorine provides an electron, giving a total of ten (or five pairs). This leads to a trigonal bipyramid with four bonding pairs and one lone pair. But how are they arranged round the sulfur? If three bonding pairs are equatorial and one is axial, we would get two signals with intensity ratios of three to one. If, however, two were equatorial and two axial, we would get two signals of equal intensity. This is the missing part: are the signals of equal intensity or not?

This is parallel to the thinking involved in the crossword clues. Readers might have found the crossword examples uncomfortable even though their structures and problem solving requirements were very similar to chemical examples. This serves to illustrate the context dependence of problem solving and the difficulty of transferring problem solving skills.

The supervisor leaves a note for his student to keep the reaction mixture at a certain temperature. The student phones him to ask if it is Fahrenheit or Centigrade and the supervisor says it doesn’t matter. What is the temperature?

This was given to a class of eighty final year honours students, but fewer than ten were able to solve it completely. The responses were interesting in that they threw light on the different problem solving strategies used. They all recognised that there must be a temperature that is the same on both scales. Most said that there was a formula linking the scales, but that they could not remember it. The problem was therefore impossible to solve.

A few recalled the formula and solved the simple algebra. Some remembered the fixed-point values for the boiling and freezing points of water, but could go no further. Very few used this information to draw a graph and find the equivalence point of the two scales. Some recognised the lack of data and suggested a method if the data had been available, but these were in the minority. By far the majority tried to solve it as a Type 1 problem, but finding that the data (given or recalled) was missing, they just gave up.

How does your knowledge of hard and soft acids and bases help to explain the composition of seawater and of sedimentary rocks?

This problem was set following a course on bioinorganic chemistry. It required a reorganisation of knowledge, allowing the mind to ‘hang loose’. Water had to be recognised as a hard base that would complex readily with hard acids from the ions in columns 1 and 2 of the Periodic Table. Carbonate ion was a competing hard base for ions such as Ca^{2+} and so on. Students whose knowledge was in a set of ‘mental boxes’ could make little of a question like this because they could not (or had not been shown how to) break down the field and change the context.

The organisation of knowledge

All these examples demonstrate the fact that problem solving often depends upon knowledge and experience laid down in memory in such a way as to allow new connections to be made. In contrast, much student learning is laid down either unattached to existing knowledge, or linearly or in a single context.

As an external examiner I interviewed a young lady who was analysing soap powders for their phosphate content. She chatted about tripolyphosphates and the fact that she had to boil them up in the first stage of her analysis. However, she had not seen the significance of the ‘tripoly-’ prefix. She thought that polymers occurred only in organic chemistry and could make no attempt to suggest a structure, although she had found the formula for the ion in a book. The boiling process did not link with hydrolysis in her mind. She then told me about doing a reaction with a molybdenum compound to get a coloured solution, but had not made any connection with the transition metal chemistry she had done. There was no recognition that a phosphate ion might be a ligand attached to a transition metal ion to give a coloured complex. The use of the Lambert-Beer Law in the photometric measurements that followed was in yet another detached box.

In my experience this case is not atypical. This student had a lot of knowledge, but it was stored in sealed boxes and so was not in a free enough state to allow for the creation of new configurations in new contexts. The way she had laid down her knowledge was firmly bound into fixed contexts. During the interview she constantly expressed surprise, and even pleasure, as she saw the new connections and saw her knowledge coming together. This may happen spontaneously for some students, but it could be facilitated by the way we teach.

I have been advocating pre-learning for a long time.[4] Pre-labs and pre-lectures are an ideal way to help students to see new connections by showing how their existing knowledge is going to help them to learn the new knowledge by forming new linkages. Post-labs and post-lectures serve the purpose of making sure that new linkages are evident and have been established in the minds of the students.

Knowledge laid down linearly can normally be accessed in that form only. The alphabet, and the sequence and electronic configuration of the first row transition elements are examples of linear learning. ‘Boxed’ learning is bound within itself and in a given context. Most teachers will have seen examples of student inability to transfer a well-known mathematical technique to a chemistry problem. Teachers have the responsibility not only to provide what to learn, but to help their students to revisit the same learning in different contexts and to make the linkages explicit. This is the essence of problem-based learning, which is being used to such good effect in medical schools. The branched learning that is needed for efficient problem solving can (but seldom does) happen spontaneously. In the same way as we do not leave students to find out all the content of a course for themselves but present what has to be learned, so also do we need to make a systematic effort to help students to form links between units of content.

Concluding thoughts

Returning to the question posed in the title of this paper, can problem solving be taught?

- We **can** teach techniques that will help to organise the problem solving process.
- We **can** help students to store and organise their knowledge in such a way as to facilitate problem solving.
- We **cannot** teach insight, which is the ultimate key to real problem solving.

How then have we, as teachers, become good problem solvers? How have we moved from stumbling novices to become experts?

Several studies in different disciplines have concluded that it takes about 10,000 hours of study and practice for a novice to become an expert and then only so in one narrow field.[5] Expertise in one field does not automatically transfer to another field unless it is very close. Transfer to other more distant fields is very poor as a generalised skill. There may be fairly good transfer between academic and industrial chemistry, less transfer between chemistry and biology and very poor transfer into everyday problem solving situations.

10,000 hours of study and experience is much longer than any undergraduate course, and so we should not be too surprised when our students lack expertise. We, as experts, have had the benefit of a long time to achieve our expertise and have had the luxury of developing it in some relatively narrow part of chemistry. We expect undergraduates to show expertise across the discipline during their undergraduate period, an expertise that we ourselves do not have! It is worth recalling how much we had to learn when we began to teach. This might provide us with a more realistic expectation of our students' problem solving abilities. It may be that, within our own narrow slot in a discipline, we have met clusters of similar problems so often that they have been reduced to Type 1 *for us* and no longer constitute a problem.

References

1 A.H. Johnstone, in *Creative Problem Solving,* C.A. Wood, Royal Society of Chemistry, London, 1993.
2 A.H. Johnstone, *U. Chem. Ed.,*1997, **1,** 8.
3 A.H. Johnstone, *U. Chem. Ed.,* 2000, **4,** 32.
4 G. Sirhan, C. Gray, A.H. Johnstone and N. Reid, *U. Chem. Ed.,* 1999, **3**, 43.
5 J.R. Hayes *The complete problem solver (2nd ed.),* Lawrence Erlbaum, Hillsdale NJ, 1988.

Proceedings

Experimental design – can it be taught or learned?

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Introduction

Do we teach our chemists the skills they need? This symposium seeks to address this question. We fear that the position has not changed much since one of us concluded that "we should put less emphasis on the teaching of chemistry and more emphasis on learning how to be chemists; because being a chemist involves knowing chemistry, but knowing chemistry does not make you a chemist."[1]
In the context of this symposium we would also add that it really doesn't matter who is asking the question, since learning to be a chemist is one of the best ways of developing the skills needed for almost any role in life.

One of the reasons for this is found in Nyholm's phrase of 'learning **through** chemistry'. A particular benefit of a scientific education is that it provides opportunities to learn to approach problems in a scientific way. What this means is discussed more by philosophers than by scientists. Black, for example, in his book *Critical Thinking*,[2] argued that there **is** something that is properly described as the scientific method, but recognised that it has never been satisfactorily defined. Medawar was one of the few practising scientists who said anything useful about the scientific method. Amongst other perceptive comments, he wrote, "Science, broadly considered, is incomparably the most successful enterprise human beings have ever engaged upon; yet the methodology that has presumably made it so, when propounded by learned laymen, is not attended to by scientists, and when propounded by scientists is a misrepresentation of what they do."[3] In spite of this rather negative comment, he later concluded that "even if it were never possible to formulate **the** scientific method, scientific methodology, as a discipline, would still have a number of distinctive and important functions to perform." We agree with the view that there may be no such thing as **the** scientific method, and accordingly we offer the following definition: "Scientific method consists of an amalgam of generic thinking skills combined and weighted appropriately to reflect the ethos of a particular discipline".[4] This definition indicates our belief that there is no **single** approach to investigations which can be described as **the** scientific method, and that the details of the scientific approach depend on the context. However, there is no doubt that an ability to handle experimental error is an important part of at least some aspects of the scientific approach to investigations. We also propose one universal principle of scientific method; it is that 'Doing an experiment is the last resort of the scientist who has nothing left to think about'. We will try to justify this in posing, as our own version of the title of the symposium, the question 'Do we teach chemists enough about the methodology of science?'

