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# University Chemistry Education

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## Old wine in new skins: Customising Linear Audio Cassettes into an Interactive CDROM Format

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### Abstract

An audio cassette from the Educational Techniques Group Trust's 'Chemistry Cassettes' series entitled '*Entropy – the driving force of change*' has been adapted from a linear format into an interactive CDROM format. Details of this process are described together with a student evaluation process of this topic. The results of the evaluation were encouraging in terms of acceptance by the students and their performance for the numerical parts of the topic, though difficulties with the abstract aspects were still encountered. It was encouraging that a large number of students asked that more topics from the 'Chemistry Cassettes' series should be produced in interactive CDROM or on-line format.

### Introduction

In recent years, there has been considerable interest and activity in self-, distance- and computer-based learning in scientific education. For example, the Open University<sup>1</sup> has invested heavily in computer-based materials to enhance its programmes, the Chemistry Video Consortium<sup>2</sup> has developed material to promote self-paced learning for practical laboratories and there are many examples<sup>3</sup> of other Universities who have produced on-line courses. The Royal Society of Chemistry now has a significant on-line learning resource<sup>4</sup>, and many posters and demonstrations at the 'Variety in Chemistry Education' Annual Conference<sup>5</sup> feature computer-based resources. In all, a considerable amount of time, effort and money is being put into this area of education.

'Chemistry Cassettes'<sup>6</sup> were developed by the Educational Techniques Group Trust (ETGT) of the Royal Society of Chemistry in the 1980s and 1990s. They covered a range of topics (see Appendix I) and took the form of audio cassettes in which a practising teacher, an expert in the field, spoke for about 60 minutes, and these were accompanied by booklets containing diagrams and questions, designed to be studied in parallel with the audio cassettes.

Clearly the cassettes are now dated, particularly in terms of their mode of delivery. However, much of the content is still relevant today, and this makes them a useful potential resource for today's Chemistry courses. Since these cassettes contain a great deal of important chemistry presented by experts in both the subject and in teaching, it would be a pity to lose such a valuable resource.

Three questions arise: "Would it be a service to convert them into a format that rescues the content and converts it into a form that is a more valuable teaching method, e.g. a computer readable interactive learning package?" "How can the delivery of the audio cassettes be up-dated in practice?" and "Will today's students view them as useful learning resources?"

In this project, an attempt was made to update the mode of delivery of one of the cassettes, to ask a group of students to study the topic and the new interactive software, and to report back on their experiences.

### Adapting the audio cassettes

Significantly changing the content was deemed to be an unnecessary task for a number of the cassettes because the subject matter is 'timeless'. With

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others, this is not the case and extensive changes would be needed. Therefore the ETGT has looked at the possibility of improving the delivery of those cassettes where only small changes in content would be required. This would involve

- Digitising the audio file so that it could be played through a PC,
- Re-working the booklets to provide a computer-based format,
- Linking the audio and the contents of the booklet in a computer based package,
- Adding a quiz
- Retaining and enhancing the interactivity of the learning package.

To test the appropriateness of this approach, the ETGT produced a demonstration<sup>7</sup> CDROM covering just one of the cassettes, '*Entropy – the driving force of change*'. Because it is a demonstration CDROM, the links between the spoken commentary and the diagrams and questions were covered in two ways on a single CDROM. Navigation buttons were used to allow students to move between the two pages containing the different approaches. In the first, the student was expected to pause the audio and click on a numbered button to reveal a pop-up diagram or question (answers to questions could be revealed by using a 'right click' on the same button; e.g. Figure 1). In the second, a transcript of the text of the audio accompanied the audio and students were expected to scroll the text as they listened and to click on 'hot' words to reveal the diagrams and questions: e.g. Figure 2. In this project no attempt was made to compare the effectiveness of these two approaches and students were not asked which approach they used.

#### **Content of the learning package: '*Entropy – the driving force of change*'**

The original cassette<sup>8</sup> was designed for 'A' level/1st year undergraduate Chemistry students and is a largely qualitative look at the concepts of probability, entropy and free energy and their role in explaining the direction of change. The topics covered include

- A few observations on the direction of change and the need for a guiding principle
- Gases in containers – chance and the positional distribution of molecules
- Probability and entropy
- Entropy and the direction of change

- Some examples involving entropy increases
- The need to consider the distribution of energy
- Standard entropies – differences between gases, liquids and solids
- Entropy changes in chemical reactions – a qualitative approach
- Entropy changes in chemical reactions – calculating the value
- The importance of both the system and the surroundings
- Calculation of entropy change in the surroundings
- Calculation of the total entropy change and the importance of conditions
- Gibbs free energy
- Free energy and the direction of spontaneous change
- Calculation of free energy changes
- Extraction of metals from their ores – Ellingham diagrams

#### **The student evaluation process**

The next stage in the project was to test the CDROM with students. This was achieved by introducing the up-dated learning package to one hundred students on the first year course for honours chemistry and subsidiary chemistry at a leading UK University, who were asked to use it during the first semester of the first year of their course.

