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Teaching errors? A case study of students learning about the analysis of data quality

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Abstract

This study examined the ways in which a small group of second year university physics students express ideas about sources of error in science, and how these ideas developed as a result of explicit teaching about errors.¹ Prior to teaching, many of these students were unable to provide appropriate qualitative descriptions of sources of error in data. Explicit teaching about errors concepts, interwoven with student project work, resulted in significant improvements in student understanding.

Students' understanding of error analysis

Developing students' ability to assess the quality of data is a key aim of university science courses. Students need to learn how to use quantitative error analysis tools such as analysis of variance or the combination of errors. However, students also need to develop an understanding of *qualitative* aspects of error analysis, such as the distinction between systematic and random errors; such insights will guide them in designing and using measurement procedures. Studies have found that many undergraduate science students have limited insights into how the quality of a data set is assessed. A recent review concludes that: "*Research on undergraduate students' understanding of measurement data and their treatment has revealed that [students] (...) make second measurements only to confirm the first one, tend to reject the variability of repeat measurements, do not grasp the necessity of standard deviation and therefore do not use it when expressing a repeat measurement result*".²

For example, studies have shown that many university science students do not distinguish between random and systematic errors^{3, 4} or accuracy and precision.⁵ In response to these concerns we designed a short sequence of explicit teaching about errors, focused on key errors concepts rather than on quantitative approaches. The impact of this teaching was then evaluated through a detailed case study of the experiences of a small number of university students. We were interested in what they learned about errors, and also in their reflections on previous experiences of learning about errors at school and university.

Teaching about errors

Rather than designing a stand-alone teaching unit on errors analysis, we chose to embed errors teaching within an existing module in which students collect and interpret their own data as part of an electronics project. We felt that this would help students to apply their developing understanding about errors in authentic science contexts. The teaching (conducted by AC) was incorporated within the module at several points over a ten-week period. It included discussion of the meaning of the terms accuracy, precision, random and systematic error, and developed students' application of these terms within the context of their project work.¹ The focus was on qualitative aspects of error analysis. The students involved had already received teaching about the quantitative analysis of data, and were able to apply these formalisms (though not always appropriately). The aim here was to enable these students to identify different types of error, and use these qualitative insights to inform their design of data collection and the appropriate use of quantitative data analysis techniques.

A case study

The subjects were all second year physics students (representing a wide range of academic ability) following an electronics module that included project work in which they collected and interpreted data. (The studies cited earlier suggest that chemistry undergraduates share similar misconceptions about errors.) The case study followed all seven students enrolled on this module.

The small sample size enabled in-depth interviews to be conducted with each student before and after teaching. These reveal the detail of students' understandings and their reflections on the effectiveness of the teaching. Larger scale studies, typically relying upon written responses alone, are unable to provide such insights.

The study began with a detailed analysis of students' understanding about measurement errors using written survey questions and individual interviews. During the teaching students were encouraged to discuss sources of error with the researcher in the context of their ongoing project work. Survey questions and individual interviews were repeated after the teaching to investigate developments in student thinking. In these latter interviews students were encouraged to reflect on previous experiences of errors teaching. All research visits and interviews were conducted by JR, who was not involved in the teaching (or assessment) of the module; this may well have led to greater openness on the students' part.

What did students learn?

Prior to teaching, these second year students exhibited considerable confusion concerning the meanings of key terms associated with error analysis: systematic error, random error, accuracy and precision. For example, the following quote is from an interview with a student who used the terms accuracy and precision interchangeably before teaching: *"Your accuracy on that measurement would be half the lowest reading (...) so it's just how precise you can make a measurement."*

Several students distinguished between accuracy and precision in terms of features of the measuring system and the actions of the measurer, rather than the nature of the errors themselves: *"Precision that is just how carefully you do it (...) just how careful you do the experiment, you know if you follow it through exactly and don't make any stupid mistakes or anything but accuracy is basically down to the equipment."*

As a result of teaching, students showed significant improvements in their use of errors terminology (systematic, random, accuracy, precision) when prompted to use these terms. Their responses were also more detailed, and drew on their projects to

exemplify their ideas. However, even after teaching these students did not tend to use errors terminology *spontaneously* when discussing sources of error in their project. Of course, these students do meet terms such as 'errors' and 'precision' in everyday use. However, the aim here was for students to recognise that these terms have much more specific, and differentiated, meanings in a science context.

The teaching module examined explicitly the main concepts of error analysis. Students were also encouraged to apply these ideas in their analysis of data as part of the project work. Several students made very positive comments about this 'hands-on', integrated approach to errors, contrasting this approach with what they saw as an overly quantitative (and decontextualised) introduction to error analysis given as part of their first and second year laboratory courses: *"In the first two [laboratory courses] we discussed errors an unbelievably large amount, but it was (...) an analytic approach to it. Actually thinking about it in a real situation (...) then trying to treat the errors ourselves: that's where all [my understanding] is coming from."*

Implications

Many students tend to use computational methods blindly when analysing a dataset. To combat this tendency we suggest that teaching should place greater emphasis on *qualitative* features of error analysis. For example, students could be asked to complete error analysis tasks that only require qualitative reasoning, e.g. 'identify all potential systematic/random errors associated with these measurements'. In reviewing such an activity, concepts of error analysis would need to be presented to students explicitly. Of course, teaching would also need to consider the quantitative analysis of errors in data. Furthermore, students need to be encouraged to apply errors concepts in a range of measurement contexts throughout their undergraduate course.

Acknowledgements

We thank the students involved for their willingness to participate in this research. The study was funded by the Learning and Teaching Support Network (Physical Sciences).

References

1. A full report providing details of the teaching, and the probes used to analyse student learning, can be downloaded from the project website, hosted by the Learning and Teaching

Support Network (Physical Sciences):
http://dbweb.liv.ac.uk/ltsnpsc/devprojs/undergrad_understanding.htm

2. D. Evangelinos, D. Psillos and O. Valassiades, *An investigation of teaching and learning about measurement data and their treatment in*

the introductory physics laboratory. Paper presented at the 3rd International Conference of the European Science Education Research Association, Thessaloniki, Greece, 21-26 August 2001.

3. M.-G. Séré, R. Journeaux and C. Larcher, *Intern. J. Sci. Ed.*, 1993, **15**(4), 427.
4. F. Lubben, B. Campbell, A. Buffler and S. Allie, *Science Education*, 2001, **85**, 311.
5. J. Tomlinson, P.J. Dyson and J. Garratt, *U. Chem. Ed.*, 2001, **5**, 16.

Undergraduate students' understandings of entropy and Gibbs free energy

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Introduction

For many students, the study of thermodynamics presents problems; it is seen as consisting almost entirely of equations which are not understood and which have to be learned by rote in order to do calculations and to pass examinations. This paper describes part of a study designed to explore students' difficulties in understanding thermodynamics. The paper focuses on students' understanding of entropy and Gibbs free energy.

There have been a large number of studies that explore students' understanding of different science topics at different levels of the education system and which show many mismatches between scientifically accepted concepts and students' conceptions (Pfundt and Duit;¹ Carmichael et al.²). The source of students' alternative conceptions lies in how they construct knowledge. When students construct their own meanings they are influenced by their existing (often incorrect) conceptions (Osborne and Wittrock³). Knowledge is constructed through a process of interaction between conceptions that already exist in the learner's memory and an outside stimulus; so that when a student sits in a lecture theatre listening to a lecture, she has previously constructed frameworks of conceptions in her memory and recalls these to interpret the new stimulus from the lecture. This process of interaction can cause existing conceptions to be modified or new ones to be created. There are many ways in which this learning process can create unanticipated learning. Two difficulties relevant to this study were, firstly, what students already knew and how knowledge was organised in the memory store and secondly, the kinds of processing required in the interaction between knowledge in that memory store and the new stimulus.

One possible cause of unanticipated learning is a mismatch between students' prior knowledge and the expectations of the teaching staff. If students do not have the requisite prior knowledge, then

building new concepts is difficult (White⁴ pp.12-21). Alternatively, if students have already constructed understandings and also arranged them in their memory stores in ways that are incompatible with the accepted scientific concepts, new learning is very difficult. Chi et al.⁵ argued that knowledge is organised in the memory in different categories. According to these authors, all scientific entities fall into three categories: Matter, Processes and Mental States. If concepts are placed in the incorrect category, then producing conceptual change to result in the accepted scientific understanding is difficult to achieve. There are many examples in learning chemistry where students incorrectly classify processes as things. Some students see the blue colour of copper sulphate as a separate substance, like a pigment in the copper sulphate, and similarly see the sweetness of sugar as being caused by a component that can pass from sugar to water to give water a sweet taste (Sanmarti, Izquierdo and Watson⁶). Students also have difficulties with some chemical reactions because they view heat as a substance taking part in the reaction (Watson, Prieto and Dillon⁷). At a higher level (years 12 and 13), students find ionic bonding difficult to explain because they view bonds as entities rather than interactions between charged particles (Boo and Watson,⁸ 2001). It is not surprising that students hold these views, as historically, differentiating substances from properties was one of the key challenges for early chemists. In addition, remnants of these early ideas persist in some of the language used to explain modern chemistry. For example, the properties of classes of organic chemicals are explained by their having certain functional groups. Even the names of some chemicals appear to contain the vestiges of the idea that properties are to be explained by entities rather than interactions. Oxygen, for example, is derived from Greek words meaning 'sour' (oxy) and 'I produce' (gen) because Lavoisier found that the substances he burnt in oxygen produced acids. The problem of placing conceptions into the wrong category was also found to be an issue in the current study.

The second difficulty lies in the cognitive demands that are needed in the processes of interaction between conceptions that already exist in the learner's memory and the new input. It is generally agreed that thermodynamic concepts are abstract. This notion is supported by Dixon and Emery⁹ who devised a way of categorizing concepts depending on their level of abstraction; they identified seven such levels. In this scheme entropy was placed on the fourth level (one below enthalpy) while Gibbs free energy occurred on the sixth level. The abstract nature of thermodynamic concepts makes heavy demands on the cognitive processing of students when constructing new meanings. In addition, thermodynamics usually involves the manipulation of two or more variables simultaneously. According to a study by Rozier and Viennot,¹⁰ students treat such systems in a series of sequential steps instead of dealing with the effects of changing all the variables at the same time. Such linear causal reasoning is an example of concrete operational thinking, whereas dealing with the effects of changing all the variables at the same time is an example of formal operational thinking.

The present study took place in England. At the time of this study, successful students in their year 11 examinations could choose to study 'Advanced-level' subjects. They usually chose just three. Although the core Advanced-level syllabus in chemistry contained no reference to entropy or to Gibbs free energy, some A-level syllabuses (e.g. Nuffield, Further Physical Chemistry module of NEAB) did include these concepts. Some students on entry to university could, therefore, be expected to be acquainted with the concepts of entropy and Gibbs free energy. The aim of the present study was to explore students' understanding of these concepts both before and after a first year undergraduate course in chemical thermodynamics, with a view to drawing conclusions about possible improvements in teaching strategies.

There have been a small number of studies of these concepts both at school level and at university. Two studies at school level have been reported: one Scottish syllabus (Certificate for Sixth Year Studies) required equilibrium to be taught from the standpoint of thermodynamics instead of the more usual approach where equilibrium is defined as the dynamic state in which the rates of the forward and back reactions are the same. Johnstone et al.¹¹ report that students who had been taught this syllabus developed a number of alternative conceptions. These included confusion about thermodynamic reversibility and the failure to appreciate that endothermic reactions could be spontaneous. Boo¹² found that A-level students

rarely cited entropy as the driving force of reactions.

The few studies that have taken place in universities show that undergraduate students have a weak understanding of the concepts of entropy and Gibbs free energy (Sozibilir,¹³ Pinto,¹⁴ Ribiero et al.,¹⁵ Thomas and Schwenz,¹⁶ Selepe and Bradley¹⁷ and Banerjee¹⁸). Sozibilir¹³ distributed questionnaires to Turkish undergraduate chemistry students in three universities, both prior to and after their course in chemical thermodynamics. Only a small minority of students showed a 'sound understanding' of the concept of entropy and Gibbs free energy. This weak understanding was mirrored in Pinto's¹⁴ study of Catalan undergraduate physics students, who did not connect different aspects of the Second Law with one another and few students used entropy to explain everyday processes. Sozibilir¹³ found that students attempted to explain entropy as 'disorder'. However, 'almost all of the respondents defined entropy from the visual disorder point of view, indicating chaos, randomness or instability in some cases'. He found that the term 'disorder' was used to refer to movement, collision of particles and the extent to which things were 'mixed up'. Students did not have clear understanding of enthalpy and energy of a system and seemed to confuse the kinetic energy of a system and entropy. Some also confused enthalpy with Gibbs free energy. Similar findings were found by Ribiero et al.¹⁵ and Selepe and Bradley.¹⁷ No student used microstates to explain disorder (Sozibilir¹³).

Another difficulty was understanding the term 'spontaneous'. Few appreciated the thermodynamic meaning of the term and believed that reactions were not spontaneous even when ΔG was less than zero. (Ribeiro et al.,¹⁵ Thomas and Schwenz¹⁶). Students also confused thermodynamic stability with kinetic stability, believing that a large value for ΔG would cause a fast reaction.

Methodology

The methodology for this study was influenced by the literature survey, which had shown that current research about students' understanding of entropy and Gibbs free energy lacked depth. Previous studies had identified weakness in understanding thermodynamics concepts, as well as some individual alternative conceptions, but the studies failed to give a picture of why misconceptions developed and how they linked to different aspects of students' understanding of chemical thermodynamics. It was, therefore, decided to place a strong emphasis in this study on exploring thoroughly the qualitative understanding of a small number of students, both before and after a taught

course of thermodynamics. Such an approach required the use of individual interviews. This type of case-study approach is not intended to generate quantitative data representing all undergraduate students studying chemistry in undergraduate courses in the UK. Rather, it is intended to provide a rich description of the qualities of thinking found amongst the sample. Some quantitative data are presented in this paper, but because of the small sample size these cannot be generalised to represent the numbers of students who would be expected to hold such views in the total year group. The data do, however, show where students had difficulties in understanding and where their common misconceptions were. Previous studies have shown (e.g. Marton¹⁹) that there is some stability in the kinds of conceptions found in groups of students, and it is therefore expected that other groups of students would exhibit conceptions of similar qualities. A reader can generalise from this small sample in so far as he or she recognises common features between the case described here and his or her own experience.

The sample

The sample was drawn from a first year undergraduate cohort of 100 students attending a university chemistry department in England, which has a good reputation for Chemistry (as measured by external evaluations of research and teaching quality). A sample of 20 was chosen randomly. The grades achieved by the sample and the whole cohort in their pre-university examinations (the English Advanced-level examinations taken at age 17-18) were similar: i.e. 22.4 ± 2.8 and 19.3 ± 2.9 respectively, as measured using the numerical values for A-level grades across all subjects. Students were interviewed twice, once before a lecture course in chemical thermodynamics and once after the course. Because of difficulties in tracking down some students and the imminence of examinations, only 16 of the original 20 appeared for the second interview. The results, which follow, refer to the 16 students present at both interviews. All the interviews were tape-recorded and transcribed in full.