Misconceptions with the language of error

The chemistry Benchmarking Document[5] gives as one of the Practical-Related Skills which chemistry graduates are expected to acquire "the ability to interpret data derived from laboratory observations and measurements in terms of their significance and the theory underlying them".

We have become aware that many first-year chemistry students have misconceptions that would be a severe barrier to the development of these skills.[6] We asked first-year students, as part of their lab report, to
"Write a paragraph summarising the reasons for drawing a straight line through data using an objective rather than a subjective method."
Rather more than half of our 65 respondents gave as a reason for using an objective method (such as least mean squares regression) that it would increase the **accuracy** of their results. With hindsight we can see that this misconception almost certainly arose from the conventional use of the phrase 'line of best fit'. For a student drilled to accept the importance of accuracy, it seemed natural to associate 'best' with 'most accurate'.

In an attempt to investigate the extent of these misconceptions, we asked our first-year students to provide written answers to a set of questions. Our conclusions have recently been published.[7] The questions we asked included the following:

1. An analytical procedure needs to be *precise* and *accurate*. How would you investigate how well a procedure meets these criteria?

2. Under what circumstances would you describe a difference between two values as *significant*?

3. Can a *qualitative* procedure prove that a constituent is absent from a substance?

In the written preamble to the questions we made the point that
"The purpose of this exercise is to give you an opportunity to think about and explain or describe how **you** would use, in a scientific context, some words which have both a technical and a general meaning. Remember that the questions are asking what **you** think; they are not asking for the 'correct' answer; (in a sense there is **no** single correct answer, since the meaning may vary with the context)."
This message was reinforced in a short explanatory talk.

We assigned all the responses to one of two categories: those that showed 'some or good understanding', and those that showed 'little or no understanding'. We tried to be generous with our evaluation, and in particular to give credit to responses that showed some understanding, even though they did not meet the requirement of describing how each respondent would **use** the words in question. In spite of our wish to be generous, when we looked at the answers to questions on the investigation of accuracy and precision, we were only able to assign 'some or good understanding' to well under half the responses.

Writing about significant differences, most respondents mentioned the size of the difference as being important, but none gave any indication that they understood that high levels of variation between replicate values (low precision) makes it hard to detect differences in mean values.

Figure 1

When it came to qualitative procedures, only 18% recognised the limitation that you cannot prove that something is **absent**, but only that it is below the level of detection. Lawrence's cartoon (**Figure 1**) taken from *A Question of Chemistry*[8] makes the point succinctly and memorably.

As we have described,[7] the student responses to these and other questions confirmed our view that first-year chemistry students would benefit from a considerably better understanding of the language used to deal with error and uncertainty in quantitative measurement. It may be that by the time the students graduate they will have picked up a good understanding of the language and the procedures, but we fear that they do not have much opportunity to do so. We have little confidence that general textbooks covering this topic do so in a way which deals with the problems faced by students trying to understand how to treat error and uncertainty. Take the word 'accuracy', for example; most books **define** it as something like 'closeness to the true value'. Of course that is what it **means**, but as an explanation it comes close to what Coldstream has called "colluding in a spoon-feeding process".[9] As a definition it is perfectly acceptable for all those students who are still living in Stage 1 of Perry's stages of intellectual development,[10] which has been paraphrased as 'Right answers to everything exist, and these are known to authority whose role it is to teach them'. The definition completely misses the point that, if you know what the true value is, you do not need to measure it. Given that you measure something in order to establish what the answer is, the important question is 'How can you know whether your result is accurate?' So, knowing what accuracy **means** is only the first (and tiny) step in being able to use the word effectively. Similar criticisms apply to other textbook definitions; they are not helpful in an operational world. Furthermore, anecdotal evidence suggests that there is no consensus amongst academics either about the correct usage of words and concepts to describe uncertainty in data, or in the best procedures available for interpreting experimental data. We are thus led to the conclusion that there is a need for much careful thought about the best ways to meet the Benchmark objective relating to data interpretation.

Scientific method in the design of investigations

The Benchmarking document also includes as one of the skills needed by graduate chemists "competence in planning, design, and execution of practical investigations". Of course an understanding of error is a key part of this – at least insofar as we are talking about quantitative chemistry, since the planning process involves thinking about the way the data will be processed.

Planning an experimental design that has the best chance of illuminating the research topic is one of the many things one has to do before the last resort of doing an experiment. But most students only think about errors when they come to write their lab reports **after** they have collected their data. We now report some previously unpublished results that illustrate some of the benefits of not doing an experiment before thinking carefully about the question being investigated and about the best way to collect data that is most likely to provide a definitive answer.

Working in conjunction with Millar,[11] we used our computer simulation pendulumLAB; this allows users to investigate the effect on the dependent variable ‘time of a pendulum swing’ of the independent variables ‘length of the string’, ‘mass of bob’, and ‘angle to which the bob is raised’. As part of a larger study we invited experienced academics to carry out a simulated investigation using pendulumLAB. The complete study involved school pupils aged about 14 and first-year university students who used pendulumLAB and several other simulations. Here we report the results obtained by the volunteer academic scientists.

Before starting the exercise, all 15 volunteers were asked to predict the effects of the variables. We regard this as good practice even though, in some investigations, there may be too many possible outcomes for any prediction to be useful. We do not accept that it is ‘unscientific’ to try to predict the likely outcome of an experiment, because prediction is a useful way to focus on possible outcomes and so to plan a strategy that is likely to distinguish between them. Of course, any such prediction must be followed up by observation; otherwise one ends up like Aristotle, whose reliance on theory led him to assert, amongst other silly things, that the semen of youths between puberty and the age of twenty-one is “devoid of fecundity”.[12] We suggest that thinking about likely or possible outcomes of experiments facilitates the rigorous testing of those predictions, that this rigorous testing is the true mark of the scientist, and that the need to do this thinking is another reason why doing an experiment is the last resort of the scientist who has nothing left to think about.

Table 1 Predicted effects of the variables on the time of the pendulum swing as made by 15 subjects

Predicted effect of increase in	Length	Mass of bob	Angle
Increase	13	7	4
No effect	1	6	10
No prediction	1	2	1

Table 1 summarises the predictions made by our 15 volunteer subjects. Before presenting the data these subjects collected, we will consider how these predictions might be tested rigorously and efficiently. The first rational step in investigating the nature of any effect would be to test whether or not an effect is observable; there is no point in trying to establish an exact relationship if no effect can be demonstrated. In establishing whether or not an effect can be measured, it is worth remembering the principle of falsification as propounded by Popper (see, for example, ref. 3). According to this principle, an hypothesis is useful when it is framed in such a way that it can be **disproved**. It follows that the **prediction** of a positive effect (such as ‘the mass of the bob **does** have an effect on the time of the swing’*)* does not translate directly into a useful **hypothesis** because it cannot be disproved; it is possible to show that any effect is too small to be measured using the available procedure, but it is not possible to prove that there is **no** effect. It is relevant to recall that the philosophical impossibility of proving the absence of a substance (or an effect) was not appreciated by most of our first-year students.

In contrast to the impossibility of disproving a prediction of a positive effect, any hypothesis that there is no effect is disproved if an effect is actually observed. Thus the prediction that angle or mass has **no** effect is an hypothesis in Popper’s sense. An efficient way to test either hypothesis is to hold two variables constant, pick two values of the third which are as far apart as is reasonable, and make enough measurements at each of these values to be able to carry out a valid statistical test of the difference between the mean values. This involves an underlying assumption that any effect is always in the same direction, but it is nevertheless a useful starting point. It is also relevant to recall that the problem of detecting a significant difference between two variables is another of the concepts with which our first-year chemists seemed to be unfamiliar.