Specifically, the students were asked to study the topic using the learning package, to complete the associated course work (see Appendix II), and to complete a questionnaire on the learning experience (see Appendix III). Students were expected to study the topic as a self-paced learning experience. They were given a CDROM and some suggestions about how they should attempt the study (see Appendix IV). The learning experience was not managed in any other way by staff at the University.

#### **Results**

Of the one hundred students who took part in the project, fifty-two completed the course work and submitted the questionnaire. Although this topic would be a formal part of the course in the second semester, the remaining students failed to engage with it at the time of the project (see the discussion section below).

Figure 1: Using a numbered button to produce a pop-up frame

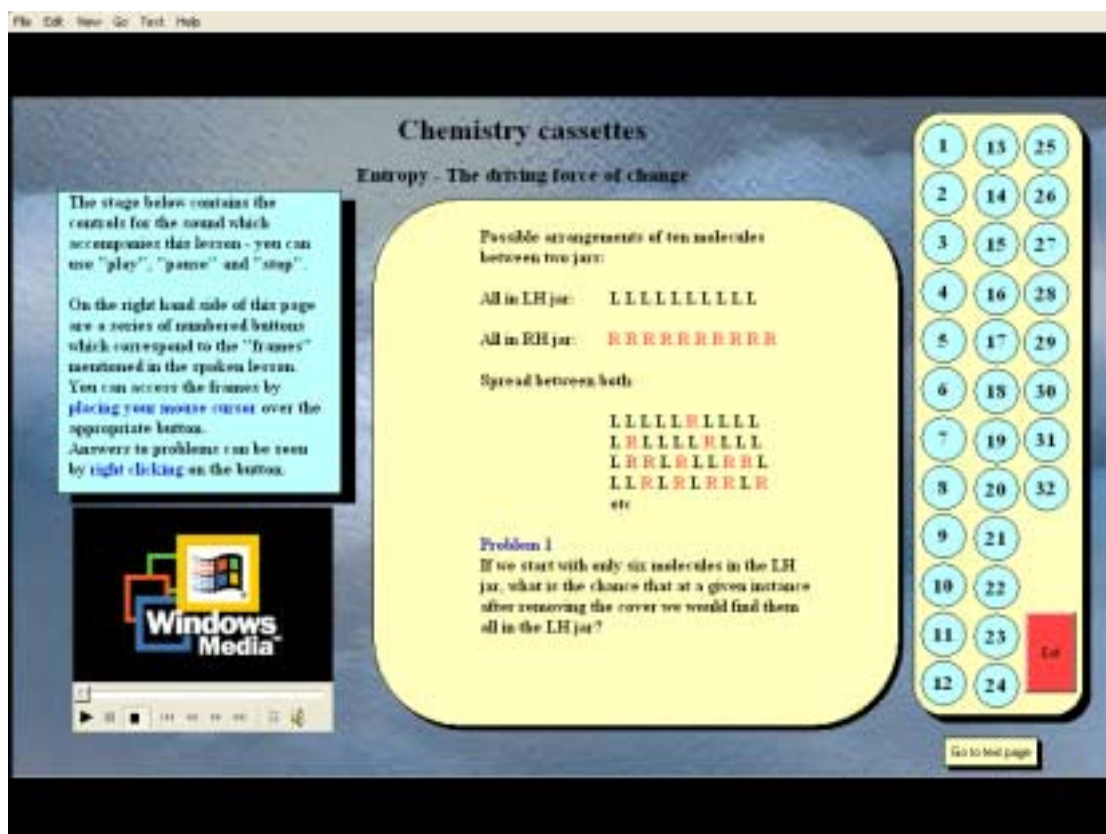
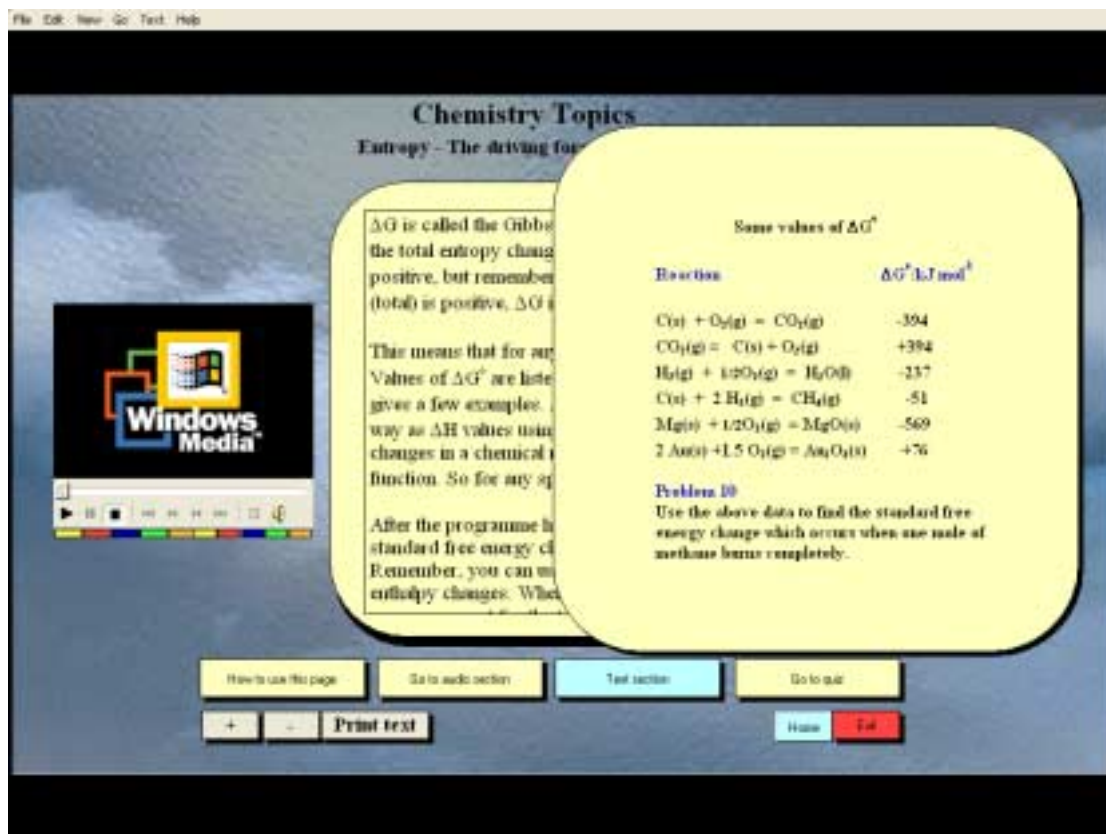