The teaching

The lecture course consisted of 13 one-hour lectures at the rate of two per week. Students were also expected to attend weekly examples classes for which problems relevant to the course were set in advance. The researcher observed all the lectures and examples classes and took field notes on the content of the lectures and the students' behaviour (such as whether or not they were attentive or restless and when they made notes). A transparency

was used to summarize the main course content; this was displayed at the beginning of each lecture, and progress discussed. It was noted that all equations that arose during the lectures were written up on the blackboard, interspersed with very occasional written summaries of more important points. It was noticeable that students only copied down material from the blackboard; only rarely did they make notes on any spoken material. In the examples classes, the students worked in small groups (2-3 students) solving problems presented in advance. The three or four staff members present helped students when required. All the problems set were calculations based on the current week's lectures.

The lecture course included the following main concepts:

Energy levels, calculation of the energy of a collection of molecules; internal energy, U ; first law of thermodynamics, heat, work; enthalpy, H ; different distribution of molecules with the same energy; entropy, S ; calculation of entropy for occupations of different energy levels; effect of changing temperature on energy level spacings; distribution of particles over lattice sites; standard entropies; heat capacity $C = q/\Delta T$, measurement of C_p and C_v ; second law of thermodynamics, equilibrium, Gibbs energy, G ; measurement of equilibrium constants and calculation from Gibbs energy; calculation of yields of reactions; ionic product of water, pH , weak and strong acids.

The statistical approach to explaining entropy was built on an earlier course in quantum mechanics in which the idea of energy levels had been explored. The concepts of entropy and Gibbs free energy, a subset of all the concepts in the course, have been broken down and form the list in Table 1.

In order to place this course in a wider context, eight other university chemistry departments were approached in order to ascertain the general thrust of their thermodynamics teaching. Analysis of the syllabuses of these eight departments revealed a very similar approach both in terms of the content of the courses and the teaching approaches. All the courses covered the same concepts, although some also dealt with more advanced concepts such as chemical potential. Courses emphasised the mathematical aspects of thermodynamics and were delivered by means of formal lectures, supported in some cases by examples classes.

The interviews

The interviews focused on three chemical reactions, which should have been familiar to the students. The reactions were:

- the neutralization reaction between hydrochloric acid and sodium hydroxide solutions, both at concentration 2 mol dm^{-3} . The reaction was exothermic and the only visible sign of reaction was the increase in temperature registered on the thermometer;
- the reaction between magnesium (ribbon) and hydrochloric acid (2 mol dm^{-3}). Again, this was exothermic but visible changes were also observed, namely the effervescence caused by the evolution of hydrogen and the 'disappearance' of the magnesium;
- the dissolution of ammonium chloride in water. This was included as the only endothermic reaction. Students, whose understanding depends on the idea that a reaction can only happen if there is a fall in energy level from reactants to products, find it impossible to explain why this reaction should occur.

After a preliminary discussion about each reaction, which included writing the equation for the reaction and describing any observations they had made, students were asked to respond in thermodynamic terms to questions about the reactions, e.g. 'What happened in this reaction to cause the temperature change?' and 'Why did the reaction happen?' Each interview consisted of two parts. In the first part, the

chemical reactions were used to focus students' ideas. During this, open questions were asked so that the students could decide the terms in which to frame a response; students referred to the concepts of entropy or Gibbs free energy only if these seemed relevant to them. Supplementary questions were asked so as to ascertain what was meant by each response. During the second part of each interview, students were asked directly what they understood by the terms 'entropy' and 'Gibbs free energy'. It was in this final part of the interviews that students who were unsure about the concepts produced most alternative conceptions.

The first step in the analysis consisted of developing a set of statements to represent scientifically accepted statements about the concepts of entropy and Gibbs free energy (Table 1). These lists were closely related to the content of the lecture course and were a subset of all the concepts covered in the course. Each student transcript was carefully studied and marked up so that each student statement was related to the statement to which it referred; if it was reasonably close to the accepted scientific view, then that statement was marked as 'correct'. If, however, the student's ideas did not correspond with the scientific view, it was identified as an alternative

Table 1

Scientifically accepted statements about the concepts of entropy and Gibbs free energy

1. Entropy gives a measure of the number of ways in which energy is distributed among energy levels within and between particles (or the number of microstates).
2. The more widely spread the energy quanta among the various energy levels, the more probable the state and the higher the entropy.
3. For a chemical reaction to be possible, the total entropy change ($\Delta S_{\text{system}} + \Delta S_{\text{surroundings}}$) must be positive or not negative.
4. A spontaneous reaction is one that is thermodynamically feasible; that is, one for which the total entropy change ($\Delta S_{\text{system}} + \Delta S_{\text{surroundings}}$) is positive. The reaction may not occur because of kinetic barriers.
5. If energy transferred from an exothermic reaction increases the temperature of the surroundings, the entropy of the surroundings is increased. [$\Delta S_{\text{surroundings}}$ can be calculated from the expression: $\Delta S_{\text{surroundings}} = -\Delta H/T$].
6. The entropy of a system can increase when:
 - (a) it gains energy;
 - (b) a change of state occurs from solid to liquid to gas;
 - (c) mixing of substances occurs;
 - (d) the number of particles increases during a reaction.
7. In order to predict whether a reaction is possible it is necessary to know either
 - (i) the total entropy change which must be positive or zero, i.e. not negative, or
 - (ii) the free energy which must be negative.
8. Gibbs free energy, G , is the maximum amount of energy that is available from a chemical reaction to do useful work (other than pV changes which are not available to do useful work). Alternatively: Gibbs free energy is the energy available to do useful work after any energy transfers have taken place which ensure that the total entropy change ($\Delta S_{\text{system}} + \Delta S_{\text{surroundings}}$) is not negative.
9. Gibbs free energy must be negative for a reaction to be possible.

conception of that statement. A further step in the analysis consisted in identifying commonalities between alternative conceptions related to the different statements in Table 1.

Results

An overview of the understandings of students before and after a lecture course is given below, followed by a detailed examination of some of the students' responses. Quotations from interviews include first the student number, and then a roman numeral, I, to indicate the interview was before, or II, to indicate that it was after, the lecture course. As the interview transcripts were read, a note was made whenever a student made a statement that showed he or she had understood one of the statements in Table 1 or had an alternative conception. During the course of an interview, a student often changed his or her mind, thus giving rise to the recording of more than one conception; sometimes all the conceptions shown by a student were alternative ones, sometimes one was correct and the others alternative.

Table 2 shows the numbers of correct and alternative conceptions that were recorded for each statement both before and after the lecture course. Sometimes the total number of conceptions recorded is greater than 16 (the number of students) because individual students used more than one explanation for a particular concept. Before the lecture course five students had heard of the concept of entropy from their school chemistry courses. Their knowledge of some aspects of entropy was classified as being scientifically

acceptable, but they did not produce satisfactory definitions of entropy in terms of microstates (or even of ways of arranging particles). They knew enough to say, with some degree of confidence, that total entropy change had to be positive when explaining why the reactions happened (statement 3). Two of these students suggested entropy as randomness or disorder. However, they did not explain what it was that was random or disordered. Some other students claimed to have heard of the term 'entropy', but had no understanding of its meaning. The large number of alternative conceptions in the interviews before the lecture course was in response to the direct question in the second part of the interview asking students what they understood by the term 'entropy'. Often it was suggested that entropy was another 'form of energy', and entropy was occasionally confused with enthalpy as the words are similar. The prevalence of the 'forms of energy' framework in students' thinking has been discussed in relation to students' understanding of enthalpy in an earlier paper (Carson and Watson²⁰)

The few who had heard of Gibbs free energy from their school chemistry courses did not explain what it meant, but were aware that the change in free energy had to be negative (statement 9) for a reaction to be possible.

After the lecture course there was a much greater awareness of the term 'entropy', and a large increase in the number of students with scientifically acceptable concepts. In particular, more students had learned that for a chemical reaction to be possible the total entropy change

Table 2

Numbers of students with scientifically accepted ideas or alternative conceptions about entropy and Gibbs free energy

Proposition	Before the lecture course		After the lecture course	
	Number of scientifically accepted ideas	Number of alternative conceptions	Number of scientifically accepted ideas	Number of alternative conceptions
1	0	12	6	11
2	0	1	7	4
3	4	3	11	7
4	2	0	3	8
5	3	2	6	7
6	2	2	12	9
7	4	10	5	8
8	0	6	0	5
9	4	2	10	6
Total	19	38	60	65

must be positive (statement 3) or that the change in Gibbs free energy must be negative (statement 9), and had learned the ways in which entropy of a system can increase (statement 6). Gibbs free energy was a concept which students found particularly obscure even after the lecture course. Though the term had become familiar, none explained its meaning (statement 8) but the number who now knew that it had to be negative for a reaction to be possible had increased (statement 9). However, alongside the increase in scientifically acceptable explanations, there was also a large increase in the number (from 36 to 65) of alternative conceptions.

During the lecture course, entropy was explained in terms of the distribution of energy among available energy levels. Therefore, some explanations of the nature of entropy in terms of energy levels or microstates would be expected from the students. However, very few of them seemed to have taken these ideas on board. As can be seen from Table 2, after the lecture course six students produced explanations in which energy levels were mentioned (statement 1) and attempts were made to clarify their explanations using diagrams of energy levels, e.g.

Student 1 (II) line 26 and 30: "It [disorder] relates back to the distribution of molecules in microstates, how the spread of microstates; it's one way of positioning the molecules over the energy levels."

Such student responses appear as 'correct' in the Table 2. As can be seen from this example, even when familiar with the idea of microstates, students found it difficult to express their understanding in words. Most students still tended to refer to ideas of randomness or disorder and were no clearer on what these terms meant than before the lecture course. It was noticeable, however, that the ability to apply their ideas about entropy to chemical reactions had improved considerably.

Even when students appeared to have grasped the idea that since a reaction had happened the total entropy must have increased, some showed their understanding was flawed because they ascribed the negative change in enthalpy during the reaction to the increase in entropy:

Student 17 (II) line 10: Well there's a spontaneous reaction so it's been a change in enthalpy heat's been evolved which is because the entropy is favourable so well spontaneous reaction proceeds.

Also, most students did not differentiate clearly between the system and the surroundings (statement 5), making it difficult to determine whether they understood that total entropy had increased.

Students found it easiest to relate entropy changes to changes of state, and some of the simpler ideas about entropy (that the entropy of substances increases in the sequence solid to liquid to gas) were well known and were used successfully in explanations. Such explanations can be accounted for if one realises that to these students the particles involved were concrete entities, and students' mental models involved images of the increasing randomness in the arrangement of particles in going from solid to liquid to gas.

After the lecture course students recognized Gibbs free energy as an entity whose relationships could be manipulated in calculations in order to predict whether or not reactions could happen. However, students showed no understanding of the concept. The only definition given in the lecture course was the relationship: $\Delta G = \Delta H - T\Delta S$. It is, therefore, not surprising that there were few alternative conceptions identified; students did not find the relationship intelligible and they were satisfied with their current framework in which Gibbs free energy was seen as another 'form of energy'.

Analysis of the transcripts from both sets of interviews revealed several ideas or misunderstandings that seemed to underlie students' alternative conceptions of entropy and Gibbs free energy:

- forms of energy explanations,
- explanations of entropy in terms of disorder or randomness,
- entropy changes explained solely in terms of change of state,
- confusion between system and surroundings.

Forms of energy explanations

In these explanations students showed some evidence of awareness that energy was in some way involved but did not clearly differentiate between enthalpy and entropy or between Gibbs free energy and entropy, seeing them all as simply 'forms of energy':

S1 (I) line 289: ...like it's [entropy] another name for enthalpy.

S2 (II) line 150: ... gases have a much higher energy a much higher chaotic energy the entropy it is much greater.

In these statements students are using entropy, enthalpy and chaotic energy as terms to simply label what they see as different forms of energy. These statements were typical of many instances of students using the underlying alternative framework of 'forms of energy' to try to make sense of thermodynamic terms.

Explanations of entropy in terms of randomness or disorder

Students using this idea talked about randomness or disorder but failed to explain what these terms meant. Such students made no mention of microstates nor of energy levels and simply explained entropy as:

Student 6 (I): randomness or disorder of everything.

Entropy changes explained solely in terms of change of state

Some students explained entropy changes solely in terms of changes of state. They seemed to recall that there was an increase in entropy in changing from a solid to a liquid to a gas, but did not give the underlying explanation in terms of increasing the ways in which energy could be distributed:

Student 2 (II) line 106: You've obviously got an increase in the amount of entropy going on . . . the solid then changing the phase . . . and just changing the phase will increase the entropy of the system and again you've also got a change of state because you've got a gas given off at the end of the process where you didn't have any to begin with so you've also got more entropy in your system because there's phase changes going on there as well. If you cross phase boundaries the entropy is increased.

Students' use of change of state to explain entropy appears to be linked to a view of entropy as randomness of movement of particles.

Confusion between the system and surroundings

There was frequent confusion about *system* and *surroundings*, often with the surroundings being ignored. This resulted in a lack of understanding of the effects of the transfer of energy to and from the surroundings. In the example below the argument is made from the standpoint of the system alone, neglecting any changes in the entropy of the surroundings:

S19 (II) line 50: If it's thermodynamically favourable a reaction will go spontaneously so generally speaking the entropy change is negligible compared with if the enthalpy change is favourable i.e. if it's large and negative enthalpy change the reaction will occur.

Discussion

This study confirms earlier ones in showing that undergraduate chemistry students have already formed some misconceptions and more general

alternative frameworks related to chemical thermodynamics before they begin their university studies, and that these have a significant impact on their understanding. Previous studies have identified confusion in the use of various thermodynamic terms like enthalpy, energy, entropy and kinetic energy (Sozbilir,¹³ Ribiero et al.,¹⁵ Selepe and Bradley¹⁷). This study goes further in that it identifies a particularly persistent alternative framework that interferes with students' understanding of new concepts in thermodynamics, i.e. 'forms of energy'. This framework, which is used in lower secondary schools, views energy as a quasi-material substance that can be transferred between entities and can take different forms. The students perceive energy as being in the category of 'matter' (Chi et al.⁵). The essence of thermodynamics, however, is a study of interactions. Terms like entropy and Gibbs free energy cannot be understood as isolated entities that can be transformed into one another. If students are to use these concepts to make predictions about whether reactions can occur, they need to understand them in the context of chemical 'processes' (Chi et al.⁵). This change in the way of thinking about chemical reactions is very difficult to achieve and involves radical conceptual change (Chi²¹). It also requires the use of more complex thinking (Rozier and Viennot¹⁰).