Two predictions are of special interest to the analysis of the strategy used by our volunteers. These are the prediction that angle has no effect on the time of swing (predicted by ten subjects) and that the mass of the bob does have an effect (predicted by seven subjects). Thirteen of our fifteen subjects came into one or both of these categories. Both these predictions are wrong and are interesting for different reasons. Angle actually does have an effect (though it is very small at low angles). Thus this prediction can rather easily be proved wrong, and so those who made it might be expected to change their minds as a result of doing the experiment. In contrast the mass of the bob has no effect (at least not at a level which has ever been detectable with the most sophisticated equipment). Thus this prediction cannot be falsified. Failure to observe an effect need not lead to the conclusion that the prediction is wrong, since it would be legitimate to conclude that the predicted effect was too small to be detected. In practice, it would be hard for a rational scientist to persist with a theory in the absence of any positive evidence on the grounds that a predicted effect was too small to be detected. However, one would hope and expect that they would only change their minds after a thorough investigation.

Table 2 Conclusions on two selected predictions after carrying out the investigation

	Confirmed by investigation	Left uncertain by investigation	Changed mind after investigation
Predicted no effect of angle	7	2	1
Predicted effect of mass	1		6

Examples of simulated investigations

Table 2 shows that our subjects did not respond as described above, and that only one subject (out of ten) was convinced of the correct conclusion that angle has an effect, whereas six (out of seven) rejected their original prediction by concluding that the mass of the bob has **no** effect. Inspection of the data collected by these subjects shows that their investigations were not carried out according to the principles outlined above, and that this may explain the somewhat paradoxical conclusions they drew.

Considering first the effect of angle, we found that seven of the ten used a strategy that made it difficult to refute the hypothesis. Six of them took either no replicate readings, or made only one duplicate or triplicate measurement. Three of these six took five or fewer measurements. Four of the seven (one of whom did take replicate readings) used a range limited to 30 degrees or less. Although it was one of this group whose opinion changed as a result of the investigation, it is plausible that most of them viewed the investigation as an opportunity to **confirm** their prediction, rather than to **disprove** an hypothesis.

The remaining three subjects in this group of ten made between twenty-two and seventy-two relevant measurements and, importantly, made four to six replicate measurements at more than one angle. A small selection of the data they collected is shown in Table 3. Subject 7948 concluded that “time is independent of mass and angle”. The other two concluded that there might be an effect. Subject 170 wrote: “The angle of swing has no (or very little) effect on the time for 10 swings. But there appears to be a **slight** decrease in time for swings with decreasing angle, which does not seem entirely within experimental error”, and 7584 wrote “Time increases a little bit with the angle, but this may very well be due to experimental error.” The data in Table 3 have been deliberately selected from each subject’s total set to illustrate how easy it is to demonstrate a positive effect. The data from subject 7584 show that the effect is harder to see when the length of the string makes for a short time of swing. But even the results selected from this subject provide convincing evidence of a significant difference between the two chosen angles. Two reasons can be suggested for these subjects not recognising the effect. One is that they were so committed to their original prediction that they did not look critically at their evidence (hardly the mark of an objective scientist). The other is that the evidence was obscured by the way it was presented by the computer. The software allows them to view all the data collected, but it lists it in the order in which it is collected. The data shown in Table 3 were not collected in two sequential blocks as displayed in the table, and so the process of abstracting the data from the complete set makes the effect easier to notice. An alternative to abstracting the data is to plot a graph, and the software allows this. However, where an effect is small (as it is in the case of angle) it is much easier to see it when plotted on paper than when displayed on a computer screen. Both these disadvantages of data presentation were almost certainly factors in obscuring the significance of the results.

Whatever the real reason why these subjects did not change their minds as a result of carrying out their investigation, we suggest that, even though they took replicate measurements, they were guilty of doing experiments while they still had things to think about.

Turning to the seven subjects who predicted that mass of the bob would have an effect we see that six of them actually changed their minds, by preferring the conclusion that there is no effect to the conclusion that the effect is too small to be measured. This is surprising, given that the **absence** of an effect is virtually impossible to prove, and our

Table 3 Selected data from three subjects who did not identify a definite effect of angle after carrying out the investigation

Subject number	7948		170		7584	
Fixed Variables	L	M	L	M	L	M
	100 cm	100 g	100 cm	50 g	5 cm	100 g
Angle	20^o	80^o	1^o	90^o	10^o	80^o
Conclusion	**No effect**		**Possible effect**		**Possible effect**	
Readings	20.1	22.4	19.9	23.8	4.5	5.4
	20.0	22.7	20.0	23.5	4.3	4.7
	20.3	22.5	20.1	23.2	5.0	5.0
	20.3	22.6	20.5		4.5	4.9
		22.6	20.4		4.3	5.1
			20.1		4.3	
Mean	20.17	22.56	20.33	23.50	4.48	5.02
S.E.M.	0.08	0.05	0.12	0.17	0.11	0.12
Relevant measurements	22		33		72	

subjects' investigations of angle suggest that they are remarkably resistant to changing their minds. Furthermore, these subjects can hardly claim that their conclusion was based on an exhaustive study. The six who changed their minds made between five and twenty-two relevant measurements, and only one of these took more than one replicate measurement. This latter subject first took single measurements at nine masses from 10 to 90 g, and then twelve replicates at a mass of 100 g. From the point of view of an effective strategy, we point out that it is actually harder to make a statistical comparison of several single values with one mean than it is to compare two mean values based on (equal numbers of) replicates. So it seems that these subjects were persuaded to change their minds on the basis of a less than rigorous investigation. The one subject who confirmed the initial (incorrect) prediction that there is an effect of mass based this conclusion on only five measurements, again suggesting a tendency to look for confirmation of a prediction rather than trying to disprove an hypothesis.

Conclusions

What conclusions can we draw from the evidence that these well-qualified and experienced scientists used strategies that might be described as naïve when judged against basic criteria associated with a scientific approach? We emphatically do **not** suggest that they do not know how to conduct investigations. It is important to take into account the artificiality of their situation. They were given a short introduction to the project, and then asked to carry out their investigation. They are all busy people and unlikely to give as much considered thought to the problem we set as they would to an investigation of genuine interest to them. It therefore seems reasonable to suggest that they reverted to an intuitive strategy. For almost all of them this involved holding two variables constant, and systematically varying the third. This is a necessary strategy for investigating the nature of a relationship between two variables, but it is not an efficient strategy for establishing whether an effect can be detected, and (as argued above) it seems rational to establish this before spending time and effort in investigating the nature of any relationship. We conclude that the Popperian principle of formulating hypotheses with a view to disproving them is not intuitive and has not been embedded in the subconscious of these subjects. The fact that only six of the fifteen systematically made replicate measurements suggests that this principle is less automatic than one might expect given the emphasis placed on it in most laboratory courses. It is a humbling thought that our complaints about the deficiencies of students are reflected in our own performance when we are placed in an unfamiliar situation. If the scientific method is assumed to be understood intuitively by scientists,[3] then this evidence suggests that intuition might be improved by some formal instruction, and that we should take this into account when we address the question "Do we teach our chemists the skills they need?"

We are convinced that one of the main benefits of a scientific education ought to be that it leads to the development of a deeply ingrained appreciation of some principles of scientific method. We do not believe that these are learned by osmosis from the kind of laboratory course which most of us run.