Figure 2: Using a hot-word to produce a pop-up frame



**Table 1. Questionnaire**

Question		1	2	3	4	5	6	7	8	9	10	11	12	13	14
<b>Responses</b>		48	48	47	45	48	48	47	48	48	48	48	48	48	48
<b>Average</b>		3.6	3.9	3.4	3.53	3.77	3.5	3.91	3.77	4.06	3.3	3.6	2.7	3.33	3.2
<b>Range</b>	Min	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Max	5	5	5	5	5	5	5	5	5	5	5	5	5	5
<b>Number</b>	5	9	12	6	12	17	10	14	17	17	6	13	5	2	8
<b>Answers</b>	4	21	26	20	15	14	13	18	13	19	16	11	4	24	12
	3	10	6	12	9	9	17	13	11	11	12	16	17	13	17
	2	6	1	5	3	5	7	1	4	0	12	6	16	6	3
	1	2	3	4	6	3	1	1	3	1	2	2	6	3	8
%>3		63	79	55	60	65	48	68	63	75	46	50	19	54	42
%<3		17	8.3	19	20	17	17	4.3	15	2.1	29	17	46	19	23

The results of the students completing the work are summarised in Tables 1 and 2.

**Table 2 Course work**

Number submitted	52
Average mark	60.2
Range of marks	27 to 90

The majority of students made no comments for question 15, but when comments were made, the main responses were

- Animate the diagrams
- Automatically scroll the text with the audio
- Annotate the diagrams
- Break up the text into smaller sections
- Do more topics in this way

## Discussion

The main aim of this work was to answer the questions of whether it would be a service to the community to rescue the contents of the chemistry cassettes and convert them into a form that is a more valuable teaching method, and whether today's students would view them as a useful learning resource.

The authors' view is that the cassettes contain a great deal of important chemistry presented by experts both in the subject and in teaching, and this project has shown that it is possible to overcome the main shortcomings – the datedness of their presentation. The project has shown that it is possible to produce a computer based learning package with greater interactivity, including a self-assessment quiz, from one of the cassettes. Further, the project has shown that the computer based

learning package works as a learning resource, with a significant number of students endorsing the package. However, the project has raised further questions, which point the way to further studies in this subject.

Firstly, the question of why such a large number of students failed to complete the course work needs answering. Did the students see this entropy course-work as an optional extra to their course, and should staff have played a more active role in managing the learning experience? Coupled with this comment is the question of exactly how such a resource could be best used in a University course – as an integral part of the course; as an add-on extra for revision or support to the main teaching or as a diagnostic tool for staff? The current project has already revealed student strengths (skill at numerical calculations) and weaknesses (understanding of the concepts of probability) in this area of chemistry.