Another example of students' difficulties in coming to terms with complex abstract ideas is their explanations relating to the use of the concept of entropy. Entropy was described in vague terms such as chaos or randomness, often without specifying what was chaotic or random. When students tried to be more specific, they related entropy changes to changes of state rather than to distribution of energy in microstates. Sozbilir¹³ reported a similar finding. In that case students seemed to be using a concrete analogical model related to ideas about kinetic theory that they had learned at school. Harrison and Treagust²² have shown, however, that students find it difficult to replace such concrete analogic models with abstract ones.

The results above reveal a mismatch between the learning needs of students and the contents and the approach of the thermodynamics course that they studied. The lecture course, examples classes and examination all emphasised numerical calculations using thermodynamic equations. There were no opportunities to elicit students' qualitative explanations to find out what they understood before they started the course and little opportunity to develop their qualitative understanding during the course. Instead, students learnt to manipulate symbols without understanding the concepts that they represented. By presenting thermodynamic

definitions only in terms of mathematical relationships, for example by defining Gibbs free energy solely as the relationship: $G = H - TS$, students are allowed to ignore the intrinsic meaning of the expression while they concentrate on using it to perform calculations. Students do not automatically invest such expressions with all the meaning that experts in thermodynamics bring to bear and it is unreasonable to expect them to do so. It is necessary, therefore, that thermodynamic entities such as entropy and Gibbs free energy are defined qualitatively before the introduction of the mathematical expression.

Implications for teaching

The results reveal the strong influence of students' prior learning on the development of thermodynamics concepts. Effective teaching needs to take into account conceptions held by students before they start the course and those alternative conceptions developed during the course. At the beginning of a course, a seminar might be held in which students would be invited to write or talk about the thermodynamic implications of some familiar chemical reactions. This would reveal the major alternative conceptions held by that group of students. Also, it would be profitable to challenge students with some already known alternative conceptions, asking them to support or deny these conceptions and explain their answers.

The main emphasis of chemical thermodynamic courses seems to be on the quantitative and mathematical aspects of the subject. One of the difficulties with this approach is that students learn by rote the facility to carry out calculations – correct answers gain good marks. They have no incentive to construct proper meanings for the ideas involved in the calculations. Concepts such as entropy and Gibbs free energy need to be described qualitatively. Because students do not read into mathematical relationships all the meaning that an equation carries, teachers need to provide students with qualitative explanations of such thermodynamic relationships.

Another influence on student learning is the style of examination questions. Questions need to be of a kind that require students to demonstrate an understanding of the concepts involved. The setting only of numerical calculations serves to emphasise that competence in manipulating equations is all that is needed to learn thermodynamics. Entwistle and Entwistle²³ found that, even when the lecturer had admirable aims in terms of conceptual understanding, unless examination papers reflected this, students were strongly influenced into rote learning.

It is necessary, too, to discuss directly the limitations of alternative frameworks such as 'forms of energy' by pointing out that, while as a model it was satisfactory in school, it is now necessary for students to realise that, for example, entropy is not just another 'form of energy'. They need to accept and to think of entropy as entropy. What is important, in general, is that teachers should address explicitly some of the mental models held by students and compare these directly with new models being presented to them in the thermodynamics course.

References

1. H. Pfundt and R. Duit, *Bibliography: Students' Alternative Frameworks and Science Education*; Institute for Science Education, University of Kiel, 1994.
2. P. Carmichael, R. Driver, B. Holding, L. Phillips, D. Twigger and M. Watts, *Research on Students' Conceptions in Science: A Bibliography*, Children's Learning in Science Research Group, University of Leeds, 1994.
3. R.J. Osborne and M.C. Wittrock, *Studies in Science Education*, 1985, **12**, 59.
4. R.T. White, *Learning Science*, Blackwell, Oxford, 1988, p12.
5. M.Chi, J.D. Slotta and N. de Leeuw, *Learning and Instruction*, 1994, **4**, 27.
6. N. Sanmarti, M. Izquierdo and J.R. Watson, *Science and Education*, 1995, **4**, 349.
7. J.R. Watson, T. Prieto and J. Dillon, *Science Education*, 1997, **81**, 425.
8. H.K. Boo and J.R. Watson, *Science Education*, 2001, **85**, 568.
9. J.R. Dixon and A.H. Emery, *American Scientist*, 1965, **53**, 428.
10. S. Rozier and L. Viennot, *Int. J. Sci. Educ.*, 1991, **13**, 159.
11. A.H. Johnstone, J.J. Macdonald and G. Webb, *Physics Educ.*, 1977, **12**, 248.
12. H.K. Boo, *J. Res. Sci. Teaching*, 1998, **35**, 569.
13. M. Sozbilir, *A Study of Undergraduates' Understandings of Key Chemical Ideas in Thermodynamics* (D. Phil. thesis), Department of Educational Studies, University of York, 2001.
14. R. Pinto Casulleras, *Some concepts implicit in the First and Second Laws of Thermodynamics: A study of difficulties in student learning* (Doctoral thesis). Department of Physics, Universitat Autònoma de Barcelona, 1991.
15. M.G.T.C. Ribeiro, D.J.V. Costa Pereira and R. Maskill, *Int. J. Sci. Educ.*, 1990, **12**, 391.
16. P.L. Thomas and R.W. Schwenz, *J. Res. Sci. Teaching*, 1998, **35**, 1151.

17. C. Selepe and J. Bradley, in M. Sanders (ed.), *SAARMSE Fifth Annual Meeting*, University of Witwatersrand, Johannesburg, South Africa, 1997, p. 316.
18. A.C. Banerjee, *J. Chem. Ed.*, 1995, **72**, 879.
19. F. Marton, *Instructional Science*, 1981, **10**, 177.
20. E.M. Carson and J.R. Watson, *U. Chem. Ed.*, 1999, **3** (2) 46.
21. Chi, M. in R. Giere (ed.), *Cognitive models of science: Minnesota studies in the philosophy of science*, University of Minnesota, 1992, p. 130.
22. A.G. Harrison and D.F. Treagust, *Int. J. Sci. Educ.*, 2000, **22**, 1011.
23. N.J. Entwistle and A. Entwistle *Higher Education*, 1991, **22**, 205.

Does Chemistry have a future?

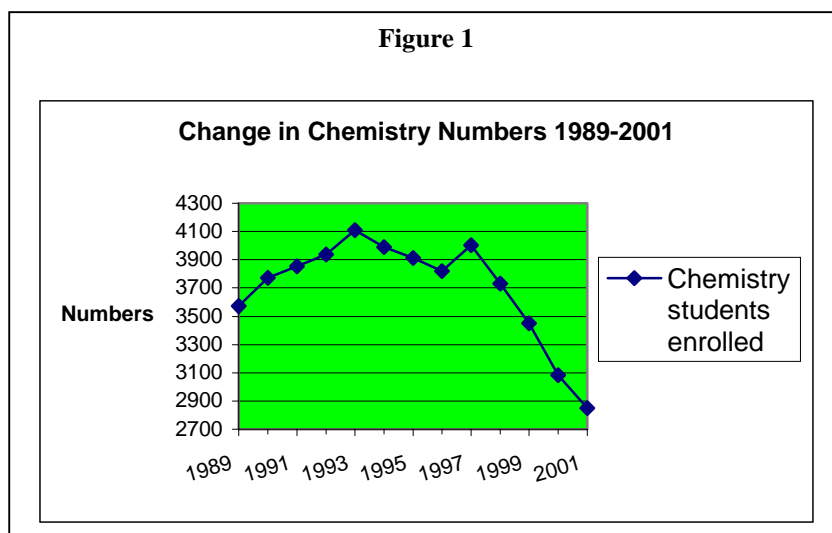
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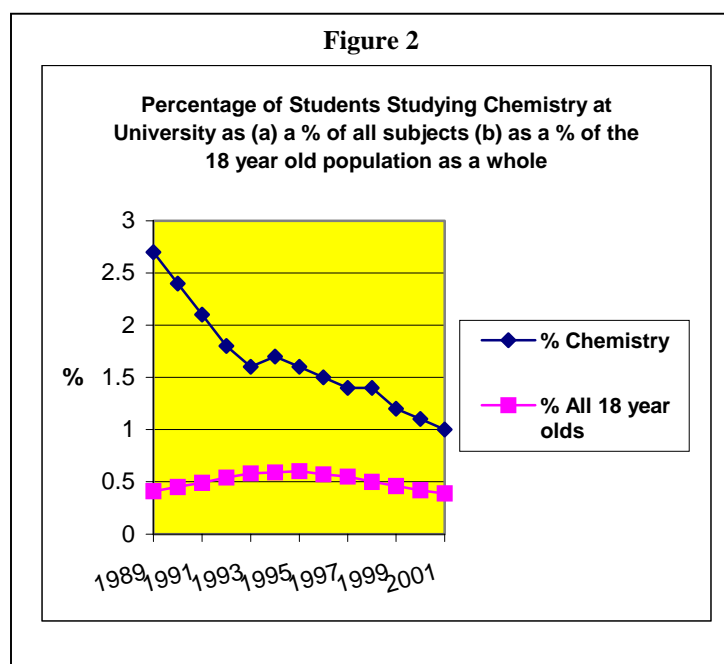
On 22 January 2002 a meeting was held at Lancaster University under the sponsorship of the RSC to address this question. It was attended by many Directors of Undergraduate Study from universities all around Britain, all concerned with the continuing struggle to maintain student numbers in our undergraduate chemistry courses. In fact this is not a peculiarly British problem; most other developed countries are experiencing the same difficulties. The purpose of the meeting was to examine the current position in detail and, if possible, to recommend strategies that may help in recruitment to the entire sector. The reflections that follow are personal views prompted in part by those discussions.

The current position

If we examine the change in undergraduate numbers enrolled on chemistry courses in UK



universities over the past 13 years¹ (Figure 1), we see that the numbers were rising up to the mid-1990s, but the main, worrying trend has been the steady decline since 1997. It was this that started the alarm bells ringing in universities and departments and accelerated the process of closing or merging smaller departments unable to fill their places with well- or at least adequately qualified student entrants. How justified is this concern? Are we looking at the end of Chemistry as we know it or only as we used to know it, and do we have to look afresh at what we are offering to more diverse types of students?



There is another way of looking at recruitment, not just at absolute numbers, but taking account of the demographics as well.¹ Figure 2 shows some interesting data. While chemistry students represent a steadily declining proportion of the total student population, as a proportion of the whole age group the picture is a little different. There is a similar shape to the curve in Figure 1, but from it we are no more justified now in concluding that the past six years' figures indicate an inexorable decline than to have said in 1995 that the previous six indicate a gratifying and sustainable rise. Comparative data for

other physical science and engineering courses and for biology over the same period suggests, after a general rise in the early 1990s, a more or less steady level of admissions with some fluctuations from year to year. In short, the apparent decline in student numbers can be largely accounted for by the growth of the numbers of students studying other, non-science disciplines. Why Chemistry numbers are not growing at the same rate is a different, if no less important, question. An understanding of the reasons for this may take us further towards finding a way to reverse this trend and thus ensure a secure future for our departments and ourselves.

Why does Chemistry lag behind in the popularity stakes?

Possible reasons include the perceived intrinsic difficulty of the subject, the negative public image of the discipline, the unattractive character of the apparent 'obvious' career, and the lack of 'glamour' in the preoccupations of chemistry and chemists as compared to, say, people in the biomedical or environmental fields. The list is not complete. Let us examine the various issues in turn.

'Chemistry is difficult'

This is a widely held view, both in the secondary and the tertiary sector, especially amongst students who have to take it because of the demands of the professions or degree schemes they really wish to follow. Whatever we think of it, many sixth-formers experience the demands of chemistry and move away from it when making their choices of university courses. Chemistry courses certainly demand more attention to be given to a greater diversity of activities and skills (literacy, numeracy, experimental skills) than many others, particularly outside the sciences, while apparently denying students the opportunity to be creative and hold and express their opinions on issues under discussion. The nature of the discipline is such that in the early stages, when the fundamentals are taught, the answers all seem to be known and it is just a matter of mastering the knowledge and reproducing it on demand. The live issues, the diverse and exciting applications still under investigation, only come before the students long after they had to make the decision to follow the path to chemistry. In addition, pressures on time and resources often mean that students get very little opportunity in the early years to experience meaningful laboratory work and gain an appreciation of chemistry as a living science rather than a dry theoretical subject. Changes in curriculum structure and organisation at the school level and context-based teaching are coming in slowly, but not fast enough to change attitudes fundamentally.

The negative image of the discipline

In the UK media the word 'chemical' has acquired a uniformly unpleasant connotation. (In Lancaster a house was advertised for sale recently with the major selling point of having a 'chemical-free garden'.) 'Chemical' almost automatically carries with it the adjective 'dangerous', whether because of toxicity, flammability or some adverse effects on the environment. One hardly ever sees penicillin or vitamin C described as a chemical. The association in the public mind with danger, pollution or some other menace is almost inevitable. People teaching chemistry at all levels, but particularly in schools where they have the opportunity to influence the entire age group, need to try to counteract this image, but it is an uphill struggle. The RSC could be more vigorous in promoting a positive image, but this will have to be done very carefully to avoid its efforts being dismissed as special pleading.

Career prospects

For far too many people the employment prospects for a chemistry graduate are represented by a white coat and a bench with glassware on it. The reality couldn't be more different. A survey² of about 2500 chemistry graduates leaving UK universities in 2000 (an 85 % response from 2882 graduates) revealed that just under half went directly into employment and about a third pursued further study, some towards a teaching career, but the majority towards a higher degree. Of those entering employment directly after graduation, about a quarter went into scientific research, analysis or development-based occupations, with the remainder spread around the widest range of possibilities encompassing IT, finance, other commercial or management, health or other occupations. Clearly, when it comes to employability, chemistry or the broad training it offers is widely seen by employers in many fields as being of value. The salaries offered to chemists are much the same as those offered to other graduates. The problem is to make this situation widely known to sixth formers when they make their subject choices. It is difficult to 'sell' our courses by saying, "*Come and study chemistry and afterwards you will be able to do anything else*", although the reality is exactly that. We know that a good degree in chemistry is a broad education as well as the foundation of a rewarding professional career, but how do we get this across to the public at large?