This means that we need to rethink our laboratory courses with the specific objective of helping students to develop an appreciation of the principles to use in planning investigations, and that this involves including explicit advice on the determination and quantification of errors and on the appropriate ways of planning to take account of uncertainty. Of course most of us investigate much more complex systems than a pendulum. Each system will yield to a different combination of thinking and experimenting. Sometimes it is efficient to do a quick experiment and then do a lot of thinking. Sometimes it is much better to spend a lot of time thinking before embarking on the last resort of an experiment. What determines the optimum strategy? Is it possible to draw up a set of guidelines that will lead one to an optimum strategy? If so, is it possible to devise learning opportunities of direct relevance to chemistry through which these can be learned? As yet we have no clear answers to these questions. However, we believe that the answer is **'yes'**, in spite of Medawar's comment that "…those who have been instructed [in scientific method] perform no better as scientists than those who have not". We therefore suggest that it would be worthwhile for a group of interested individuals to consider both what principles of scientific method should be explicitly taught and what methods of teaching and learning are most likely to be effective. On the basis of such a set of guidelines it should be possible to develop a valuable new range of teaching resources.

We do, however, end with a cautionary note. In the end, in teaching our chemists the skills they need, all we can really do is to stimulate and enthuse them, and point them in the right direction.

Acknowledgements

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References.

1. J. Garratt, *U. Chem. Ed.*, 1997, **1**, 19.
2. M. Black, *Critical Thinking, an Introduction to Logic and the Scientific Method* (2nd edn), Prentice-Hall, Englewood Cliffs, NJ, 1962.
3. P.B. Medawar, "Induction and Intuition in Scientific Thought" in *Pluto's Republic*, Oxford University Press, Oxford, paperback edition 1984.
4. J. Garratt, T. Overton, J. Tomlinson and D. Clow, *Active Learning in HE*, 2000, **1**, 152.
5 *General guidelines for the academic review of Bachelors Honours Degree Courses in Chemistry* 1998, Quality Assurance Agency , Gloucester.
6. J. Garratt, A. Horn and J. Tomlinson, *U. Chem. Ed.*, 2000, **4**, 54.
7 J. Tomlinson, P. J. Dyson and J. Garratt, *U. Chem. Ed.*, 2001, **5**, 16.
8. J. Garratt, T. Overton and T. Threlfall, *A Question of Chemistry*, Longman, London, 1999.
9. P. Coldstream, *U. Chem. Ed.*, 1997, **1**, 15.
10 D. C. Finster, *J. Chem. Ed.*, 1991, **68**, 752.
11. R. Millar, *Understanding how to deal with experimental uncertainty: a 'missing link' in our model of scientific reasoning*?, in M. Komorek et al. (eds.), *Research in Science Education. Past, Present and Future* (pp. 276-278). Proceedings of the Second International Conference of the European Science Education Research Association (ESERA), 31 Aug. - 4 Sept. 1998, Kiel, Germany, 1998.
12. P. and J. Medawar, Aristotle to Zoos, Oxford University Press, 1985.

Proceedings

Teaching Chemists to Communicate? Not my job!

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Nyholm was an exceptional chemist, who was recognised internationally not only for his research, but also as an avid supporter of quality and innovation in teaching. I believe he would have been an enthusiastic advocate of the importance of developing the communication skills of our up-and-coming chemists. After all, research is of little value if it is not transmitted effectively to others, and teaching is the profession of communicating knowledge, method and reasoned argument to students. Nyholm might not have expected employability to be another factor in the case for teaching communication skills at university, but it undoubtedly is – our students expect it, employers expect it, and with more than half of chemists entering other professions after graduation we have a responsibility to provide a broad and rounded education for our university students. But are these arguments really convincing, or should we instead concentrate on ensuring that the chemistry we teach is of the highest standard, without diluting the syllabus with generic skills? And even if these skills should be part of our undergraduate degree programmes, should we, as professional chemists (but generally untrained as teachers), undertake the teaching of communication skills, or should we leave this task to those with the appropriate qualifications?

In this paper, I:

- Re-state the case for embedding the teaching of communication skills within a chemistry degree programme;
- Present the case for communication skills being taught centrally by universities, as a generic skill;
- Give the counter argument for these skills being taught by chemists within the chemistry degree programmes;
- Provide my own view of the key features of communication skills that all chemistry degree courses should embrace, with some examples and sources of material.

The terms 'generic skills' and 'transferable skills' will be used synonymously, to refer to skills that are generally supposed to be not subject specific, and which can be applied to many disciplines and situations. 'Communication skills' are also largely generic and concern all aspects of transmitting and receiving information and ideas; but in spite of this there is a strong case for teaching them within a subject context.

Why teach communication skills within degrees?

During the past five years three bodies have emphasised the importance of communication skills within degree courses: the Dearing Committee, the Quality Assurance Agency and employers, with their views being supported by major reports or research data.

The Dearing Report.[1]

The Dearing committee was composed of individuals from a diverse range of backgrounds: academic, industrial, educational and public sector. They appeared to be strongly united in their support for the final report, which made 93 main recommendations. Of these, three have had a major impact on the universities. The first concerns student fees, which were intended to provide money to help redress the serious under-funding of the infrastructure of universities. The second concerns the provision of wider access to HE. The third concerns the content of HE degrees, and what they should aim to provide. The Dearing Report "emphasised the need for students and employers to be well-informed about what higher education offers. They need clear statements about the intended outcomes of higher education programmes…"

Moreover, the report (paragraph 38) stated[2] that "There is much evidence of support for the further development of a range of skills during higher education, including what we term the key skills of communication, both oral and written, numeracy, the use of communications and information technology and learning how to learn. We see these as necessary outcomes of all higher education programmes."

Underpinning this is recommendation 21, which requires all degrees to have a "programme specification", which "gives the intended outcomes of the programme in terms of"

Knowledge/understanding of subject (syllabus)
Special subject skills (e.g. lab work)
Cognitive skills (methodology, critical analysis)
Key skills:

- Communication
- Numeracy
- Use of IT
- Learning how to learn

The chemistry degrees in most departments meet the first three criteria, although the balance and quality of this education might vary widely. The debate continues to rage about the size of the syllabus, the importance and nature of lab work, and the extent to which students carry out what can justly be called critical analysis. But it is the area of key skills that is probably covered least adequately by chemistry departments in the UK.

Quality Assurance Agency

Although the Teaching Quality Assessments had been going on for some years, the Dearing Report certainly influenced the way that the QAA modified its assessment procedures subsequently. In particular, Chemistry, History and Law underwent trial TQAs in 1998, in which the programme specification was a major feature. In order to provide some sort of national framework for the core requirements of degrees in particular subjects, the benchmark documents were produced by appropriate bodies; for Chemistry, this was the RSC.[3] Their programme specification for chemistry mirrored Dearing's, with four main headings as summarised below:

Programme specification – Chemistry benchmark:

Subject knowledge (syllabus)
Chemistry-related cognitive abilities and skills
Chemistry-related practical skills
Transferable skills

'Transferable skills' correlates to Dearing's key skills, and had the following sub-headings:

- Communication (written and oral)
- Problem-solving (and critical thinking)
- Numeracy and computing
- Information retrieval
- IT skills
- Interpersonal skills
- Organisational skills (including time management)
- Skills for continuing professional development

The programme specification was sensible and wide-ranging, but the Chemistry benchmarking panel (uniquely amongst the subjects in the TQA trial) specified levels of proficiency that were expected for various standards of degree, and the transferable skills were embedded within these criteria. So transferable skills are a requirement for professionally accredited degrees in chemistry, and proving that they are indeed delivered by us will be one aspect of all future TQA exercises.

Employers.

In 1999, Duckett, Garratt and Lowe published the results of an extensive survey of recent chemistry graduates.[4] The types of employment were wide-ranging, and about a quarter were in non-chemistry jobs. Summarising the results of the survey, the following seven areas are those that were identified as very important, and for which graduates felt that their university training had been inadequate (roughly in this order):

- Time management
- Updating one's skills/knowledge *by oneself*
- Contributing to discussions
- Presenting information using computer software
- Self-appraisal
- Understanding/evaluating the views of others
- Talking/writing persuasively to non-specialists

Notable from various analyses of employee shortcomings is that the chemistry *syllabus* does not feature, and yet this is probably the issue that is debated most heatedly in departments (e.g. "How could we consider graduating someone who doesn't know…?"). All the concerns that do feature might be considered as aspects of transferable skills, and most could be regarded as communication skills. In the same paper, Duckett et al. reported the following top seven areas of deficiency of recent graduates, as perceived by chemical company employers:

- Awareness of intellectual property
- Communication/presentation skills
- Ability to relate to all levels
- Innovative thinking
- Leadership qualities
- Commercial awareness
- Practical skills

This view of recent graduates was reinforced in the Mason Report (1998);[5] of major issues identified by employers, "…concern was expressed about weakness in interpersonal and communication skills, accuracy in documentation and practical laboratory skills."