Secondly, the question of whether a student questionnaire was the most appropriate way to judge the usefulness of the learning package needs addressing. Is there a better way of judging the effectiveness of the package as a learning tool? It is now clear that there should have been an attempt to compare the students' performances on this part of the course with those on other parts and this will be a feature of any further work.

Thirdly, what of the other chemistry cassettes? Should this work be repeated using one of the other topics? If the conversion is deemed to be of value, how will the other cassettes be converted? The task is not small and the ETGT may need to ask for volunteers to help with the work

## Conclusions

It has to be assumed that those students who did not return course work and questionnaires did not

complete the study of this learning package, and it was disappointing to see that forty-eight out of the one hundred students fell into this category. It is suggested that this situation would have been improved if staff had taken a much more active role in managing the learning experience, perhaps meeting with students to assess progress regularly, and perhaps introducing tutorials at appropriate parts of the course. To put the situation into context, lectures were not delivered on the topic during the coursework period; these come on stream during the following term together with appropriate tutorials. It is also possible, therefore, that the project was tried at too early a stage in the students' course, and the students may not have been aware of the help this exercise would give them in mastering an important topic later.

However, the results for the students who did complete the project were encouraging. For example, even though course-work was undertaken as part of this project and before the lectures and tutorials in term 2, the marks fell in the range 27 to 90% with an average of 60, showing a very good spread, indicating that the course work was discriminating, and a good average mark showing that the learning experience was effective. Student responses to the learning experience were also encouraging with most questions in the questionnaire receiving the majority of replies in the '3, 4 and 5 categories', and it was also encouraging to see the large number of students who would like to see more topics developed in this way. Some students had taken the time and trouble to identify such topics: e.g. Ionic crystals; Ions in solution; Some organic reaction pathways; Some reaction pathways of double bonds; Aromaticity; Symmetry in chemistry; Quantisation; The architecture of matter; pH and its measurement; The periodic law; An introduction to NMR spectroscopy; Radicals and their reaction pathways.

Staff marking the course-work were able to identify particular student problems with their understanding of 'Entropy'. For example, students generally did well on the numerical parts of the topic, and much less well on the more abstract idea of the meaning of probability and entropy. In particular, many students were unable to relate their ideas of probability and entropy to available energy levels. This should lead to more effective teaching in the forthcoming year.

The project reported here is a preliminary study but it has encouraged us to continue with the development and updating of these materials.

## Acknowledgements

We thank Miss Fiona Walker and the Royal Society of Chemistry for making available a full set of files for "Chemistry Cassettes" via the www (see [www.rsc.org/chemistrytopics](http://www.rsc.org/chemistrytopics)), the ETGT for supporting the adaptation, and the students for their participation in the evaluation process.

## References

1. The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK. (Examples include 'The molecular world'; 'Metals and chemical changes'; 'The third dimension'; 'Separation, purification and identification'.)
2. The Chemistry Video Consortium, c/o Dr A.J. Rest, School of Chemistry, University of Southampton, SO17 1 BJ, UK. (Examples of computer-based work include 'Physical Chemistry Experiments'; 'Practical Laboratory Chemistry'; 'Le Bon Geste Practique en Chimie')
3. Universities employing significant computer-based learning in science include College of Charleston, Penn State University, University of Illinois, University of California, Imperial College, and Leeds University.
4. The Royal Society of Chemistry, Burlington House, Piccadilly, London, UK, W1J 0BA whose contributions include its Library and Information Centre Knovel databases ([www.rsc.org/library](http://www.rsc.org/library))
5. Variety in Chemistry Education (Teaching) is an annual conference for staff in Higher education run by the LTSN Centre, Department of Chemistry, University of Hull, Hull, HU6 7RX, UK ([www.physsci.ltsn.ac.uk](http://www.physsci.ltsn.ac.uk))
6. ETGT commissioned and published a series of audio tapes and booklets by leading experts from 1975 to 1990
7. Details of the demo CDROM are available from Dr A. J. Rest, School of Chemistry, University of Southampton, SO17 1BJ, UK, or from Dr D. Brattan, [dbrattan@hotmail.com](mailto:dbrattan@hotmail.com).
8. 'Entropy – The driving force of change' by Dr Graham Hill who was deputy Head Master at Dr Challenor's Grammar School, Amersham and John Holman, who was Head of Science at Watford Grammar School

## **Appendix I**

### **Some aspects of the Electrochemistry of solutions**

by Graham Hills

### **Ion Selective Electrodes**

by Arthur Covington

### **pH and its measurement**

by Arthur Covington

### **Ionic Crystals**

by R B Heslop

### **Solving Inorganic Spectroscopic problems**

by Alan Vincent

### **Ions in solution**

by John Burgess

### **The periodic law**

by David Johnson

### **Some organic reaction pathways**

by Peter Sykes

### **Some reaction pathways of double bonds**

by Peter Sykes

### **Radicals and their reaction pathways**

by Peter Sykes

### **Aromaticity**

by Peter Sykes

### **Linear free energy relationships**

by Peter Sykes

### **Symmetry in chemistry**

by Sid Kettle

### **The theory of transition metal compounds**

by Sid Kettle

### **Coordination chemistry**

by Sid Kettle (two cassettes)