Unglamorous chemistry

Fashions change in science much more slowly than in clothes, but they do change. A few decades ago the physical sciences represented the pinnacle of ambition for a budding scientist. More recently

developed concerns about the environment and the dramatic growth in our understanding of living systems means that now molecular biology, biochemistry, environmental chemistry and forensic science are the areas that excite young (and not so young) people. This is partly because of the possibilities for greatly enhanced understanding opening up through new techniques, but also because they represent areas of science where altruistic ambitions can find full expression. The idealism of the young is excited by the prospect of curing disease, of feeding the hungry and of protecting the biosphere. Of course, we know that chemistry enables them to do all those things, but that is not widely recognised. In vain do we protest that much of what is needed is the application of chemical knowledge either directly by the making of new drugs or ever more selective pest-control materials, or indirectly through the understanding of biological processes at the molecular level. These aspects have been 'cherry-picked' by colleagues in differently labelled disciplines; although their techniques and approaches are very often based on ours, they are perceived to be separate and different. These developments just reinforce the public image; when a new drug is synthesised and introduced into medical use, it is a great triumph for medicine or pharmacology, but when an intermediate for its manufacture is spilled because a tanker carrying it is involved in an accident, that is the spillage of a dangerous chemical. It is easy to become paranoid.

Another aspect of this is the nature of the problems being tackled by the different disciplines. Some of these are Big Problems, readily comprehended in their grandeur if not in their detail by the person in the street. The physicists have their cosmology: the nature, origins and mysteries of the universe reinforced by the stunning images from the Hubble telescope; the biologists, the rapidly growing knowledge about ourselves at the molecular level via the Human Genome Project, and other developments offering salvation from disease and the ravages of aging. Hardly a week goes by without the announcement of the identification of the gene for this or that quality or propensity.

Not only do chemists deal with matters that are difficult to express in such simple but high-sounding terms, but the discipline has reached a state of maturity where the broad outlines of its account of the world are there and likely to remain so. There is a tremendous amount of reliable knowledge now about the structure, properties and transformations of a wide range of molecules, and the theories we use to gain this understanding are quite good approximations. There will undoubtedly be new developments in the years to come, but these will be refinements on what already exists

rather than fundamental revisions in the way that physics changed with the coming of quantum theory and relativity and biology changed with the development of molecular biology.

The best illustration for this can be found in the answers to the RSC's Scientific Forward Look for Chemistry.³ A few years ago the RSC approached its divisions and subject groups with a number of questions concerning the likely major scientific innovations over the next 20 years, current hot topics, and what breakthroughs are needed to make significant moves forward. The answers are illuminating. They generally indicate that the expected developments will result in our doing what we are doing now, better, faster, with a much better understanding, with greater precision and in an environmentally more benign way. It is evolution, not revolution. No major problems were identified whose solutions were not implicit in our present knowledge and framework, if only we can get the details right. There are plenty of important matters and challenging problems, to be sure, but not sexy in a way that will attract a young person not already favourably disposed towards chemistry.

Does Chemistry have a future?

Of course it does. The real question is whether we can expect our student numbers to rise in parallel with those of the media studies and sports science courses or whether we should accept that chemistry is a specialised taste, not for everybody, and go for quality and not quantity. The debate within the profession is over the question of the purpose of university chemistry courses. In the blue corner are the traditionalists, recognising that there will continue to be a relatively small number of very able students who want to study chemistry because they love it and who will stay with it to provide the comparatively small number of specialist graduates needed for the survival of the profession. These could be taught successfully in fewer universities than are teaching chemistry at the moment. In the red corner are the reformers, who view a chemistry course as an excellent education for whatever subsequent career the graduate chooses to follow. Within this approach lies a greater emphasis on process and less on content in the undergraduate courses, with the high-level training required by the future professional being left to the post-graduate stage. Under this strategy, student recruitment should be maximised by whatever means to ensure that the greatest number will benefit from such high-quality education. Since a chemistry course is much more expensive to run than others in, for example, the humanities, the onus is on us to prove to our academic and political paymasters that the quality of 'the product' is correspondingly better. The market, in the form of starting salaries offered

to new chemistry graduates, does not support that claim.

But this only deals with questions about 'pure' chemistry courses. Alongside is the continuing demand for chemistry and chemical knowledge in other disciplines. A case can be made for saying that chemistry is 'the mathematics of the natural sciences' in the following sense. In the physical sciences the topics being studied are matter and its properties, but the language in which the results are often expressed is that of mathematics. Properties, relationships, are often seen to be truly understood only when they can be expressed in mathematical terms in the form of an equation that fully and predictably describes them. In a similar way, many biological, geological (and of course biochemical) properties and relationships are explained and understood in chemical/molecular terms, even though the systems are too complex to be describable as 'only chemistry'. The descriptive chemistry used by our sister professions is only a small part of the total, but the principles underlying its use cover most of the important theoretical structure. Thus, chemistry will continue to be needed, even if sometimes masquerading under other names.

The meeting on 22 January did not produce magic solutions to solve the immediate recruitment problem; perhaps it was unrealistic to expect that it should. It may be that the tide will not turn and produce increased numbers of talented students applying for single honours chemistry programmes. Perhaps an additional, new breed of 'chemical science' type of course will need to proliferate in order to attract further students and produce many chemically literate graduates with no particular plans to enter the chemical profession. This course of action has to be approached with care, however,

since we may be saying to prospective students, "*Come and study chemistry with us. It will open the doors to many professions for you, but unfortunately, not the door to chemistry.*" Perhaps this is best done by institutions that can run both types of course side by side, with the possibility of transfer between them as the students' perceptions of their career choices evolve. It is a pity that for status reasons the Ordinary Degree has largely gone out of fashion; it could have provided a different, alternative route with a broader, less specialised educational profile.

Time will tell whether we shall be able to halt the drift of students away from chemistry, and it will be interesting to see how the curriculum will develop in order to attract the ever more choosy student. Watch this space.

Acknowledgments

I am very grateful to Dr R G Wallace of Nottingham Trent University for locating and collating the quantitative data, including Figures 1 and 2, and to Dr T L Overton for useful discussions.

References

1. The data are based on that provided by the RSC at www.chemsoc.org/pdf/LearnNet/rsc/stats/3pop.pdf, and on information gleaned from UCAS, the UK's central organisation for the admission of students to universities.
2. http://www.prospects.ac.uk/student/cidd/wdgd/articles02/ed_science.htm
3. <http://www.rsc.org/lap/polacts/forwardlookdocs.htm>

Is the mathematics problem recognised by the chemical industry?

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The Mathematics Problem in Chemistry, as recognised by academics, is not present to any great extent in the United Kingdom chemical industry. Although the mathematical skills of many chemistry graduates are deficient in some areas, such employees are still seen by employers as being essentially numerate. Mathematical requirements in the industry are often low, and can be enhanced by the use of computers. Many employers place great emphasis on statistical techniques, and this and other applications of mathematics are seen to be lacking to some extent in mathematics courses provided to chemists at university.

Introduction

The key skills agenda is now well established within higher education. The National Committee of Inquiry into Higher Education¹ of 1997 recognised a number of such skills: communication, numeracy, the use of information technology and learning how to learn. It is probably true that most chemistry undergraduate programmes have evolved in recent years to encompass these. For example, communication skills are now widely taught through a variety of approaches in such courses.

Student deficiencies in numerical skills have been recognised widely among the science and engineering disciplines. A report² from the Royal Society in July 1997 made a number of recommendations about the teaching and learning of algebra at the pre-university level, and more recently a joint seminar³ was held by the Engineering Council, the Learning and Teaching Support Network, the Institute of Mathematics and its Applications, and the London Mathematical Society to discuss the 'Mathematics Problem'.

While poor mathematical skills may be seen as more of a problem by the bodies listed above than by chemists, there have also been concerns among physical chemists in particular for some time. This is evidenced by a meeting on the subject held by the Royal Society of Chemistry in 1996 and by a series of meetings for both chemists and physicists organised by the LTSN Centre for Physical Sciences. A number of chemists have written papers on the subject^{4, 5}, and produced

textbooks designed to meet the needs of chemists rather better than more generic offerings.

The study reported in this paper was carried out in order to ascertain whether the perception in academia of the poor mathematical skills of chemists is shared by those in the chemical industry employing chemistry graduates. While many such graduates do find employment elsewhere, the needs of this well-defined group of employers are thought to match most closely the professional aims of chemistry degree courses. The key skill of numeracy was not explicitly included in a survey of chemistry graduates⁶ reported in 1999.

Methodology

Suitable employers were identified from the database of the Chemical Industries Association.⁷ A pilot study was performed by e-mail, which involved sending out 178 questionnaires. In the light of responses very slight changes were made to the questionnaire. The final version (Figure 1) was sent by regular mail to a further 386 employers, marked for the attention of the Graduate Recruitment Officer.

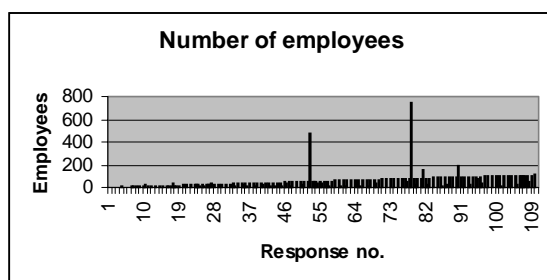
Results and Discussion

A total of 110 completed questionnaires were returned, 12 in response to the e-mail version and 98 in response to the paper version. This represents response rates of 7% and 25% respectively, with an overall value of 19.5%. The number of useful replies is felt to be

Figure 1. Final version of questionnaire.**QUESTIONNAIRE**

1	Approximately how many graduates of chemistry (or chemically related) does your organisation employ?	
2	Has anyone in your organisation ever expressed concern about the mathematical ability of graduate chemists?	Yes/No
3	Do you screen chemistry graduates on the basis of the mathematical skills as part of your selection process?	Yes/No
4	Do you consider that, on the whole, chemistry graduates can be described as numerate?	Yes/No
5	Please rate how essential you would regard possession of mathematical skills in the following areas: Statistics Calculus Algebra Arithmetic	Essential/Useful/Not required Essential/Useful/Not required Essential/Useful/Not required Essential/Useful/Not required
6	Are there any other mathematical skills which chemistry graduates typically do not possess?	
7	Does your organisation provide training in mathematical skills for chemistry graduates you employ	Yes/No
8	Do you believe that universities are generally aware of the mathematical skills industry expects their chemistry graduates to possess	Yes/No
9	Do you believe that time spent on mathematical training in chemistry degree courses would be better spent?	Yes/No
10	If YES, in which areas should this time be spent?	
11	Please add any comments you wish to make about the mathematical ability of the chemistry graduates you employ	
12	Finally, could you please provide some brief details about yourself Name: _____ Position in Organisation: _____ Company name: _____	

sufficient to give meaningful results across a range of companies. These employed a total of 2958 people with the average size of 27 employees. Questionnaires were completed by

Figure 2. The sizes of companies included in the survey.

company representatives holding a variety of job titles, including managing director, process improvement manager, research and development manager, general manager, technical manager, marketing director, operations director, business manager, human resources director and operations general manager.

Figure 2 shows the spread of the number of chemistry graduates in each company surveyed. There is clearly a bias towards smaller companies, but the survey did cover employers of approximately 3000 graduates of chemistry or related subjects. Some respondents made the point that they were part of a much larger organisation. For example, in one case it was stated that

the small number of graduates in the United Kingdom branch were expected to demonstrate the same level of mathematical competence as their counterparts in the parent organisation in Japan. The responses also included those who don't employ chemistry graduates directly, but have experience of them through contracted out work and were therefore able to provide useful information.

The responses to question 2 show that only a small number (18 or 16%) of employers reported any explicit concern in the mathematical ability of graduate chemists. If these results are weighted according to the number of employees, however, the proportion shrinks to only 10%. It is likely, of course, that the number of specific instances of concern will be rather lower than this, assuming that mathematical ability is not spread evenly across the chemistry graduates in an organisation. It is interesting that the organisations expressing concern were those of low to medium size; the maximum number of chemistry graduates was 40 amongst those employers with a positive response here.

That the 'Mathematics Problem in Chemistry' is not apparently recognised by the chemical industry is an interesting result, although perhaps not too surprising if they are able to be reasonably selective. However, some of the free response answers to be reported later do suggest that there are concerns that are not apparent from the responses to this question.

The overwhelming number of responses (97) indicated that employers do consider chemistry graduates to be numerate. Not surprisingly, of the small number of negative responses to this question five also belonged to the group who had expressed concern about mathematical ability. These findings suggest that the marketing of chemistry as a numerate discipline is still valid; this may also be important for those graduates who go into numerate non-scientific careers such as accountancy.⁸

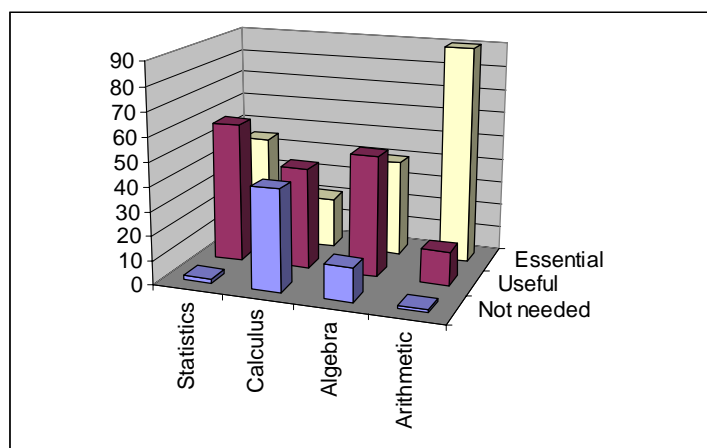
Figure 3 summarises the responses that rated statistics, calculus, algebra and arithmetic as not needed, useful or essential. It can be seen that arithmetic was regarded as the most essential skill, with statistics next. Not too surprisingly, the skill that was felt likely to be of least use was

calculus, although one respondent made the point that both calculus and algebra are useful for building concepts. Another surprising result from this section of the questionnaire was that 13 respondents felt that all four skills were essential. This group represented companies employing 254 chemistry graduates, and suggests that a minority of companies do have high mathematical expectations of their graduates.

The majority of respondents felt that the areas outlined above did cover all of the mathematical skills they might wish chemistry graduates to possess. However, when asked if there were additional areas, 5 respondents mentioned statistics again, suggesting that this is an area of particular concern. In addition, data manipulation and the quoting of values to acceptable levels of precision are related areas that were mentioned. Other suggestions were: estimation, basic numeracy, equations describing a straight line, physical modelling, geometry, mental arithmetic, and mechanics. The need to be able to apply mathematical knowledge, for example in setting up spreadsheets, was also mentioned. An additional area, probably not taught in most basic mathematics for chemistry courses, was working with commercial business data.

Twelve of the organisations surveyed did provide some mathematical training themselves, although in several cases this was restricted to statistics. These were split almost evenly (seven to five) between those who had expressed concerns about mathematical ability and those who had not. A clear majority (sixty-four) did believe that universities were generally aware of the mathematical skills industry expects their chemistry graduates to

Figure 3. Employers' perceptions of the importance of categories of mathematical skills.



possess, with only twenty-nine believing that this was not the case.