In conclusion, there is an overwhelming case for our courses to support the development of communication skills by our students, both because of external assessment of us, and because our students need these skills. But should this be our job?

Why WE shouldn't teach communication skills

Of course communication skills feature as part of chemistry degree courses now. All departments require students to carry out literature searches, give oral presentations, prepare reports and (often) posters, as part of their chemistry degree programmes. But these integrated parts are (almost always) too insubstantial on their own, although they allow reinforcement of skills the students already possess. The problems are that

- Students don't learn how to give talks by doing it once or twice.
- They don't have much incentive to do it well if it counts nothing towards their degree.
- Despite the apparent emphasis by TQA and chemistry departments, not many departments allocate more than 100 hours of dedicated work to these skills and this amounts to only about 2% of student time in a degree course.

So, assuming that a couple of talks, two team exercises and a literature search don't constitute enough, where should the extra tuition come from? There is a strong case for teaching communication skills centrally, and arguments that have been put forward in support of this include the following:

- Special expertise is needed to teach communication skills at an appropriate level. If most of us are untrained as teachers, at least we have specialist knowledge that we can impart to others within our discipline. For a topic such as communication skills, we are ill prepared as tutors.
- The skills are generic, and thus there are advantages in teaching the skills using general examples and exercises, rather than within a subject specific context.
- Centralised teaching of these skills can be a more efficient use of both resources and time, than if it is done in departments. Resources include reference materials (books, CD-ROMs, Web information), computing facilities (hardware and software), videoing capabilities, team exercise material, and dedicated rooms. Concerning time, both central timetabling and the use of experts to teach large(ish) groups might help to make efficient use of time by both students and tutors.
- If there is a special university course, it is easier to identify the content of the programme, and to monitor the topic; this issue should not be underestimated, particularly if one is to prove to external assessors that one is teaching 'communication skills' adequately.
- There is already insufficient time to teach the students all the chemistry they need to know! At least an intensive central course would provide the teaching they need with minimum disruption of delivering the all-important syllabus.

Although one may have reservations about most of these statements, there is a valid argument for the centralised teaching of generic communication skills at university. Yet it is often observed that students disengage from activities that seem irrelevant to them, and they perceive centralised teaching to be so for two reasons:

Students believe that the skills needed to communicate effectively in chemistry are subject specific. Our students come to university to study chemistry, and that is what we should teach them – they simply don't believe that being taught generic transferable skills is relevant to them, and to the subject they have chosen.

It is very hard to build in a marks scheme that gives appropriate weighting to communication skills. If many marks are assigned to these, then departments argue that the subject-specific degree is undervalued; but if the weighting is low, students perceive the course teaching such skills as low priority, and are likely to be content with a modest performance (e.g. getting a minimum pass mark if it is a course requirement).

So, despite the strong case for the centralised tuition of communication skills, I think it extremely difficult to make these relevant enough for students, if they are taught generically.

Teaching communication skills within a chemistry context

As an example of an exercise requiring communications skills in chemistry, imagine being asked to write a short news article about some new discovery or development in chemistry. As usual, something like this actually requires several skills:
Comprehension

Writing a clear, concise report
Computer keyboard skills
Creating visual impact

A cursory analysis of how such articles are constructed in *New Scientist* shows that its half-page news items usually have roughly the following structure:
A catchy title (6 word maximum)
A catchy graphic
One sentence summary (20 words)
One paragraph summary (80 words)
Four paragraph summary (320 words)

There is also a strong human angle, in two ways:
Articles must be relevant to the reader – typical items cover medicine, new devices (e.g. gadgets that we might use), helping others (dealing with problems like earthquakes, health issues), our origins (particle physics, the Big Bang, evolution).
The articles always talk about the scientists, as well as the science, often including a few quotes from the researchers and other leading experts.

Most trained chemists ought to be able to construct such articles from papers in any issue of *Chemical Communications*. As examples, key parts of two articles from *Chemical Communications*, 2000, issues 16 and 17 are in Appendix 1; the first section of each paper (title, authors, abstract), their graphical abstracts, their introductory paragraphs and their final conclusions or summaries. You might like to choose one of the articles, and try to produce a catchy title, and the first sentence (20 word summary … don't forget the human angle).[6]

I hope that you have taken up my challenge (and done better then me).[6] If you did, it may have been because, like chemistry undergraduates, you could imagine being in a position where you might wish to do this, and you have the technical skill to understand (and, hopefully, to explain) the science. Had you been asked to prepare something similar in a non-scientific (or even just non-chemical) area, it might have seemed irrelevant and inappropriate, even if the material had been quite easy to understand. However, and this is a key point, the skills required for this exercise are primarily generic ones.

This type of exercise quickly engages the interest of students. They can gain the satisfaction of using the specialist knowledge they have acquired in chemistry, yet they need to use much more wide-ranging generic skills to produce a good article. Two examples produced by students at Heriot-Watt are in Appendix 2.

What communications skills should we teach?

Although there is a case for teaching key skills centrally, it is my firmly held view that these should be part of the teaching and learning of chemistry degrees within our departments; the reason for this is simply relevance. There are three other important aspects of communication skills:

Firstly, learning key skills isn't about having a couple of away-days solving business games in teams, and a final-year literature review and oral presentation. If 5% of a degree course is intended to cover this topic, this requires about 200-300 hours of work from the students. So it requires lots of time, and that has to be rigorously built into the degree programme.

Secondly, the skills are almost unteachable but they are learnable. This means giving students the chance to try things several times, with effective feedback and review mechanisms to help them identify how to improve.

Thirdly, there must be pressure on the students to do the tasks well. Peer pressure is very effective, but it is essential that their work must actually count towards their degree.

Like most departments, we at Heriot-Watt embed aspects of communication skills in our course, but (unlike most places) there is also a big component in a specific module that is a chemistry degree requirement. All chemistry students must take (and pass) a module called 'Communicating Chemistry' in their penultimate honours year. This is at the heart of the key skills parts of our chemistry degrees, and requires about 100 hours of work from each student (most of it as private study). Although the content of the module varies from year to year, the list below shows a typical module content of 10 typical exercises, with the approximate amount of time required of the students indicated:

Week 1	Fluorofen problem (industrial, team exercise; 1h) Scientific paper (comprehension; 3h)
Week 2	Keyboard skills (using software to prepare material; 10h) *New Chemist* assignment (as described above; 18h)
Week 3	Information retrieval (*Chemical Abstracts* and *Web of Science*; 8h)
Week 4	Dictionary of Interesting Chemistry (20h)
Week 5	Chubli Fruit project (multi-part team exercise; 8h)

Week 6	Annual review (individual oral presentations; 12h)
Week 7	Interviews (they attend and conduct interviews; 8h)
Week 8	Team project (research plan, presented as a poster; 12h)

More information on the module can be found in references 9 and 10.

Here are some of the features that help such a module to run successfully.
Each exercise starts ‘cold’, so the students are caught up in the scenario from the start of the exercise.
There are time pressures to submit work within tight deadlines.
The students must pass all exercises to pass the module, and the module itself is a prerequisite for our chemistry degrees.
They work singly, in pairs or in teams (depending on the exercise).
There is strong peer pressure created by teamwork and peer judgement.
Prizes are awarded, and this adds a bit of fun and incentive at certain points in the module.