### **An introduction to NMR spectroscopy**

by Bruce Gilbert and Richard Norman

### **Quantization**

by Peter Atkins

### **X-ray crystallography I**

by Stephen Wallwork

### **X-ray crystallography II**

by Stephen Wallwork

### **The chemistry of biological nitrogen fixation**

by Raymond L Richards

### **Heavy metals as contaminants of the human environment**

by Derek Bryce-Smith

### **Using chemical abstracts**

by an ETGT/RSC editorial team

### **The architecture of matter**

by Graham Hill and John Holman

### **Competition processes**

by Graham Hill and John Holman

### **Entropy- the driving force of change**

by Graham Hill and John Holman

## **Appendix II: Entropy demonstration CDROM – some questions**

1. 20 gas molecules are placed inside a container that has two identical sections. What is the chance of finding all 20 molecules in one of the sections?
2. Use the ideas of probability to explain why the entropy of the system increases when
  - b) a solid melts



- c) the temperature of a gas increases
- d) two gases are mixed

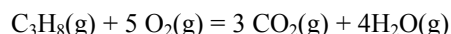
Your answers should not exceed more than 100 words for each section of this question.

3. Plots of free energy against temperature for the following reactions are linear, described by the equations given.



Explain why the two plots have such different gradients.

4. Use the data given below for the reaction



to calculate

- a) the standard enthalpy change at 298 K
- b) the standard free energy change at 298 K
- c) the standard entropy change at 298 K

The standard entropy change in the surroundings and the total entropy change that would accompany the reaction at 298 K

Comment on your results.

	$\text{C}_3\text{H}_8(\text{g})$	$\text{O}_2(\text{g})$	$\text{CO}_2(\text{g})$	$\text{H}_2\text{O}(\text{g})$
$\Delta G_f(298)/\text{kJ mol}^{-1}$	-23.4	0	-394.4	-228.6
$\Delta H_f(298)/\text{kJ mol}^{-1}$	-103.8	0	-393.5	-241.8
$S(298)/\text{J mol}^{-1} \text{K}^{-1}$	270.0	205.1	213.7	188.8

### Appendix III: Questionnaire

Please answer the following questions by circling one of the numbers; **5** indicates a positive response and **1** a negative response to a question.\*

[\* A referee commented that this was a rather vague instruction and the wording may have weighted the numbers of 1 and 5 responses gained. It would have been better to say that 4 and 5 represent positive responses, 1 and 2 negative responses and 3 represents a neutral response. With hindsight we agree with this comment but this questionnaire was the actual one used.]

a) **The format of this package.**

1. The learning package was easy to use

1      2      3      4      5

2. The instructions for using the package were simple to understand

1      2      3      4      5

3. The links between the audio text and the pictures/frames was easy to control

1      2      3      4      5

4. Using 'right click' to obtain answers to the questions was satisfactory

1      2      3      4      5

5. Being able to read the text and listen to the audio at the same time was useful

1      2      3      4      5

6. The ability to vary the size of the text on the screen was helpful

1      2      3      4      5

7. The quiz at the end of the learning programme was a useful revision exercise

1      2      3      4      5

8. Being able to print out the text and/or the frames was useful

1      2      3      4      5

9. It would have been helpful to have had section headings/numbers and page numbers for the text

1      2      3      4      5

10. This was a useful way of studying a topic, e.g. entropy and free energy

1      2      3      4      5

11. I would rather have studied this topic in a lecture/tutorial situation

1      2      3      4      5

12. I would rather have studied this topic by reading a book or written handouts

1      2      3      4      5

13. This learning package has helped my understanding of the subject

1      2      3      4      5

14. I would like to see other topics developed in this way

1      2      3      4      5

15. Please feel free to write any other comments about this package (either positive or negative views would be welcome).

Additionally, it would be particularly helpful to know whether you think scrolling the text files alongside the commentary is a good idea and which other titles from Appendix 1 you would like to see customised into CDROM format (question 14).

#### **Appendix IV: Suggestions about how to study of the learning package**

Although the audio part of this learning package lasts for just over **40 minutes** in length, the overall package should be considered as involving from **five to six hours of study time** because it will be necessary to study the diagrams and frames which accompany the audio tape and attempt the problems. It is therefore suggested that you study the package in **five roughly equal, parts** and take about one hour on each part. Make some summary notes on each part and, before you start another part, quickly **revise the previous part** by using your notes or listening to that part of the audiotape again.

A possible breakdown of the package could be:

- A few observations on the direction of change and the need for a guiding principle; gases in containers – chance and the positional distribution of molecules; probability and entropy; entropy and the direction of change; some examples involving entropy increases.