The question on how the time currently devoted to mathematics courses for chemists could be better spent was answered in a number of ways. Three respondents (who had not had cause for concern about mathematical ability) identified various aspects of chemistry to fill this time. The opportunity to mention statistics again here was taken by twelve respondents, emphasising that this is seen as a very important area. This was tied to applications of statistics and the use of appropriate computer packages in some responses. Seven respondents mentioned applications of the basic mathematical material, and another mentioned stoichiometric calculations specifically. Other mathematical techniques mentioned once each were arithmetic, simultaneous equations, and algebra. One respondent suggested that courses should be run at a lower level, but that mastery at that level should be ensured. This raises a more general point about the level of skill necessary to achieve a pass in a given module, but studies in the area of medicine have failed to produce information on this.⁹

When asked to make any other comments about the mathematical skills of chemistry graduates, the group who had noted concerns in this area described abilities as variously 'fairly good', 'adequate' and 'not particularly good'. Weaknesses in statistics were noted by two of the respondents, and one noted that graduates were very competent in arithmetic, but less so in other areas. A specific example of a problem was the case where a graduate could not immediately see why reporting the result of a titration calculation to five significant figures was wrong. One respondent felt that basic mathematical ability should be ascertained before admission to chemistry degree courses and that this was clearly not the case. One suspects that admissions tutors would be delighted to be able to do this, but that in the current climate this would not be a sensible strategy in terms of student numbers.¹⁰ More pessimistically, another respondent believed that newly qualified graduates were not ready for any form of employment. This general statement needs to be put in the context of the individual mission statements of higher education institutions that seek to address the question of graduate employability in different ways.¹¹

The group of respondents who had not expressed any concerns in this area described

the mathematical ability of their chemistry graduates as varying from 'poor to middling' to 'normally excellent'. Three respondents highlighted deficiencies in statistical methods as problematic, and the inability of many graduates to perform simple standardisation calculations was mentioned. One respondent mentioned that arithmetic is often poor and skills in mental arithmetic are non-existent. It was noted that organic chemists tend to stay away from and lack confidence in mathematics, but deficiencies may become apparent when graduates are employed as process chemists. One respondent suggested that mathematical deficiencies were more likely to be in the general arithmetical skills of part time degree students.

While these responses may at first sight seem surprising from this group of employers, further comments do shed light on why such deficiencies in mathematical skills may not be problematic. Several noted that they only require fairly basic mathematical skills, such as working out molar ratios and percentage yields, converting mass into amount of substance, and calculating heats of reaction from bond energies. One respondent also noted that much of the basic arithmetic required is now performed by automated equipment and computers. Two respondents noted that specialised mathematical skills would be bought in as required; one did, however, qualify this by stating that it is useful for someone to be able to review the underlying mathematics of large projects. One also felt that chemistry graduates were able to learn what they didn't already know in this area, suggesting a certain level of mathematical skill as opposed to knowledge. This also suggests that the chemistry graduates concerned are able to 'learn how to learn' as envisaged by the National Committee of Inquiry into Higher Education¹.

Some of the more general comments backed up the findings reported in the previous paragraph. Several other skills were felt to be more important than mathematics; those mentioned were computer literacy, chemical knowledge, practical skills, teamwork and communication. One respondent noted that the improvement in computer literacy in recent years has led to the more effective analysis of data through the use of computer packages. It is also evident that there are other problems too. Poor English was felt to be a more important problem by one respondent, and another was far more concerned about the

chemical ability of chemistry graduates in the United Kingdom.

Conclusions

A very low proportion of the companies surveyed expressed concern about the mathematical ability of the chemistry graduates they employ. Chemistry graduates are still seen by the overwhelming majority as being numerate, so this aspect of the marketing of such degrees is still valid.

Arithmetic is seen as an essential skill by most employers, but many also require statistics and deficiencies in this area were often highlighted. Higher level mathematical skills involving calculus are regarded as useful by around half the employers surveyed, and as essential by some, suggesting that such topics should be retained in mathematics for chemistry courses. There are calls for more applications of mathematical knowledge to be taught, which may provide support for the teaching of such courses by chemists rather than by mathematicians.¹²

Many employers require only basic mathematical skills, and automation procedures may even remove much of the need for these. Some employers do see the effective use of computer software as having improved the extent to which students are able to perform mathematical tasks. Higher level skills can be bought in as required. Deficiencies in English and even in chemical knowledge are seen as being of more concern than those in mathematics.

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References

1. National Committee of Inquiry into Higher Education, <http://www.leeds.ac.uk/educol/ncihe/>.
2. Royal Society and Joint Mathematical Council of the United Kingdom Joint Report: Teaching and Learning Algebra pre-19, The Royal Society, July 1997.
3. Measuring the Mathematics Problem, <http://www.engc.org.uk/gateway/3/mathsreport.pdf>.
4. G. Doggett, *Educ. Chem.*, 1997, **34**, 105.
5. J. Lee, *MSOR Connections*, 2001, **1**, Part 3, 26.
6. S. B. Duckett, J. Garratt and N. D. Lowe, *U. Chem. Ed.*, 1999, **3**, 1.
7. Sourcerer, <http://www.sourcerer.co.uk>, Chemical Industries Association.
8. New Scientist Graduate <http://www.newscientistjobs.com/graduate/cac/Career.jsp?id=career1>.
9. P. Board and M.A. Mercer, *Medical Teacher*, 1998, **20**, 104.
10. V. Barker, *Educ. Chem.*, 2001, **38**, 126.
11. M. Atlay and R. Harris, *Innovations in Education and Training International*, 2000, **37**, 76.
12. P.C. Yates, *Educ. Chem.*, 2002, **39**, 78.

On the use of chemical demonstrations in lectures

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Introduction

It is something that you hear often from students and colleagues: “*I remember clearly the time when I first saw a piece of sodium dropped into water...*” It must be almost the universal experience of chemists to have seen this demonstration, and to remember it with such clarity and, sometimes, affection. What is it about a simple experiment that it holds such a place in people’s memories? Maybe it is the slight element of danger, or the illustration of theory in vivid, tangible form, or perhaps it is the sheer entertainment value of the noise, the flame and the action. Whatever the reason, chemical demonstrations—the reaction of sodium in water is a particular example—

Figure 1. ‘Barking dog’ demonstration—ignition of CS₂ and NO, performed in a well-ventilated laboratory.



appear to have a significant effect on observers. People believe there is a positive effect on observers, and this view is supported by the enormous volume of ‘tried and tested’ demonstrations that are widely published (e.g. in *J. Chem. Ed.*) and are used by chemistry teachers at all levels.¹ In addition to those, a long and distinguished history of demonstrations exists with Faraday’s lectures perhaps being the first real, lasting example of the impact of chemical demonstrations on audiences; the legacy of his Christmas lectures continues today. There are also many available resources; numerous books exist on the

subject, and information on the World Wide Web seems to grow weekly. In short, there appears to be little doubt that demonstrations excite and ‘charm’ students² and have educational benefits (Figure 1).

Despite the large amount of available material on how to perform certain demonstrations, a careful search of the literature shows that there is not much agreement on the educational value of demonstrations; given the general acceptance of demonstrations as educationally beneficial, this is somewhat surprising. Reporting on the WPI conference ‘Demonstrations as a Teaching Tool in Chemistry: Pro and Con’ Beall relays the comments of Kelter who says that “*The primary purpose of demonstrations should be to entice students to ask questions and develop a classroom situation where questions are asked freely*”.³ Shakshiri in his introduction to ‘*Chemical Demonstrations: A Handbook for Teachers of Chemistry*’ argues how carefully planned demonstrations can make a positive impact on a student’s understanding.¹ Others criticise the use of demonstrations, making the point that they are time-consuming and often are merely present for entertainment rather than educational reasons.³ There is currently no strongly persuasive evidence for or against the educational benefits.⁴ Maybe the lack of a strong indication reflects the difficulty in assessing the educational value of demonstrations.

Student Survey

In an attempt to evaluate the benefits of lecture demonstrations, we have carried out our own empirical survey on a group of undergraduate students. The students were asked to complete a questionnaire after they had attended a lecture course (Acids and Bases, first year undergraduate) that was augmented with demonstrations; the results are given in Table 1. The results strongly support the notion that demonstrations are popular teaching tools. Importantly, the results show that a very large proportion of the students agreed that demonstrations helped them understand the

theories—an encouraging link between demonstrations and educational value.

The results of this simple survey encourage the belief that the use of demonstrations is an important part of chemistry higher education, and that they have educational value. This paper offers practical advice and tips to those

effort in the research in finding an appropriate demonstration and the physical act of practising it.

In terms of finding out an appropriate demonstration, a vast number of resources are available. Perhaps the best sources are '*Chemical Demonstrations: A Handbook for Teachers of Chemistry*' by Shakishiri,¹

Table 1. Results of student survey on the use of demonstrations. Sample size was 87 first year honours chemistry students, surveyed directly after a lecture course which contained demonstrations

	Question	% Either totally or partially agreeing
1.	Demonstrations help me understand theories	87
2.	Demonstrations are a waste of time	0
3.	Demonstrations keep my interest during the lecture	95
4.	One demonstration per lecture is the correct frequency	98
5.	A live demonstration is better than a 'video' demonstration	60
6.	All demonstrations should be colourful or noisy	71
7.	The most effective demonstration is where there is an element of danger	79

who are convinced by the positive evidence and are considering the use of demonstrations. By encouraging people to try out demonstrations in their teaching, it may generate further discussion about their educational value.

Using Demonstrations

There seem to be three main hurdles confronting those contemplating demonstrations: worries about safety, lack of confidence on the part of the teacher, and the time and effort needed to put together a successful demonstration. All these are important considerations but not insurmountable, and methods for overcoming these hurdles are discussed below.

i) Time commitment

There is little doubt that setting up and performing a demonstration either in class or lecture is both time-consuming and needs considerable motivation on the part of the teacher (a point which is often lost on students). There are two golden rules for preparation; the first is always to practise the demonstration in advance; the second is to make sure that the demonstration is relevant to the material being taught. Implementation of both of these golden rules requires time and

'*Chemical Magic*' by Ford,⁵ '*Tested Demonstrations in Chemistry*' by Alyea and Dutton⁶ and '*Demonstrating Chemistry*' by Humphreys.⁷ There are enough demonstrations described in these volumes to keep a teacher going for most of a career. Shakishiri's texts are excellent: each demonstration is linked in detail with the background chemistry and the methods for performing the demonstration. Such is the comprehensive coverage of the volumes that they should be an essential part of a chemistry department's library.

The World Wide Web

In terms of speed and coverage nothing can surpass the World Wide Web. Inserting 'chemical demonstration' into a search engine returns a veritable plethora of sites. The problem, of course, is the reliability of such sites; here some discretion and professional judgement are required. Nevertheless, one quickly acquires a list of good sites. A bonus of these sites is that they may contain video or still images of demonstrations that are useful in themselves, although it is not clear whether a live or recorded demonstration is best (see the results of the student survey above). A short list of useful web sites (with some commentary and a personal rating) is given in Table 2, although there are very many others.

Table 2 Selected Web sites with information about demonstrations

<http://www.chem.leeds.ac.uk/delights/>

A very comprehensive site maintained by Mike Hoyland at Leeds. There are lots of chemical details for about 40 lecture demonstrations—mostly the experiments that Mike Hoyland performs in his lecture to school children. Particularly valuable about this site are the video clips of the various demonstrations and the very thorough chemical details. Well worth a look.

Rating = *****

<http://chemlearn.chem.indiana.edu/demos/democont.htm>

A good number of selected demonstrations. Some chemical details are given. There are also some descriptions of the underlying chemistry.

Rating = ***

<http://www.chem.uiuc.edu/demos/>

About 10 demonstrations are described here, some of which are only tenuously related to chemistry. There are some very good still photographs, and also some video clips. Content is slightly below degree level.

Rating = ***

<http://genchem.chem.wisc.edu/demonstrations/>

Lots of demonstrations (>100) are described here. Nearly all have still photographs. What is good about this site is that the demonstrations are broken down into the various branches of chemistry, and it is easy to navigate your way around. For instance the 'inorganic chemistry' section has some very colourful transition metal demonstrations. There is also a beautiful silver mirror demonstration (the best I've seen) described here; unfortunately, precious few details are given. Less good about the site is that the demonstrations are hardly described in terms of preparation or chemistry.

Rating = *****

<http://chemistry.csudh.edu/oliver/demos/index.htm>

About 10 techniques are described. These are not so much lecture demonstrations, but more like laboratory procedures. Also, the content is probably below degree level. What is attractive about this site though, is the very thorough way in which each demonstration is described, with good use of stills and video clips.

Rating = ***

<http://chem01.usca.sc.edu/proton/ppdemo.htm>

There are about six fairly basic demonstrations described in excellent detail. There are no pictures or videos to help the viewer, but the demonstrations seem to be effective and simple to perform. Rating = **

<http://journals.springer-ny.com/chedr/bang.html>

A site dedicated to a single demonstration (the Pd-C catalysed explosion of H₂ and O₂). The site is excellent. The preparation, safety and chemistry details are very good. If you ever perform this particular demonstration, then look at this site first.

Rating = *****

http://www.shsu.edu/~chm_tgc/chemilumdir/chemiluminescence.html

The starting point if you want to perform a chemiluminescence demonstration. Lots of videos, photographs and procedures. There are also links to other chemiluminescence web-sites (of which there are very many). The only criticism is that it is difficult to unearth the chemical/preparation details if you are interested in performing any of the demonstrations.

Rating = ***

<http://www.flinnsci.com/homepage/chem/chemdem.html>

There are only about 10 demonstrations, but this is a very well laid-out site. Each demonstration is described in great detail, with each having some assessment of hazards. Most of the demonstrations are for effect rather than for teaching, but you may find something that ties in with your teaching subject matter.

Rating = ***

<http://users.erols.com/merosen/demos.htm>

An excellent site, with about 40 demonstrations. The demonstrations cover a range of chemistry. Each demonstration is described in very good detail—some have pictures and video-clips. The site author has also included ideas from others about tips/improvements. Probably one of the first web-sites to look at if you are thinking about doing a lecture demonstration.

Rating = *****

<http://antoine.frostburg.edu/chem/senese/101/demos/resources.shtml>

This site is a selected collection of other chemical demonstration web sites. Most of the material is 'kitchen chemistry' designed to be done at home. However, there are some very nice descriptions of 'old' demonstrations (e.g. elephant's toothpaste from the decomposition of hydrogen peroxide). If you want to entertain your audience, then this site may be a good starting point.

Rating = ***

On the other golden rule "*always practise the demonstration immediately before the class*", there is very little substitute for actually carrying out the demonstration oneself, no matter how many times it has been done

beforehand. Only by practising it can one get a clear idea of the difficulty of the demonstration. It can also reveal the unexpected. Simple things like glassware size, temperature effects, etc. can ruin a

demonstration in class if they are not right. By practising, one can also assess the impact and timing of the demonstration, which are both important aspects. It should be noted that a demonstration which takes longer than 5 minutes to perform is probably not appropriate as part of a lecture.