Three of these points are worthy of elaboration:

Setting the scene and requiring tight deadlines is important. If students are asked to prepare for an exercise by carrying out some background reading, not all of them will do it. However, there is an excitement and involvement from being suddenly required to tackle an urgent problem, which is simply lost if material is distributed beforehand. A sense of immediacy and realism can be achieved by setting a plausible scenario (e.g. an urgent problem that a manufacturing company must solve; an article that must reach an editor by a deadline; a presentation that has been requested at short notice). The scenario can be set using a role-play, a short explanation, or simply by handing out an ‘urgent memo’.

Peer pressure is a huge incentive, and requiring their work and presentations to be seen (and hence judged) by their peers is one of the strongest incentives for students to produce high quality work. However, it does not follow that students are good at actually awarding marks to the work of others. To state an obvious problem, a weak student will often regard a poor piece of work as quite good, whereas very able students are usually harsh in their marking. One useful compromise is to discuss and agree a marking scheme with the class for some of the exercises. Nevertheless, students are good at perceiving high quality work, and there is always strong agreement between students about the best pieces of work from an exercise, which usually matches the tutor’s views. The peer selection process can usefully be used in the allocation of modest prizes. Using peer judgement has the added advantage that some students might not be clear what was wrong with their piece of C-rated work, but they can clearly see that someone else’s was worth an A.

Feedback and assessment are essential components of any programme that aims to develop communication skills.[7] Whilst peer pressure is hugely effective in encouraging high quality work, we at Heriot-Watt also require students to pass every component of our ‘Communicating Chemistry’ module; they can’t get away without having had a valid attempt at everything, and everything they attempt is given a letter grade. They also get extensive feedback, although just as important is providing them with copies of the best work from their colleagues, so that they can see high quality examples. Their feedback can be collated into a final feedback sheet, and it is worthwhile to require them to use this to help them produce a summary of their strengths and weaknesses. Finally, we produce an average letter grade (including judgement of the amount of work they did, and team input), which is entered into the University system as a mark:

A*	outstanding	=80%
A	excellent	75%
B	very good	65%
C	good	55%
D	OK	45%
E	minimally acceptable	40%
F	unacceptable	0%

Students seem completely happy with this marking scheme, which is explained at the outset of the module. Moreover, it helps to emphasise that this is not a linear marking system. Once students are producing really good work, smallish improvements in style and presentation are potentially worth a lot of marks; outstanding work can receive 90%, but it must be precisely that – work that stands out from the rest.

Our module at Heriot-Watt gives students the chance to tackle a wide range of exercises in communication skills, requiring them to access and deliver information in a variety of interesting chemical scenarios. They have a substantial time allocation for ‘Communicating Chemistry’ within their degree programme, for which they work singly, in pairs, or in groups. They judge each other’s work, and receive feedback and assessment for all aspects of the module. Our emphasis is not so much on the teaching of communication skills as on enabling the students to start learning these skills, and helping them to realise some of their own strengths and weaknesses. Most importantly, although they probably do not realise it at the time, they are developing generic skills that will be of value to them in whatever career they subsequently follow.

There are many ways in which communication skills can be taught within chemistry degree programmes, but we must always try to identify how our students can best acquire the skills we would like them to have, an issue that Johnstone has addressed in this issue of *U.Chem.Ed.*, and elsewhere.[8] All of us ought to have a commitment to help our students develop communication skills, and this is best achieved within our subject. That means having a clearly defined programme of such skills, so that we really can see that our students get the chance to try, to criticise, and to develop the full range of communication skills that will underpin their careers. And what would have been Nyholm's view of this? As he famously said, "You don't learn from chemistry. You learn through chemistry."
I totally agree.

Acknowledgements
I chose my co-presenters at the Nyholm Symposium (York, 21 February 2001) with great care, as I wished us to produce some answers to the question "Do we teach our students the skills they need?" The symposium contributions from David Phillips, Tina Overton, Alex Johnstone and John Garratt are presented in the accompanying articles in this issue of *University Chemistry Education.* I would like to thank them for their inspiration as colleagues, and for their practical contributions to the Symposium. I would also like to thank colleagues and students from the Universities of York and Heriot-Watt (especially Sara Shinton and John Garratt) who have helped me develop materials and ideas for teaching, and the RSC for its support via the Cutter Bequest, HE Teaching Award, and Nyholm Lectureship.

References

1) "*Higher Education in the learning society*", report of the National Committee of Inquiry into Higher Education (chairman: R. Dearing), Crown Copyright, 1997.
2) P. Coldstream, *U. Chem. Ed.*, 1997, **1**, 15 (in which Coldstream looks at the skills that employers need, and picks four key areas of communication, numeracy, teamwork, lifelong learning; this was pre-Dearing!).
3) a) *The Bulletin of the Quality Assurance Agency for Higher Education*, **1(3)**, March 1998; b) *General Guidelines for the Academic Review of Bachelors Honours Degree Courses in Chemistry*, Quality Assurance Agency for Higher Education, 1998.
4) S.B. Duckett, C.J. Garratt and N.D. Lowe, *U. Chem. Ed.*, 1999, **3**, 1.
5) "*Change and Diversity: The challenges facing chemistry higher education*", report by Geoff Mason, Royal Society of Chemistry (with CIHE), 1998.
6) Although you can probably do better, I suggest: a) *Cheaper, safer fertilisers* – "Chemists from Greece have now found how to make ammonia, the main component of many fertilisers, using mild reaction conditions"; b) *Watch-sized computers* – "Impregnating special clays with tellurium compounds generates tiny semiconductors, which could be used to make mini-computers, according to Canadian chemists".
7) P.D. Bailey, *U. Chem. Ed.*, 1999, **3**, 64.
8) A.H. Johnstone, *J. Chem. Ed.*, 1997, **74**, 262.

Some teaching materials and advice:
Courses in communication skills – refs. 9, 10.
Team exercises (multiple skills) – refs. 11, 12, 13.
Oral presentations – refs. 14, 15.
Critical thinking – refs. 16, 17, 18.
Searching/using chemical literature – refs. 19, 20.
Professional development and IP skills – ref. 21.
Student quick reference guide – ref. 22.
Chemical Web sites to search – refs. 23, 24.

9) P.D. Bailey, *U. Chem. Ed.*, 1997, **1**, 31.
10) "*Communicating Chemistry*", by P.D. Bailey and S.E. Shinton, pp.141, RSC, 1999 (tutors' guide to 10 exercises, available from RSC Education Department).
11) a) S.T. Belt and L.E. Phipps, *U. Chem. Ed.*, 1998, **2**, 16; b) S.T. Belt, M.J. Clarke and L.E. Phipps, *U. Chem. Ed.*, 1999, **3**, 52.
12) S.B. Duckett, N.D. Lowe and P.C. Taylor, *U. Chem. Ed.*, 1998, **2**, 45.
13) W.J. Kerr, R.E.G. Murray, B.D. Moore and D.C. Nonhebel, *J. Chem. Ed.*, 2000, **77**, 191.
14) P.D. Bailey, *Chemistry & Industry*, 1994 (No. 5), 190.
15) T.P. Kee, *Chemistry in Britain*, 2001 (June), 59.
16) T.L. Overton, *U. Chem. Ed.*, 1997, **1**, 28.
17) T.P. Kee and J. Ryder, *U. Chem. Ed.*, 1997, **1**, 1.

18) C.J. Garratt, T.L. Overton and T. Threlfall, *A Question of Chemistry (Problems in Critical Thinking)*, Pearson Education Ltd., Harlow, 1999.
19) S.W. Breuer, *U. Chem. Ed.*, 1997, **1**, 5.
20) H. Schofield and A.O. McDougall, *U. Chem. Ed.*, 1998, **2**, 5.
21) R. Maskill and I. Race, *Personal and Professional Development for Scientists*, HEFCE, 1999 (see http://www.uea.ac.uk/che/ppds)
22) *Getting the Message Across: Key Skills for Scientists*, RSC, 1999. (Original text by P.D. Bailey and S.E. Shinton, 2nd edition edited by D. Rafferty – available from RSC Education Department, new edition in preparation – see RSC Web site[23]).
23) http://www.chemsoc.org/networks/learnnet/
24) http://www.physsci.ltsn.ac.uk/

Electrochemical synthesis of ammonia at atmospheric pressure and low temperature in a solid polymer electrolyte cell

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The heterogeneous electrocatalytic synthesis of ammonia from nitrogen and water is carried out at Ru cathodes, using a Solid Polymer Electrolyte Cell (SPE), at atmospheric pressure and low temperature; the reduction rate increases with increase of temperature up to 100 °C, while with the increase of the negative potential a maximum is observed at −1.02 V *vs.* Ag/AgCl and gradually decreases in the hydrogen discharge region.