- The need to consider the distribution of energy; standard entropies – differences between gases, liquids and solids; entropy changes in chemical reactions; a qualitative approach; entropy changes in chemical reactions; calculating the value
- The importance of both the system and the surroundings; calculation of entropy change in the surroundings; calculation of the total entropy change and the importance of conditions
- Gibbs free energy; free energy and the direction of spontaneous change; calculation of free energy changes
- Extraction of metals from their ores – “Ellingham diagrams”

## Ideas Underpinning Success in an Introductory Course in Organic Chemistry

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e-mail: N.Reid@mis.gla.ac.uk**Abstract**

Students coming to university chemistry courses have often been taught a considerable amount of organic chemistry at school level and may bring to their university course important ideas. These ideas are discussed in the context of the Scottish Higher Grade Chemistry course. The extent to which these ideas have been understood was measured with 367 first year chemistry students before the students started their first organic chemistry course at university, using structural communication grid questions. Their understanding was related to their performance in the class examination at the end of the course. It was found that bond polarity was the area of greatest difficulty, with problems also arising from the student understandings of functionality and stereochemistry. What this study has shown is that certain ideas in school chemistry are well established, and others are not so well established, and that performance in a first level chemistry course in specific areas of organic chemistry reflects the grasp of the underlying ideas gained from school. This emphasises the importance of knowing what ideas pupils bring with them from school courses and how they came to gain these ideas. It also pinpoints some topics that may need to be developed further before introducing new organic chemistry ideas.

**Introduction**

Organic chemistry has gained importance in general education in secondary schools during the 20th century and this has had effects on higher education courses. Students at the University of Glasgow in their first year of study of chemistry take a course in organic chemistry covering the various functional groups and the general physical and chemical properties of organic compounds. The course is taught mechanistically, seeking to show the students why the various groups of organic compounds behave in the way observed. Reactivity and stereochemical aspects are introduced where appropriate. Students are encouraged to ask questions such as, "what class of organic compound is this?" "what kind of reaction can I expect it to undergo?" "are there any specific aspects to the reactivity of the compound that I need to bear in mind when deciding on the likely product(s) of the reaction?"

One of the major organisational principles of first year organic chemistry is functionality. In high school and university chemistry courses, textbooks usually present the chemistry by functional groups. Although students may memorise these groups, confusions often occur. It is not easy to see how functional groups can be *understood* although the properties of these groups can be presented in such a way that they make sense. Experience and practice is needed to enable the student to gain confidence with functionality. At school, structure is often presented before reactions are

discussed, while, in a university course, the third 'layer' of mechanistic rationalisation is frequently added, along with a more sophisticated presentation of stereochemistry.

Inevitably, organic chemistry can be somewhat like a foreign language for first year students. Students must learn the vocabulary (names, functional groups) and the grammar (reactions, mechanisms) in order ultimately to develop a rudimentary style of composition (mechanistic explanations, evidence of structures). The mechanistic approach is an attempt to present a bewildering array of information in such a way that an underlying structure and rationalisation can be perceived and understood.

**Historical Perspective**

In the 1960s, there were many science curriculum projects at school level and, in Scotland, new chemistry syllabuses emerged in 1962 at school level. The Scottish Alternative Chemistry syllabus<sup>1</sup> was fully evaluated in the late 1960s<sup>2</sup>. A common feature of such syllabuses was to present an updated content in a logical order<sup>3, 4, 5</sup> and organic chemistry assumed a higher profile.

One of the major aims in all these curriculum and syllabus developments was to promote student *understanding* of the basic chemical concepts. Much is now known about difficulties in understanding concepts in science curricula and it has been argued<sup>6</sup>

that a better approach might be to present the material in an order that takes into account the psychology of the learner rather than the internal logic of the subject which may only be apparent to relatively advanced learners.

Early studies on the Scottish syllabus showed that topics like esterification, hydrolysis, condensation, saponification, and carbonyl compounds posed problems<sup>7</sup> while a few years later, the problem of recognising functional groups was explored.<sup>8</sup> As a result of this early work, the presentation of organic chemistry at school level was modified in the Scottish system and this was reflected in the new textbooks.<sup>9</sup> At the same time, ideas were being developed to explain *why* the problems existed where they existed, in terms of the way the learner handles information.<sup>10</sup>

### Underlying Ideas

This project seeks to focus on the learning of organic chemistry at first year university level. In looking at a first year university course, it is important to recognise that students come with experience gained at school (the Scottish Higher Grade). Some of this is information that they have remembered, but of greater significance is the grasp of the ideas that underpin organic chemistry, these ideas coming from their school experience.