Naturally, all of this preparation and practice requires time and effort, and there is a calculation to be done to assess whether it is worth it. In balancing effort with value, my suggestion is to try using a demonstration and see how it changes the way that students perceive your teaching as shown, for example, by course evaluation questionnaires. I have never regretted spending time developing a demonstration for lectures; the student feedback has always been overwhelmingly positive (see above). It is perhaps worth pointing out here, that one demonstration per class or lecture is probably enough. Certainly, all student feedback that we have obtained has suggested that this frequency is about right. In other words, one does not have to develop very many demonstrations to benefit from their impact. One further point about the time involved in preparation and practice is that there are usually willing volunteers around in any department. It is surprising what knowledge (and motivation) is available from academic and non-academic colleagues; it is always worth asking someone. In some institutions this has been taken a step further with the formal identification of a member of staff (often a non-academic) whose role it is to help in the preparation of demonstrations. If such a person is available, then they are invaluable in that they will have experience of many demonstrations and will know immediately what to and what not to do. Departments may want to consider whether technicians or similar persons could be asked to become 'expert' in this area.

ii) Confidence

The next potential hurdle to performing demonstrations is a lack of confidence on the part of the teacher. This lack of confidence has two aspects. One is the personality of the teacher, where he/she may feel that chemical demonstrations do not fit in with the adopted teaching style. The second area is where the teacher is not confident that demonstrations add anything to the subject matter. In addressing both concerns, one should note the evidence that suggests that demonstrations could add to chemical education.^{1,3} Even with abstract subjects, such as group theory and atomic wave functions, where it is not immediately apparent what, if any, demonstration can be used, there is often something that can be shown or done. For example, in the teaching of atomic wave functions, a standing wave can be demonstrated with the use of a 'slinky spring'. Others have been able to demonstrate in lectures the emission spectra of hydrogen using a simple hand-held spectroscope, (although a willing student volunteer is required). Even if the demonstrations simply communicate the teacher's motivation and enthusiasm along with the principles, then they are surely worthwhile.

To enhance the value of demonstrations in class, the following method seems particularly good. The teacher performs the demonstration and asks students to write down their observations in a simple table (Figure 2). After the students have completed the observation side of the Table, they are asked to pass it to another student for him/her to complete the deductions side of the Table, against the other student's observations. This very simple exercise (of observation and deduction) is central in any practising chemist's thinking and—when coupled with theory—probably is the essence of what chemists do as part of their profession.

Figure 2. Observation/deduction table.

Observation	Deduction

iii) Safety

The final potential hurdle to performing a demonstration is that of safety. There is no doubt that this is a very important consideration when it comes to performing chemical demonstrations in front of an audience. Safety considerations must be paramount, and this stance necessarily restricts many of the more spectacular demonstrations. I believe that the message is simple: as teachers of chemistry we are obliged not only to teach accurately, but also to convey a professional and responsible attitude towards the handling and use of chemicals. Seen in this light, it is apparent that demonstrations in class can be used as part of communicating such a responsible and professional attitude. For instance, consider the very simple demonstration where a basic aqueous solution containing universal indicator is made acidic by mixing it with solid carbon dioxide. The demonstration, which is visual and dramatic, going through some attractive colour changes, helps to illustrate the point that not all acids (CO_2 in this case) are proton donors in the first instance. It is a relatively easy exercise to work through the potential hazards of the demonstration, and the appropriate procedures for preventing accident. Such information can be presented to students in class before performing the demonstration. The very act of going through the hazard assessment and then practising the safety measures (safety glasses, rubber gloves etc.) in front of the students is an important and beneficial message to communicate.

In practice, there are several reasons for demonstrations to be ruled out on safety grounds. These are as follows:

- Demonstrations that have the potential to give out noxious gases or fumes.
- Uncontrolled flames, explosions or detonations (NI_3 is a borderline case here).
- Very loud noises (e.g. ignition of CH_4/O_2 mixtures)
- Demonstrations that could give out solid or liquid projectiles (e.g. flying corks from 'pressure demonstrations'), for instance from the reaction of sodium bicarbonate and an acid in a sealed test tube).
- The department's insurance policy does not allow them (always worth checking!)

Whilst this may seem to be an unnecessarily constraining list that successfully removes

most of the 'best' demonstrations, it does not mean that the more spectacular demonstrations cannot be shown. Firstly, there is usually video footage available that can be played in a lecture. Videos of the more spectacular demonstrations (e.g. ignition of cotton wool soaked in liquid oxygen) can be found on the Web. In saying this, there is a word of caution to add in the use of videos. A live demonstration is always more impressive (see Table 1); the difference between a live and recorded demonstration is similar to the difference between live performances and TV. Furthermore, in a live demonstration there is ample opportunity for the teacher to communicate his/her attitude towards handling the chemicals.

Secondly, portable fume hoods are now more widely available. These can easily be brought into a lecture theatre (if it does not already have a fixed fume cupboard) to allow one to perform demonstrations that would otherwise be ruled out. Also, modern fume cupboards are often transparent on all sides, allowing the audience to see through the 'back' of the fume cupboard to the demonstrator who faces the audience. For instance, the ignition of a mixture of magnesium and barium perchlorate powders would be normally ruled out because of the potential of an uncontrolled flame and the generation of clouds of dust. Performed within a portable fume cupboard, this spectacular demonstration presents very little hazard to the audience (both flame and fumes are contained) and none of the visual impact is lost (Figure 3).

Indeed, with a portable fume cupboard, many of the more spectacular demonstrations can be considered. The only extra item to check is whether the filter for the fume cupboard is both regularly maintained and appropriate for the demonstration that is to be performed.

In the absence of a portable fume cupboard, it is always possible to perform the demonstration outside the classroom, say in a laboratory. Of course, this means that the students have to be moved from a classroom to a laboratory. Obviously, this disruption to a class is unsatisfactory, but the hassle of doing it should never be used as an excuse for doing the demonstration in a class room where it is patently unsafe; in those cases do not do that demonstration.

Figure 3. Use of portable fume cupboard to demonstrate ignition of barium perchlorate and magnesium powders.



Conclusions

Evidence presented herein and elsewhere suggests that the use of chemical demonstrations in class add to the student learning experience. Notwithstanding the likely benefits of demonstrations, there are questions to ask and answer before ever performing a demonstration. The most important of these questions is that of safety. But, with appropriate safety controls and common sense, safety procedures can not only be followed in full, but can also be amplified by the use of a demonstration.

No doubt there are teachers of chemistry who will still find it difficult to include demonstrations in their classes, for whatever reasons. However, in every case I know of where teachers have started to use chemical lecture demonstrations, they have continued, motivated by the positive impact they have had on their students and on themselves.

References

1. B. Z. Shakishiri, *Chemical demonstrations: a handbook for teachers of chemistry*, The University of Wisconsin Press, Madison, Wisconsin, 1983 and references therein.
2. G. M. Bodner, *U. Chem. Ed.*, 2001, **5**, 31.
3. H. Beall, *J. Chem. Ed.*, 1996, **73**, 641.
4. L. Cristiaens, A. Hieb, S. Cox, S. Kujawa, D. Hobbs, D. Coe, and A. Stierle, *Abstracts of Papers of the American Chemical Society*, 2000, **219**, 760.
5. L. A. Ford, *Chemical magic*, Dover Publications, Inc., 1993, Mineola, NY
6. H. N. D. Alyea and F. B. Dutton, Eds, *Tested demonstrations in chemistry*, Division of Chemical Education of the American Chemical Society, 1965.
7. D. A. Humphreys, *Demonstrating chemistry*, McMaster University, Hamilton, Ontario 1983.

Promoting active learning through small group laboratory classes

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Abstract

Limitations of routine laboratory work are summarised and the importance of synergy, time and motivation to the promotion of meaningful learning is identified. A recent attempt to promote active learning through the introduction of student-led pre- and post-lab sessions into two environment-based group laboratory assignments is described. The innovation was evaluated through a student questionnaire and classroom observations and a number of advantages and disadvantages of the approach are identified.

Introduction

Modern undergraduate practical classes have their origins in the 1820s when Liebig introduced laboratories for general student use at the University of Giessen in Germany¹ and the first book to deal with laboratory technique, Michael Faraday's *Chemical Manipulations*² was published in the UK. Laboratory work quickly came to be regarded as an essential and major component of chemistry teaching. The Royal Society of Chemistry in the UK typically requires a minimum of 200 hours practical work for any course to be recognised as being of graduate status and many degree courses contain far more. Quantity has, however, never been a guarantee of quality and traditional university teaching methods have been increasingly questioned over the past twenty years. While major concern has focused on the ubiquitous didactic lecture, the value of much laboratory work has also been questioned, with concerns expressed not only about the learning experience^{3, 4} but also about each of the following aspects.

- (a) *Cost*: Laboratory work is expensive in resources, time and space; with the present restricted funding it is increasingly viewed as a luxury.^{4, 5}
- (b) *Health and Safety*: Recent legislation has greatly reduced the freedom that can be given to students in laboratories and the resulting restrictions may well reduce both pedagogical value and student motivation.^{6, 7}
- (c) *Employment opportunities for graduate chemists*: Although the importance of Chemistry continues to increase (it underpins the Life and Earth Sciences, both old and new) the need for

traditional analytical chemists is decreasing. Increased automation of laboratory instruments has both changed the nature of the employment and reduced opportunities in many laboratories. While the skill of the analyst may still on occasion be critical, it is now common for the quality of the instrumentation to be the controlling factor in the work.⁸

- (d) *The changing nature of the student population*: A decreasing percentage of students studying chemistry intend to become practising chemists. The development of good laboratory technique is thus of limited value for the majority of our students,⁹ though it remains vital for those who do wish to go on to become professional chemists.

The idea of preparing the learner for laboratory activities is not new. Jenkins reported¹⁰ that discussion and written tests were being used to introduce practical work in secondary schools at the beginning of the last century. While similar approaches may well have been used from time to time in higher education, it is only recently that the rationale for and the aims of such pre-lab exercises have been clearly enunciated.¹¹ The past five years have seen a general interest in improving learning through such pre-labs, and a number of innovative and productive computer packages have been described.^{12, 13, 14} The use of post-labs to facilitate reflection and to promote the consolidation of learning would appear to be relatively new.^{15, 16} However, such an approach is clearly consistent with current theories of learning and is likely to become more widely used in the future.^{15, 17} The current study

differs from earlier work in that the students were given control of both pre- and post-lab activities.

Although the value of much laboratory work can justifiably be questioned, one surely can't be a chemist (or even a chemically educated person) without a sound appreciation of the role experimentation plays in the development and practice of the discipline. It is equally vital for non-scientists to appreciate what can and what cannot be achieved through experimentation. Laboratory work obviously remains essential to the development of a range of practical skills; there is a limit to what can be achieved through computer simulations and video discs¹⁸ and it is often asserted that practical work can help students to acquire knowledge and develop understanding of concepts, principles, models and theories.^{19, 20} It is also suggested that it is through practical work that students can begin to understand what scientists do.^{21, 22} After all, here we do have the active involvement of the learner. However, for meaningful learning to take place, it is the brain not just the hands that must be active. Unfortunately, effective thinking in the laboratory is often inhibited because of information overload in our limited working memory.²³ Although laboratories can provide a potentially rich learning environment, there does not appear to be any convincing evidence that routine laboratory work does in fact help students to understand concepts and theories.²⁴ However, where laboratory work is supported by the need for planning and outside reading, as in much project work, improved understanding may well occur.²⁵ Three factors, *synergy*, *time* and *motivation* can be seen as essential to the promotion of meaningful learning, although they rarely seem to be considered in the planning and implementation of practical programmes.

Synergy literally means working together, so that the whole is greater than the sum of the parts. Nowhere is this more important than in education, where everything that we learn has the potential to interpret, qualify, enhance and redefine a wide range of other things that we thought we already knew. Education isn't just about learning more, it also involves learning better, but it is only when new information is successfully related to what is already known that any meaningful learning will occur.¹⁷ It is therefore important to ensure that what students are being required to do in laboratories is linked as well as possible both to the formal lecture programme and to the world in which they live. All too often students see laboratory work as unconnected to other aspects of their tuition and it is here that pre- and post-lab assignments can be particularly useful, both to

identify and subsequently to consolidate the links to what is already known.

Thinking time is required to enable new information to be linked and interpreted.²⁶ Unfortunately, students seek to reduce the time they think about practical work to an absolute minimum. Laboratory instructions that enable students to follow a recipe to complete an experiment without even thinking about what they are doing thus militate against learning taking place.²³ However, appropriate pre- and post-laboratory tasks have the potential to promote more effective learning by increasing the time when students are required to be thinking about laboratory exercises.

Because learning is an active process, the learner must be motivated to make the effort to learn. Motivation is, however, an extremely complex issue. We need to distinguish between intrinsic or task-orientated motivation, which leads the learner to want to learn something for its own sake, and extrinsic or ego-orientated motivation, which leads the learner to learn something only to try and achieve some additional goal.²⁷ All too often students see laboratory work as a form of assessment and are motivated not by the opportunity to learn but only by the marks that may be obtained. To make matters worse, because they are required to do something different each time they go into a laboratory, our students rarely feel comfortable with what they are doing and tend to believe that they are poor practical workers. Thus, far from being motivated by practical work, many students actively dislike it and complain that it provides little reward in the way of marks for the time and effort that they are required to devote to it. Motivation is likely to be increased when students consider laboratory activities to be more relevant,^{28, 29, 30} are given greater control over the process^{30, 31, 32} or are permitted to work in small groups.^{33, 34} The current study made use of all three of these factors

Despite all their apparent potential to promote learning, our expensive and time consuming laboratory classes usually fall well short of expectation.³⁵ If practical work is to continue to play a significant role in the education of chemists, and non-chemists studying chemistry as part of their courses, it is essential that it should provide a meaningful and positive learning experience. To achieve this it is surely necessary that students be encouraged to think far more about what they are going to do, about what they are doing, and about what they have done in practical classes. It is also important that they should enjoy doing it. To promote these aims, student-led pre- and post-lab sessions

were recently introduced into two established laboratory assignments.

The Study

Student centered pre- and post-labs were introduced into two of the ten practical assignments associated with a second year module, *Environmental and Safety Issues*, taken by students on the B.Sc. (Hons) Applied Biochemical Sciences degree. All experiments were group based and all could have incorporated the innovation easily. The two chosen experiments, *Examination of a Natural Water Sample* and *Heavy Metal Analysis of Solid Samples*, were considered particularly suitable because students could be given responsibility for the collection of samples in these experiments. The water experiment required students to investigate a range of physicochemical parameters, i.e. appearance, odour, pH, conductivity, total dissolved solids and hardness. The heavy metal analysis required levels of lead and zinc to be determined by atomic absorption spectrometry. Although the metals to be analysed were specified, it is possible and probably desirable that in future the students themselves should decide which metals to investigate.