Industrially the synthesis of ammonia takes place by passing N_2 and H_2 over Fe or Ru surfaces at about 430–480 °C and 100 atm.[1] The synthesis of ammonia over these catalysts at ambient temperatures is a very difficult process because of the high energy barrier for the breaking of the N≡N bond which is about 1000 kJ mol^{-1} at 25 °C.

Numerous efforts have been reported so far on the conversion of nitrogen to ammonia at room temperature and atmospheric pressure using, photocatalytic,[2,3] electrochemical[4–11] or catalytic methods.[12] Recently, Marnellos and Stoukides studied the electrochemical synthesis of ammonia at Pd cathodes using a solid proton conductor at 570 °C and atmospheric pressure and pointed out that the thermodynamic demand for high pressure can be compensated by the use of an electrochemical reactor.[13] However, the operation temperature of that cell is high and ammonia undergoes decomposition at this temperature.

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$$N_2 \longrightarrow NH_3$$

This is the first report regarding ammonia production at atmospheric pressure and low temperature. The main problems that exist at the present are the low rate of ammonia formation and the hydrogen evolution at the cathode. Further work to optimize these factors is in progress.

Preparation, characterization and condensation of novel metal chalcogenide/MCM-41 complexes

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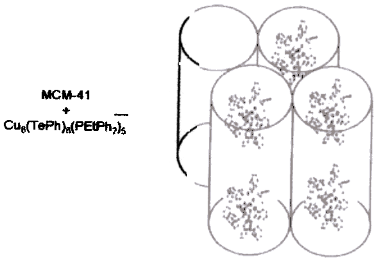
Hexagonally ordered mesoporous MCM-41 with 3 nm pores has been impregnated with the metal chalcogenolate $Cu_6(TePh)_6(PPh_2Et)_5$ 1: the analysis and condensation of this material is a step toward the synthesis of semiconducting nanowires.

The ability of mesoporous materials to act as hosts for quantum structures has been the focus of numerous research efforts as exemplified with reports on the absorption and subsequent polymerization of analine,[1] the encapsulation of semiconducting Ge filaments,[2] the preparation of ferrocenophane polymer[3] and the fabrication of nanostructured Pt clusters and wires.[4]

The independent development of the chemistry of mesoporous materials and metal chalcogenide clusters over the past decade have seen dramatic growth.[5–7] The union of these two fields, the encapsulation of metal chalcogenide clusters and their subsequent condensation into size limited semiconductor particles, should provide novel one-directional nanostructures.

1811 **Preparation, characterization and condensation of novel metal chalcogenide/MCM-41 complexes**



Thermally activated condensation of 1 inside the pores of MCM-41 is also possible with complete loss of $TePh_2$ and PPh_2Et moieties with only copper telluride remaining as characterized by PXRD. We are currently perusing the characterization of the condensed materials and the general applicability of this method to metal chalcogenolate complexes.

New Chemist Article
Student Examples

Helping holes make computer screens better!

Neil Polwart and **Martin Mella**

COMPUTER screens on laptop computers may soon be able to have full colour displays if work done at Toyota's Research and Development Labs makes it to the production line.

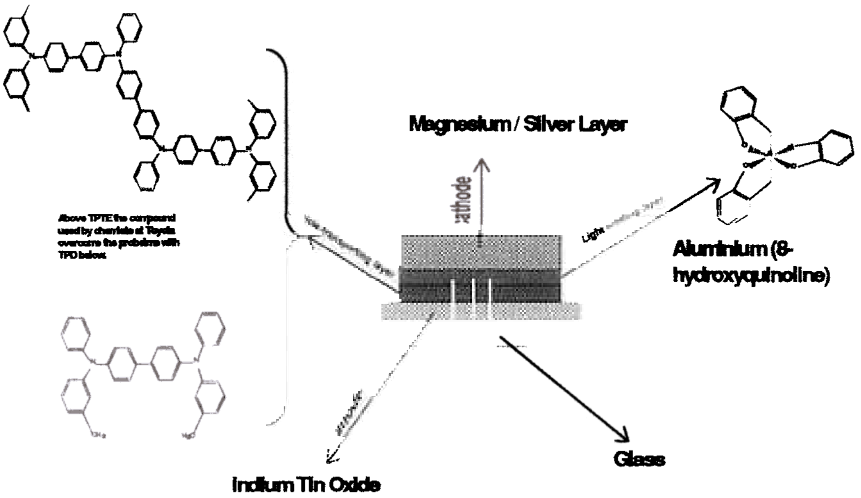
Scientists believe that electroluminescent (EL) devices made from layers of polymer are likely to hold the future for full colour flat panel display systems. Such displays would not only offer the full range of colours detectable to the human eye but would also need to use only low voltages, and be able to operate highly efficiently. Techniques are available to produce such devices, however they degrade very quickly. This instability, which results in a reduction in luminescence and an increase in drive voltage, is believed to be the result of changes in the arrangement of molecules in a thin film which carries electronic holes - vital to the properties of these devices.

Typically such devices use *N,N'-Diphenyl-N,N'-(m-tolyl)benzidene* (TPD) as the hole carrier. As the device is used it heats up and reaches temperatures close to a critical point known as its glass transition temperature, here molecules move around in the thin film and this is believed to cause changes in their electrical properties.

Recently another group of scientists fabricated devices with long life times - using a starburst shaped molecule (called TCTA), unfortunately the devices require almost three times as much energy to emit light that standard TPD devices.

TPD is made up from two smaller units called TPA, the team at Toyota's lab have managed to produce a series of compounds made from two to five of these units with increasing glass transition temperatures. EL devices have been fabricated with optical and electrical properties similar to those made from TPD. The difference being that with these devices they could operate at 100 °C for 100 hours without serious damage, whilst the TPD device broke down after a few seconds at those temperatures. Toyota's team says in *Chemical Communication (21/09/96, 18. p2175)* this is directly linked to the glass transition temperatures.

Obviously some work still needs to be done before we see full colour EL devices in mass production , but perhaps in a few years time you will be reading an on-line version of New Scientist on a full colour laptop computer.

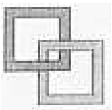


Organic Chemists Redundant ?

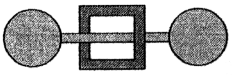
Dawn Robinson and Trish Drennan

MOLECULES that build themselves could lead to a new generation of molecular electronic devices and antibiotics. Such complicated systems could be constructed from molecules which could uniquely identify each other and self-assemble in a "jigsaw" like fashion.

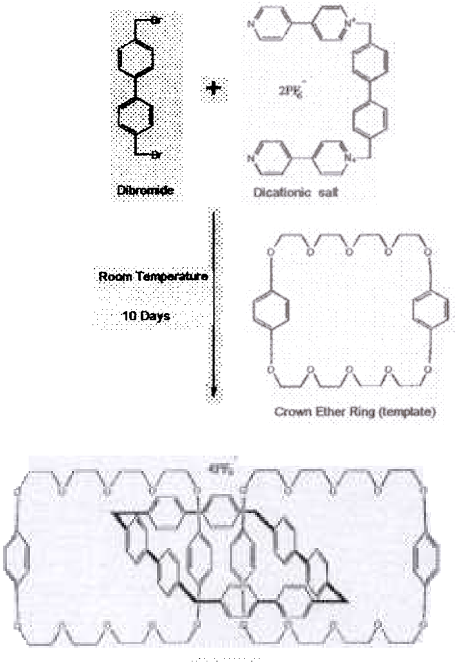
Currently two classes of molecular building blocks are being used to construct primitive molecular switching devices and large molecular assemblies. These are namely the catenanes and rotaxanes, the former being two or more interlocking rings giving rise to a "chain" like structure and the latter being one or more rings threaded onto a dumbbell shaped molecule where multiple threading gives rise to an "abacus" type molecule.