At school level in Scotland, laboratory work and taught material are highly integrated. Nonetheless, it is still not always easy to link the molecular understanding to observations. This point was well made by Johnstone<sup>11</sup> when he pointed out that understanding chemistry involves working at three levels: the level of the macroscopic (phenomena which are open to the senses); the level of the sub-microscopic (the molecular level); and the level of the symbolic (the use of chemical and algebraic equations to represent or describe a phenomenon). The point that Johnstone was making is that it is difficult for the new learner to operate easily at all three levels simultaneously. However, in the learning of organic chemistry, it is customary to present the material at the start in symbolic form (symbols and equations) with reactions being interpreted at the molecular and electronic level by means of mechanistic representations.

Another weakness of the school presentation lies in the way organic chemistry is laid out. The entry point is through hydrocarbons, often related to the oil industry. This moves on into cracking and polymerisation. Quite inadvertently, the emphasis is placed on the carbon skeleton, with pupils having to remember the naming systems for hydrocarbon homologous groups along with basic ideas of isomerism. Later at school, and much more at university level, the emphasis moves to the idea of functionality in that reactivity is determined largely by functionality. In this, the carbon skeleton

becomes much less important apart from, of course, its stereochemical features. Thus, pupils are taught initially to focus on the skeleton and then they have to switch to the functional groups. It is little wonder that, at times, organic chemistry becomes a strange world where the manipulation of the symbols C, H and O develops a confusing algebra all of its own.

Gagné<sup>12</sup> and Ausubel *et al.*<sup>13</sup> both agree that prior knowledge can influence learning, but there is a major difference in their ideas regarding the nature of the influence of prior knowledge. Gagné considered the optimum order to be teaching sub concepts on the way to developing higher concepts, leading to a hierarchy of learning. On the other hand, Ausubel considered that learning is an active process in which students construct their own meaning from new information. In other words, a concept has to be reconstructed when it passes from the teacher to the student and meaningful learning is an active process of transferring new knowledge into the existing knowledge in the individual's cognitive structure. Ausubel stated that: "If I had to reduce all of educational psychology to just one principle, I would say this: The most important single factor influencing is what the learner already knows. Ascertain this and teach him accordingly."<sup>13</sup>

Ausubel's emphasis was on meaningful learning. According to Ausubel *et al.*<sup>13</sup> and Novak,<sup>14</sup> learning will be 'rote' if the material to be learned lacks logical meaning or the learner lacks the relevant ideas in his/her own cognitive structure. This study seeks to offer some insights into the underlying ideas held by students in an attempt to pinpoint those areas where the problems are greatest.

### This Study

The aim of this study is to focus specifically on some of the underlying ideas that students bring with them from school chemistry and to see the extent to which basic organic chemistry concepts are held in the long-term memory of first year students *before* they start their university organic chemistry course. The results will then be related to student success in the university course. Four underlying concepts were identified arising from the Higher Grade syllabus: the nature of the covalent bond; bond polarity; stereochemistry and the importance of molecular shape; and functionality.

Structure is absolutely critical when learning organic chemistry. It forms the basis for predicting and rationalising reactivity on the molecular scale and physical properties at the macroscopic level. The central theme of the teacher's approach at university level is to emphasise the relationship between structure and reactivity. To accomplish this it is necessary to choose a teaching strategy that combines the most useful features of the traditional functional group approach with one based on reaction mechanisms.

Such an approach aims to emphasise mechanisms and their common aspects as often as possible, along with the functional groups and the structural aspects, to offer to the students a meaningful insight into organic chemistry.

For this approach to work, it is important that students have a clear grasp of the underlying ideas: structure and stereochemistry, the ideas of bond and molecular polarity, and the nature of the chemical bond and formal charge. In this way, the student can make intuitive sense of mechanisms. Of course, students need to know, and recognise with confidence the important functional groups.

Chemists have devised various types of two-dimensional diagrams to represent three-dimensional structures. All these seek to present on paper what is a three-dimensional structure. Not all are equally effective in terms of the informational value they possess.<sup>15</sup> In work done many years before, Johnstone *et al.*<sup>16</sup> demonstrated that students needed to move backwards and forwards between two dimensional and three dimensional representations using physical models, illustrations and paper representations. Looking at molecular models is not enough; they have to be handled, rotated, and manipulated.

The stereochemistry of organic molecules is generally controlled by the 'rules' of geometry, coupled to the laws of electrostatic repulsion. This approach is well developed in one textbook for school use<sup>9</sup> but most texts do not develop these ideas at school level, and school leavers may not be able to relate the physical reality of the three dimensional structure to the two dimensional representations, some of which bear little relation to the actual molecular shapes.