The week before carrying out either of these experiments, students in assigned groups of six or seven were required to discuss the factors they thought may influence the parameters they were to measure, agree what samples each student would obtain, and investigate and write a brief synopsis of their ideas as to how they expected the parameters to vary. They were thus being required to think about what they were going to do and to form a working hypothesis. This took place during the laboratory period and occupied about 30 minutes. The instructor provided no input at this stage and the students were free to choose their own samples. It is therefore fair to consider this to be a student led pre-lab. Water samples selected included samples from various locations on the River Lagan and samples from a range of lakes throughout Ulster, while solid samples included scrapings from the exhausts of motor vehicles using a range of fuels and dust sweepings from various locations.

Students were required to collect their samples and then carry out the analytical procedures during the next laboratory class. Standardisation of reagents and calibration of equipment, including any associated calculations, were shared by the group but all students were responsible for obtaining and investigating their own samples and for calculating their own results. The group was required to

reconvene in a subsequent laboratory period to pool the results obtained and to consider how the experimental results compared with their earlier predictions. The group was asked to revise their earlier ideas in the light of the results obtained and to suggest two additional samples that they would now like to analyse to support or check their ideas. This process appeared to take less than 30 minutes, again there was no input from the instructor and so this can be considered to be a student led post-lab. Students were required to submit a report in their laboratory books on the analyses personally carried out and also to submit a brief separate report on the group project and any conclusions they felt could be drawn.

Evaluation

A student questionnaire was used to assess student reaction to the approach and this was supported by my own classroom observations. The questionnaire was in two parts. The first six questions asked students to evaluate aspects of the practical programme in terms of both understanding of what they were doing and their enjoyment of the laboratory sessions, using a six point Likert scale,³⁶ and the remaining eight questions were open response. The questionnaire, which was anonymous, was given out at the end of the laboratory session in week 9 of a twelve-week semester. By this time all students had completed eight practical assignments, including the two featuring the innovations, and a safety incident role-play / case study. One student agreed to collect and return completed forms; thirty forms from a class of thirty-eight were subsequently returned. The missing forms were accounted for by absentees and early leavers and there was no reason to believe that the returned forms were not representative. The questionnaire, with responses to the Likert scale questions, is in Table 1.

The vast majority of students (29) clearly indicated that they much preferred the approach used here to that normally encountered in laboratory sessions. One student indicated that he/she much preferred the usual approach (Q7). Nine students suggested that they believed understanding/learning was improved, ten suggested that team working and communication skills were improved and two suggested that their confidence was improved. One student stated that they had learned to deal with people who wanted to do everything themselves and wouldn't listen to anyone else's point of view (Q8). Five students suggested that working with smaller groups would be an improvement, as it had proved hard to get everyone to cooperate. Five recommended that students should choose their own groups from friends

Table 1. Student Opinions on Laboratory Exercises**Course: Environmental and Safety Issues**

Please indicate, by ticking the appropriate box, how helpful you have found each of the following features with respect to (a) understanding and (b) enjoyment of laboratory exercises (*starting with 0 to indicate useless, rising to 5 where you would consider the feature indispensable*).

Q	Features of the course		0	1	2	3	4	5
1	Laboratory manual	(a)		1	1	7	14	7
		(b)		3	5	13	6	3
2	Working in groups	(a)		1	4	6	10	9
		(b)		1	3	2	7	17
3	Pre-lab discussion on sample selection	(a)		2	4	10	8	5
		(b)	1	4	5	13	4	2
4	Post-lab discussion on results obtained	(a)	1	3	4	7	9	6
		(b)	3	2	7	8	6	3
5	Pooling individual results	(a)	1	3	5	6	7	8
		(b)	2	5	2	10	8	3
6	Case study presentations	(a)			2	5	7	16
		(b)			2	6	5	17

7. How do you consider the general approach used in these practicals compares with normal laboratory sessions?
8. What do you believe you have gained by working in small groups?
9. What suggestions do you have for improving the working of the groups?
10. Which experiment did you find the most interesting? Why?
11. Which experiment did you find the least interesting? Why?
12. Do you have any general suggestions for improving these practical sessions?
13. How do you believe performance in these practicals should be assessed?
14. Any other comments you would like to add.

who could be relied on, while four suggested that there should be delegated tasks for each individual in the group (Q9).

Strong support was shown for the two pre-lab/post-lab experiments, with thirteen students naming the heavy metal analysis and nine identifying the natural water sample experiment as the one they found to be most interesting. However, no significant reasons were given for these choices. Only one student identified the session in the sewage laboratory as the most interesting, explaining that this experiment had enabled a question posed at an interview for an industrial placement position to be well answered (Q10). The sewage laboratory experiment was considered the least interesting session by the largest number of students (9), with a lack of direct student involvement being given by a number of people as the reason for this choice (Q11).

Students suggested that the practical sessions would be improved if they were required to do fewer experiments and if the demonstrators knew more

about what they were doing. Although this was referred to in only three of the returned questionnaires, criticism of the performance of the demonstrators is a cause for concern. A recent report suggests that active learning strategies can be undermined where demonstrators are either unfamiliar with or do not successfully fulfill their required roles.³⁷ Unfortunately, as no problems were apparent while the laboratory course was in progress and as the questionnaires were anonymous, the reasons for this criticism are at present unclear. It is, however, the intention to observe this interface more closely in future. Some students also suggested that they had found the pre-lab sessions particularly useful and that wider use of such pre-labs would be beneficial (Q12), much as reported previously.¹¹ Attendance, contribution, understanding and accuracy were suggested in various combinations as the recommended basis for assessment (Q13). No significant comments were made under Q14.

Students appeared to settle quickly into their assigned groups, with one individual usually taking on the role

of coordinator. Usually this individual was also the dominant contributor to the group's practical activities, though in two groups the coordinator seemed to adopt the role of 'foreman' and left most of the practical work to others. Following the pre-lab session students did appear, at least to my subjective eye, to have a greater sense of understanding and purpose about their activities. A few incidents of friction were observed between individuals in the groups, but these were rare. Students clearly discussed the tasks within the groups and thought about what they were doing. It was quite common for students to check values with each other to see if their earlier ideas were being borne out. However, once the group had accepted an idea, there was little evidence of any attempt to improve on this. This is consistent with the suggestions by Garratt³⁸ that students need to become familiar with a new learning approach before they can be expected to engage with it fully.

Conclusions and Reflections

This study illustrates the way in which an inquiry-type dimension can be incorporated into what are essentially expository or recipe-following types of exercise.³⁹ While the analyses described are likely to form part of the laboratory programme for a wide range of degree schemes, the present approach should enable students to appreciate why it can be important to continue to carry out such analyses. Analyses may be necessary for example to show compliance with legal standards or to establish spatial and/or temporal variations of the parameters. In a typical experiment a group of students analysed the lead and zinc content of dust sweepings from a garage floor, a number of domestic backyards from different locations in the Belfast area and a farmyard. The pre-lab discussion led to the suggestion that heavy metal levels were likely to be highest for the garage sample while levels for the other samples should decrease as sampling moves to more rural locations. However, the subsequent analyses showed that levels in the sample obtained from the farmyard were considerably higher for both metals than for any of the other samples. The post-lab discussion focused on possible activities in farmyards and recommended that analyses should be carried out on samples from other farmyards. The facilitation of discussion in peer groups through the pre- and post-lab sessions encourages deeper thinking about experiments before they are carried out and deeper reflection on the results than is usually found with recipe-following procedures. In addition, by giving students control of the process and the freedom to make choices, interest and motivation are likely to be increased.³⁰ Such experiments would

appear likely to promote what Burmester called⁴⁰ *scientific thinking*, as well as team working and time and task management skills.

Convenience of sampling was undoubtedly a major variable in the procedure discussed. There is little doubt that students could have been directed to collect an intrinsically more interesting set of samples or that students would welcome such help. On balance, however, it seems very likely that giving students more responsibility for the process produces a better learning outcome. Although ideas were discussed in the post-lab sessions, it was clear that students were looking for early resolution; once an acceptable idea had been tabled there appeared to be no interest in looking for alternatives or in trying to improve on it. This then is clearly an area for future improvement. We have no plans to move back towards a more teacher centred procedure and have decided that in future groups will be required to make an oral presentation of their results and ideas to the class. Each presentation will be followed by a general discussion of alternative ideas.

Student questionnaires, particularly those dependent on quantitative indicators like the Likert scale questions used here, must be interpreted with care if unwarranted conclusions are not to be drawn.²⁶ Nonetheless, some general conclusions are probably justified. Although a large majority of students expressed support for the arrangements, a small number were clearly unhappy with key aspects of this laboratory programme. This is consistent with the suggestion of Bodner⁴¹ that any significant classroom intervention is likely to be harmful to some students even though others will benefit. There was a significant variation between student opinion of effectiveness with respect to understanding and with respect to enjoyment for all aspects except the Case Study Presentation (Q6). This is important, because while cognitive and affective factors are not likely to be independent of each other, students clearly felt able to distinguish between them here. In general, students appear to feel that working in small groups helped understanding and, in particular, their enjoyment of the laboratory exercises (Q2). On the other hand, enjoyment and to a lesser extent understanding associated with the pre-lab discussion, the pooling of results and the post-lab discussion were rated much lower. Most of the problems identified in the free response section clearly related to problems with group dynamics. It seems likely that, while most students enjoy the social interaction of group work, many are not yet functioning efficiently as team members

The responses to the questionnaire strongly suggest that interest increases as students are given more control over their experiments. Twenty-two out of thirty respondents considered one of the two innovative experiments to be most interesting, while the afternoon in the *Sewage Laboratory*, which consisted largely of demonstrations by a technician, was considered the least interesting by the most students. Interestingly, of the six aspects assessed through the Likert scale questions, the highest rating for enjoyment and understanding was expressed for the Case Study Presentation. This involved groups representing the interests of various parties involved in a serious laboratory accident, thus generating direct competition between the groups. This appeared to result in high levels of commitment to, and cohesion within, the group. A positive effect of controversy on the promotion of learning has previously been reported.⁴²

There are also, however, a number of disadvantages associated with such experiments. Firstly, they are time consuming and there is a need to balance the perceived benefits of enriched learning from a particular task with the desirability of increasing the range of experimental work experienced.⁴³ One experiment on exhaust gas analysis was dropped and the sharing of tasks, such as calibration and standardisation, created the time for the pre- and post-lab discussions in the present case. Assessment is a more complex problem and it is likely to be both difficult and time consuming to differentiate reliably between group members. Currently each student is assessed independently for his/her individual sample analysis and a further mark common to the group is awarded on the basis of the pooled results and the pre- and post-lab reports. Although much-valued group working skills were being developed, there were clear examples of conflict within some groups and not all students appeared comfortable with this approach. Many students suggested that some of their peers were not pulling their weight, although this was clearly an oversimplification. There are many possible reasons for lack of cohesion within a group and it will be important to understand exactly why individuals are not working efficiently in such situations if we are to help them improve.

Expository type laboratory activities will continue to be needed to nurture the development of experimental technique and reliability with respect to data collection. Such experiments, however, do little to promote interest, are ineffective in promoting the use of higher order cognitive skills, and provide an unrealistic portrayal of scientific experimentation. The introduction of an inquiry-type dimension into an

experiment enables a *learning cycle*^{33, 39} approach to be taken. The results reported here suggest that such an approach is likely, in general, to improve both the learning experience and student motivation in laboratories. While not all experiments may be suited to such modification, several recent publications describe how expository procedures can be easily modified to introduce an inquiry dimension into laboratory activities. There is clearly a case for introducing such experiments into the early years of university courses before students become disenchanted with laboratory work.^{16, 32, 44, 45}

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References

1. J.J. Lagowski; *J. Chem. Ed.*, 2000, **77**, 818.
2. M. Faraday, *Chemical Manipulation*; London, W. Phillips, 1827.
3. D. Hodson, *Journal of Curriculum Studies*, 1996, **28**, 115.
4. P. A. Kirschner and M. A. M. Meester, *Higher Education*, 1988, **17**, 81.
5. J.Hanson, J.Hoppe, and W.Prichard, *Chem. Br.*, 1993, **27**, 871.
6. P. Borrows, *Educ. Chem.*, 1999, **36**, 158.
7. M. Pickering, *J. Chem. Ed.*, 1984, **61**, 861.
8. D. Gaskell, *Chem. Br.*, 2001, **35**, 35.
9. S.W. Bennett, *Educ. Chem.*, 2000, **37**, 49.
10. E.W. Jenkins, *Educ. Chem.*, 1997, **14**, 166.
11. A. H. Johnstone, R. J. Sleet and J. F. Vianna, *Studies in Higher Education*, 1994, **19**, 77.
12. J. Garratt, *U. Chem. Ed.*, 1997, **1**, 19.
13. B. S. Nichols, *U. Chem. Ed.*, 1999, **3**, 22.
14. J. Garratt, D. Clow, A. Hodson and J. Tomlinson, *Chemistry Education Reviews*, 1999, **14**, 51.
15. A. H. Johnstone, *J. Chem. Ed.*, 1997, **74**, 262.
16. M. A. Ditzier and R. W. Ricci, *J. Chem. Ed.*, 1994, **71**, 685.
17. G. M. Bodner, *J. Chem. Ed.*, 1986, **63**, 873.
18. J. Keeler, *Educ. Chem.*, 2000, **37**, 95.
19. A. Hofstein and V. N. Lunetta, *Review of Educational Research*, 1982, **52**, 201.
20. J. Head, *School Science Review*, 1982, **63**, 631.
21. R. M. Gagne, *Journal of Research in Science Teaching*, 1963, **1**, 144.
22. R. G. Gilbert, C. M. Fellows, J. McDonald and S. W. Prescott, *J. Chem. Ed.*, 2001, **78**, 1370.
23. A. H. Johnstone and A. J. B. Wham, *Educ. Chem.*, 1982, **19**, 71.