Catenane



Rotaxane



[3]catenane

Synthesis of the "chain" type compounds is trivial with the [3] catenane, self-assembled in 25% yield by reacting a simple dibromide with a dicationic salt, in the presence of a templating agent, such as a crown ether ring. The reaction occurs at room temperature over a period of ten days (*Journal of the Chemical Society, Chemical Communications* 1996, No. 4, p 487).

Rotaxanes can be synthesised in a similar manner where a ring is unravelled to give a linear molecule with large bulky groups at either end acting as stoppers, to retain the threaded ring(s).

By assembling a rotaxane such that the two end groups have different physical and chemical properties, the ring(s) can be induced to "shuttle" between the two alternate ends. The properties of such a molecule resemble a switch, with two positions, on and off. Such a molecular system is capable of expressing binary logic and could be the first step towards a molecular computer.

Structural recognition, self-organisation and self-replication are known to be key elements in nature. These features are inherent in this chemistry, and subsequently could be used, with a bit of imagination, to mimic biological processes.

So perhaps the organic chemist is not quite redundant yet ?!

Letters

Is your web site legal?

From Roger Gladwin
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Many of us now are web producers. We may be placing lecture notes on departmental or institutional web sites, producing whole web sites for our teaching or maintaining web sites for our departments. Tools are now available to make web pages quite simply; but I would advise caution. Is your web page/site legal? At the recent *Variety in Chemistry Teaching* meeting at Lancaster it was clear that some participants were unaware of recent legislation covering the needs of disabled students in education. This prompted me to write to alert colleagues to the situation.

Disability Discrimination Acts

The *Disability Discrimination Act 1995* outlawed discrimination against disabled people in employment, the provision of goods and services and the selling/letting of property. Education was exempted. However, the *Special Education Needs and Disability in Education Act 2001*, which became law on 11th May 2001, legislates for the prevention of discrimination against disabled staff and students in the provision of education, training and other related services. From September 2002 the new legislation is effective, although there is an additional year (until September 2003) to allow the incorporation of reasonable adjustments (e.g. induction loops) and a further two years (until September 2005) for physical adjustments to be made (e.g. access to buildings). At present, Northern Ireland is excluded from this new legislation.

This new law affects education and training providers (i.e. further and higher education institutions, local education authorities, adult and community education and youth provision) and covers more than the web or even C&IT issues. An institution is required to take ‘reasonable steps’ to ensure discrimination is avoided. However, the level of responsibility needs to be judged against criteria for what is ‘reasonable’. These might include:

The need to maintain academic standards
Availability of funds and cost of adjustments
Practicality
The interests of other students
Health and safety

What does this mean for web producers?

The implications for education are wide reaching and are still being interpreted, but for the web it is likely that the producer will be considered legally responsible for compliance. In reality it is probable that, in the event of a dispute, arbitration and conciliation will resolve the situation. But if a student continues the complaint to the limit, it may be the web producer who ends up in court! Thus, it is wise to ensure that your web pages/sites comply with the criteria of this new legislation.

What might this mean in practice?

A web developer needs to keep in mind the potential users of the information being presented on the site. How will they find their way to the information they need and how will they interact with the site? This is true for all cases, not just for disability access, and it is argued that ‘good’ web design will aid the developer in meeting the requirements of the Act. Thus, if a web site is largely based around graphics or multimedia, as may well be the case for the sciences, then an alternative way of presenting the information may be required. Some examples:
Use alternative text for graphics. This helps if the user turns ‘load graphics’ off or uses a text-based browser.
Select non-justified text, as this may be more readable for dyslexic readers.
Choose colour combinations carefully as some can cause problems for the colour-blind (particularly red/green combinations).
Use scrolling text, animated graphics, horizontal lines, etc., sparingly. These may look attractive but too many can be a distraction for users who need narration software to interact with the web.

Enabling technologies

Enabling technologies (e.g. screen audio readers, text magnifiers, Braille converters) can improve accessibility of web sites, and many operating systems have add-ons that can be installed. However, these additions can also present their own difficulties. For instance, it may be impossible to test web sites with the enabling technologies; performance and functionality may be compromised if web pages are adapted to work with these technologies; and delays in setting up the adaptation may still disadvantage the disabled student. Thus, where possible, reliance on these technologies should be avoided.

Where can you find support?

The Learning and Teaching Support Network (LTSN).
The LTSN Physical Sciences Subject Centre (http://www.physsci.ltsn.ac.uk) is able to advise on web design.

World Wide Web Consortium (W3C) Web Accessibility Initiative (WAI).
This consortium promotes web accessibility and produces guidelines for web developers.
http://www.w3.org/WAI

CAST Inc.
This organisation offers the free software Bobby, which allows users to check web pages and whole sites for accessibility.
http://www.cast.org/bobby

Technology for Disabilities Information Service (TechDis).
The Joint Information Systems Committee (JISC) has set up this service to support institutions wishing to ensure compliance with the Act.
http://www.techdis.ac.uk.

The JISC Legal Information Service.
This service was set up to respond to the issues and concerns generated by the new legislation.
http://www.jisc.ac.uk/legal.

Further information

Disability Discrimination Act 1995
http://www.legislation.hmso.gov.uk/acts/acts1995.htm

Special Educational Needs and Disability Act 2001
http://www.legislation.hmso.gov.uk/acts/acts2001.htm

HEFCE Publication 99/05: Guidelines for Accessible Courseware is generally applicable but Appendix 2 particularly relates to web design issues.
http://www.hefce.ac.uk/Pubs/default.asp

JISC Senior Management Briefing Paper 15, Disability, Technology and Legislation, September 2001, presents a useful synopsis of the current situation.
http://www.jisc.ac.uk/pub/index.html#briefing.

Learning in the Laboratory

From Daniel S. Domin
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I read with great interest the article by Johnstone and Al-Shuaili[1] that recently appeared in your Journal. In it the authors address many important aspects of learning in the science laboratory: its purpose, the strategies available, and how learning may be assessed. While I laud the authors' efforts to familiarize your readers with developments in the field of science-laboratory instruction, I am disturbed by the apparent lack of rigour when it comes to citing their sources. For example, Table 1 (p. 45) of their paper comes directly from an article (p. 543) I had published in the *Journal of Chemical Education* back in 1999.[2] Also, I believe much of what Johnstone and Al-Shuaili say regarding different styles of laboratory instruction should be attributed to the same paper. Lastly, the authors mistakenly attribute a quote to me (p. 44) that should be accredited to the late Miles Pickering.[3]

References

1. A. H. Johnstone and A. Al-Shuaili, *U. Chem. Ed.*, 2001, **5**, 42.
2. D. S. Domin, *J. Chem. Ed.*, 1999, **76**(4), 543.
3. M. Pickering, *J. Chem. Ed.*, 1987, **64**, 521.

Editor's note.
Following receipt of this letter, Professor A H Johnstone modified their review to take account of these points and it is the modified version that is now on p. 42. See also the following letter.

Dear Editor,

We must begin by apologising to Dr Domin, to you and to your readers for a serious omission in our review paper. A paragraph, attributing a section of the paper to Domin's published work, was omitted in error during the series of revisions that the paper underwent prior to publication. This has now been rectified in a new version of the paper that you have been kind enough to publish. The reference to the late Miles Pickering has also been correctly attributed.

Since this was a review paper, we were not claiming any originality of our own for what we were reporting and so there was no question of intentional plagiarism. The problem arose from a genuine, but regrettable mistake for which we accept entire responsibility.

Yours sincerely,

A. H. Johnstone and A. Al-Shuaili