24. D. S. Domin, *J. Chem. Ed.*, 1999, **76**, 109.
25. M. L. Vallarino, D. L. Polo and K. Esperdy, *J. Chem. Ed.*, 2001, **78**, 228.
26. W. Byers, *U. Chem. Ed.*, 2001, **5**, 24.
27. R. J. Ward and G. M. Bodner, *J. Chem. Ed.*, 1993, **70**, 198.
28. R. A. DePalma and A. H. J. Ullman, *J. Chem. Ed.*, 1991, **68**, 383.
29. J. Bennett, *School Science Review*, 2001, **82**, **59**.
30. C. Hunter, S. Wardell and H. Wilkins, *U. Chem. Ed.*, 2000, **4**, 14.
31. T. P. Houghton and J. H. Kalivas, *J. Chem. Ed.*, 2000, **77**, 1314.
32. A.H. Johnstone and A. Al-Shuaili, *U. Chem. Ed.*, 2001, **5**, 41.
33. Y. J. Meichtry, *School Science and Mathematics*, 1992, **92**, 437.
34. M. H. Towns, K. Kreke and A. Fields, *J. Chem. Ed.*, 2000, **77**, 111.
35. M. S. Byrne, *Educ. Chem.*, 1990, **27**, 31.
36. Likert scale questions require a graded response to a simple statement. The Likert scale questions used in the present study invited responses from 0 to 5.
37. C. R. Landis, G. E. Peace, Jr., M. A. Scharberg, S. Branz, J. N. Spencer, R. W. Ricci, S. A. Zumdahl and D. Shaw, *J. Chem. Ed.*, 1998, **75**, 741.
38. J. Garratt, *U. Chem. Ed.*, 2001, **5**, 40.
39. D. S. Domin, *J. Chem. Ed.*, 1999, **76**, 543.
40. P. A. Kirschner, *Science and Education*, 1992, **1**, 273.
41. G. M. Bodner, D. MacIsaac and S. White, *U. Chem. Ed.*, 1999, **3**, 31.
42. E. G. Cohen, *Review of Educational Research*, 1994, **64**, 1.
43. D. Clow, *U. Chem. Ed.*, 1998, **2**, 21.
44. J. B. Allen, L. N. Barker and J. H. Ramsden, *J. Chem. Ed.*, 1986, **63**, 533.
45. C. Herman, *J. Chem. Ed.*, 1998, **75**, 70.

Critical Thinking

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In 1995, in response to the many messages that Chemistry departments were then receiving from employers about the skills they required from graduates, we put together a second-year module designed to improve IT and communication skills amongst our students. The course runs for 12 weeks, at 4 hours per week. For one of the sessions, designed to promote group working and critical thinking about chemistry, we have for some years used a selection of the exercises in *A Question of Chemistry* by J Garratt, T Overton, and T Threlfall. I actually started using this material some years before the publication of the book, having been introduced to it in a preliminary form at a Variety in Chemistry Teaching meeting in York.

For the session the class is split into groups of about 5 students, each with a designated 'leader' chosen at random. Each exercise is presented to the class, they are given a few minutes to discuss the task, and then each leader presents the group's conclusions, justifying their choice. The session thus meets at least two objectives: critical thinking about chemistry and teamwork.

The student response to this activity is overwhelmingly positive. Some of their comments are appended, under headings reflecting the two main objectives mentioned above. All but one student assessed the session as 'useful'.

Critical Thinking:

Makes you analyse and justify statements.
 Helps one think more about chemistry.
 Useful exercise in analysing information.
 Useful exercise in critical thinking.
 Nice way to discuss chemical problems.
 Increased awareness of the need to think about what one is reading.
 Helped learn how to summarise complicated material.
 Good to see that people have different ways of discussing chemistry and how such differences may alter meaning.

Group Working:

Group discussions are very important because communication is the key to enlightenment. Good to encourage group discussion. Helps get to know other members of the class better.
 More useful than just working on one's own.

Other comments:

Should do more of these.
 A good way to combine chemistry and teamwork. Improves individual confidence.
 Important lesson: sometimes it is best to stick to one's instincts.
 Be open-minded - don't follow others like sheep.

Clearly, the students find this exercise stimulating, and they all take part enthusiastically even though it is the one section of the course that does not contribute to their marks!

I can recommend this approach to colleagues.

Teaching experimental design

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Garratt and Tomlinson in their paper 'Experimental design – can it be taught or learned?'¹ elegantly demonstrate that even experienced, practising scientists may slip up in their experimental design when faced with an unfamiliar situation or subject matter. The paper presents the arguments for the essential feature of a scientific hypothesis: the need to formulate it in such a way that it can be disproved.

While this approach to experimental design is undoubtedly applicable in many cases, it has been argued² that Popper's methodology is not a complete account of how all of chemical research is done. Neither much of analysis, nor much of structure determination or synthesis is done by the formulation of a hypothesis and subsequent testing to try to refute it. Therefore I would question the value of any instruction in scientific method (whatever that is) that is anything other than the encouragement of students to carry out varied types of chemical experiments of increasing sophistication and independence, combined with

careful and guided analysis of what they are doing, why they are doing it and what the results may or may not mean.

Good experimental design is difficult; we have all read scientific papers in print or while refereeing, and spotted flaws in the experimental design that invalidated the conclusions claimed. And this was in papers by experienced scientists writing after careful consideration about their area of expertise and refereed by other experts.

There were two examples in recent years where flaws in the experimental designs of senior and experienced scientists were exposed very publicly indeed. These were ‘cold fusion’³ and Pusztai’s report on nutritional problems with genetically modified potatoes.⁴ Both topics are so important that the investigators must have known their results would be subjected to the closest scrutiny, so they must have believed they had got their experimental design and the derived conclusions right. However, in both cases the people reported results from fields on the edge of their expertise. This kind of case strengthens my belief that, in addition to clear thinking, it is necessary to have an intimate knowledge of the subject being investigated if one is to design reliable experiments producing valid conclusions.

So, we have to accept that all of us are fallible. However, this needn’t stop us preaching the importance and teaching the skills of good experimental design, since if we don’t, who will? But I believe this has to be done by example and with a case-by-case approach, in areas of the subject we each know best. Even the most mundane expository experiment can be used, with well-designed pre- and post-lab activities,⁵ to get students to think about what they did, how they did it, why they did it that way and what it means as a piece of science.

References

1. J. Garratt and J. Tomlinson, *U. Chem. Ed.*, 2001, **5**, 74
2. Max Perutz, *Is science necessary?*, OUP (pbk), 1991, Oxford, pp. 197-199.
3. F. Close, *Too hot to handle*, Princeton U.P., Princeton, 1991.
4. Royal Society report, June 1999, ref. 11/99; A. Trewavas, *Chemistry and Industry*, 22.5.2000, p. 334.
5. a) Pre-labs: A.H. Johnstone, *J. Chem. Ed.*, 1997, **74**, 262; b) Post-labs: B.S. Nicholls, *U. Chem. Ed.*, 1998, **2**, 10.

Calculating oxidation numbers of carbon in organic compounds and balancing equations of organic redox reactions

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We have observed two specific problems encountered by our students concerning oxidation numbers of organic compounds:

- They often have difficulty identifying whether reactions are oxidative, reductive, or non-redox.
- They cannot readily balance organic reactions; often this is not important, but is required whenever the stoichiometry of the reaction is important.

The currently accepted oxidation number method and ion-electron (half reaction) method for balancing inorganic reactions can be applied to balance organic reactions.¹⁻³ This approach also reinforces the concept of using oxidation levels to identify redox reactions, whilst its application to half reactions allows equations to be balanced simply and rapidly. However, although there are a number of published methods of determining oxidation numbers of carbon,^{4,6} we have found them to be generally unwieldy for students, thereby limiting their value.

We present here an equation that we have developed for rapidly determining the oxidation number of carbon in organic compounds, and extend this to offer a rapid and convenient method for balancing equations for organic redox reactions. Our equation is an easy-to-use expression of the general formula:

$$\text{Oxidation number of carbon} = 4 - (C + 2E + N)$$

Where C = number of C–C bonds.

E = number of bonds to ‘more metallic’ atoms (see below).

N = number of nonbonding electrons (zero for carbon, but relevant for heteroatoms such as nitrogen in nitro/amine – see below).

In general, E applies to ALL less electronegative atoms such as H, P, B, Si and to metals, but must be qualified to exclude all elements in the non-metallic region of the periodic table running down diagonally from carbon to iodine (thereby excluding Se and I). This generates a rule that is

applicable in virtually all examples that undergraduates are likely to encounter.

In the application of the oxidation number method for balancing equations of organic reactions,¹ we suggest that the determination of electron gain and loss for C directly (instead of first calculating the change in its oxidation number) is a useful short cut; students should be reminded that this is appropriate when only carbon changes its oxidation number, but they need to be aware of O/N/P sometimes doing so (e.g. peroxy, nitro, P^{III/V}). Breaking or formation of each C–H (or another less electronegative atom) bond means one electron loss or one electron gain for C, respectively. However, breaking or formation of each C–O (or another more electronegative atom) bond means one electron gain or one electron loss for C, respectively. By determining the net change in the number of bonds attached to C, the number of electrons ‘lost’ or ‘gained’ by C can be easily found in the oxidation or reduction of organic compounds. We exemplify these approaches with the dichromate oxidation of ethanol to ethanoic acid:

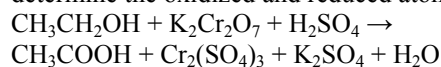
Oxidation numbers of the carbon atoms carbon in the starting material and the product:



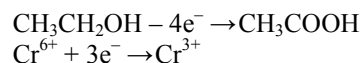
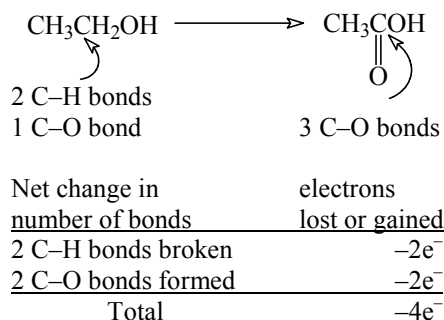
$$\begin{array}{ll} \text{C1: } 4 - (1 + 2 \times 2) = -1 & \text{C1: } 4 - (1 + 0) = 3 \\ \text{C2: } 4 - (1 + 3 \times 2) = -3 & \text{C2: } 4 - (1 + 3 \times 2) = -3 \end{array}$$

To balance the oxidative redox equation, electrons ‘lost’ or ‘gained’ by carbon atoms can also be found by determining the net change in number of bonds to carbon atoms (step B) instead of using oxidation numbers of carbon atoms.

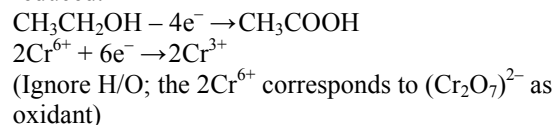
Step A: Write the unbalanced equation and determine the oxidized and reduced atoms.



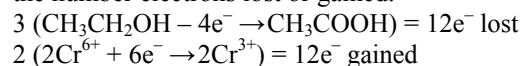
Step B: Write two partial equations. For the oxidized and the reduced C atoms, find the number of electrons ‘gained’ or ‘lost’ by determining the net change in number of bonds.



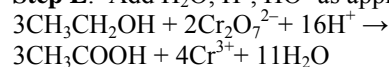
Step C: Balance the number of atoms oxidised and reduced.



Step D: Add coefficients to balance the change in the number electrons lost or gained.



Step E: Add H₂O, H⁺, HO[–] as appropriate:



References

- J.C. Bailar, T. Moeller, J. Kleinberg, C.O. Guss, M.E. Castellion, and C. Metz, *Chemistry*, Academic Press; New York, 1989.
- S.S. Zumdahl, *Chemical Principles*, Heath, Lexington, MA, 1995.
- G. Calzaferri, *J. Chem. Ed.*, 1999, **76**, 362.
- D. Kolb, *J. Chem. Ed.*, 1978, **55**, 326.
- E.M. Holleran and N.D. Jespersen, *J. Chem. Ed.*, 1980, **57**, 670.
- H.H. Sisler and C.A. Vanderwerf, *J. Chem. Ed.*, 1980, **57**, 42.

Administrators undermine degrees

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Following my recent experiences as an external examiner and on assessment panels, I fear that university administrators are undermining the quality of our undergraduate degrees, and we are acquiescing in this! In order to forestall potential criticisms of unfairness by external assessors (e.g. QAA) or students (litigation), universities are devising degree regulations that attempt to pin down precisely what is meant by the various classes of degree. As a consequence, many chemistry departments are required to follow strict marking and classification guidelines. The educational argument in favour of this approach is a powerful one:

- Surely, they say, we have identified the intended learning outcomes.

- Thus, we ought to be able to set and mark an exam to test for these.
- Hence, if the examinations and the marking process are fair, it is inappropriate to classify students on other criteria (e.g. the whim of external examiners moderating borderlines, or the performance of a student in an oral examination).

This, however, misses the point. Whilst it is easy to set exams that can be marked very precisely, such exams are not appropriate for testing many of the skills at honours degree level. The Chemistry Benchmarking document¹ identifies an excellent set of criteria for achieving various standards but, unlike in most subjects in the humanities/social sciences, it is possible in our discipline to set questions with a specific 'right' answer, thereby responding to the pressure to have precision in our assessment processes. However, I EXPECT questions to be set for which there are several possible answers, and these particularly test the 'key skills' that Dearing² and employers^{3,4} have identified as vital characteristics of high quality graduates (e.g. communication skills, critical thinking, etc.). In my experience, the rules imposed by many universities are leading us to set less demanding exam questions. Far better, surely, to set the exams we really think are appropriate at honours degree level, and ask respected fellow academics to comment on the exams and then provide moderation once they have seen how the whole of the assessment process has been conducted (i.e. the exam paper itself, the answers given, the marking process, the balance of assessment procedures, and any special factors).

Whilst one would rarely expect the classifications to vary greatly from pre-set guidelines (e.g. 70% = 1st, 60% = 2i, etc.), oral examinations offer an additional chance to correct for the imprecision of marking at this level, for students just missing a higher degree classification. Sadly, several institutions are now discontinuing oral examinations on the grounds that they discriminate against some students (don't all exams do that?), and because the assessment process 'ought to be

sufficiently accurate using the prescribed criteria'. It is my view that the orals not only help to ensure fairness just below the borderline, but that they help external examiners to assess the degree standards compared with elsewhere in the UK, and to provide more feedback for improving the courses.

Whilst I clearly have an old-fashioned view of the best way to maintain standards, it is ironic that I think the traditional approach is the most appropriate way of assessing the results of the very best and most innovative of teaching. One change I would advocate is that one external examiner should always be allocated from a pool of assessors (i.e. not chosen by the department), in order to ensure consistency. Although trained assessors were considered (but rejected) by the QAA about four years ago, the simpler procedure of drawing from a pool of experts (*cf.* EPSRC Colleges) has merit. In the long run, the assessment procedures have a profound effect on how courses are designed and delivered and therefore on how students learn, and on the skills they develop; I believe that we have a responsibility to ensure that we really do assess our students in ways that we believe are appropriate at degree level in Chemistry.

References

1. 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.
2. *Higher Education in the learning society*, report of the National Committee of Inquiry into Higher Education (chairman: R. Dearing), Crown Copyright, 1997.
3. *Change and Diversity: The challenges facing chemistry higher education*, report by Geoff Mason, Royal Society of Chemistry (with CIHE), 1998.
4. S.B. Duckett, C.J. Garratt and N.D. Lowe, *U. Chem. Ed.*, 1999, **3**, 1.