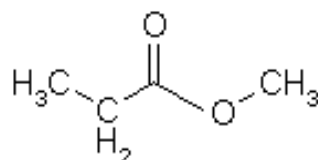
There are many studies which look at issues relating to the three dimensional problem. Some have addressed the issue whether molecular models really contribute to the better understanding of the concepts of the atom and the molecule<sup>17, 18, 19, 20</sup> while others have used computer simulation.<sup>21</sup>

Baker and Talley<sup>22</sup> stated that: "An examination of the type of thinking that is required for mastery of chemistry indicates that visualisation of chemical reaction by the use of physical models is an important vehicle for the communication and analysis of chemistry concepts". In another report, Baker<sup>22</sup> noted that students find stereochemistry very difficult to grasp. He explained that this arises largely owing to the restrictions inherent in a lecture-theatre environment, where molecular shapes are necessarily drawn using the blackboard or paper. While large ball-and-stick molecules can be used to illustrate the idea of shape, mirror image and enantiomers, he concluded that the best teaching exercise for the students is for them to manipulate the models themselves, confirming

Johnstone's findings.<sup>23</sup> Many<sup>21, 24, 25, 26</sup> have used molecular modelling in an undergraduate chemistry curriculum and have argued that they offered real benefits to students in understanding concepts.

However, in many models of learning, a *mechanism* for learning is missing.<sup>27</sup> Such a mechanism of learning can show us what the reasons are for the difficulties in understanding certain concepts in organic chemistry or in science generally and can help students' teachers/lecturers to avoid problems. Such a mechanism can be found in an information processing model.<sup>28</sup> This draws on other models of learning but offers interpretation in terms of information flow and processing.

Johnstone<sup>29</sup> and Johnstone and El-Banna<sup>30</sup> confirmed that working memory space has a very limited capacity and, when exceeded, this can make learning almost impossible. When this is applied to the learning of organic chemistry, the problems are readily apparent. Take a 'simple' molecule such as  $\text{CH}_3\text{CH}_2\text{COOCH}_3$  (methyl propanoate), which can be represented as



If a person who knows no organic chemistry was presented with this structure for ten seconds and then was asked to reproduce what he saw, the task would probably be well beyond his capabilities. This is simply because the amount of information in the structure is well beyond the working memory space capacity of the learner.

However, another person with some knowledge of organic chemistry might be able to group the  $(\text{CH}_3\text{CH}_2)$  group as a 'chunk' (with or without the name 'ethyl') and recognise the ester functional group (COO) as a 'chunk' and the final methyl group as a third 'chunk'. This has the potential to reduce the load to three pieces only. Provided that the linkages can be appreciated, this gives the person a chance of holding the formula within the capacity of the working memory. An experienced chemist would see the structure as one unit or 'chunk' (methyl propanoate) and would be able to store, reproduce or manipulate such structures easily within the working memory. The novice learner has no such ability.

However, while working memory is important, what is already held in long term memory is also important for new learning. What is already known provides a filter to select and interpret new information. In addition, new information, if it is to be understood meaningfully, has to be linked on to information and concepts already held in long-term memory.

Generally speaking, learning involves the linking and interpreting of incoming information with what is already known by an individual.<sup>13</sup> As each person has different stores of knowledge in long-term memory, each may interpret incoming information differently. If the new information cannot be linked on to previously held ideas in a meaningful way, then the student may resort to rote memorisation. None of these, of course, represents acceptable learning outcomes from the perspective of the teacher.<sup>31, 32</sup>

### Scottish School Chemistry

Students are taught organic chemistry from S3 (age around 14) in Scottish secondary schools. At the start, the work is centred on hydrocarbons, the oil industry and related materials such as plastics. Later, they start a brief look at food chemistry, with some reference to ethanol and ethanoic acid. While ideas like isomerism are considered, there is a very limited development of ideas of functionality and organic reactivity.

In the Higher Grade course (age around 16-17), organic chemistry is treated more systematically. The reactions of various functional groups are discussed, especially those of alcohols, acids, aldehydes and ketones. Often there are attempts to emphasise patterns in properties and reactions. Nonetheless, pupils can resort to memorisation in an effort to achieve examination success.

Examination performance at school level suggests that students cope fairly well with carbon chains, simple naming and isomerism. However, the move towards organic reactivity and the focus on functionality has less to do with the initial emphasis on carbon skeletons. Another problem may arise because organic reactions seem different from other reactions in that, in many reactions studied, things seem to proceed slowly (compared to many ionic solution reactions already met). While the nature of covalent bonds and bond polarity have been developed, the significance of these ideas in the context of organic reactivity may not always be apparent to students meeting organic reactions for the first time.

The covalent bond and the ionic bond are introduced early in the syllabus at school. Bond polarity and the polar covalent bond are often taught later, perhaps implying that the polar bond is less common. The idea that bonds can be made to be polarised by external electrophilic or nucleophilic reagents is not really developed much at the school level. At this stage, there is little concept of organic reaction mechanisms in general, including the stereochemical aspects of reaction mechanisms.

While there is no specific emphasis on reaction mechanism at school courses, students should have

some understanding of the following key basic concepts related to organic chemistry:

- (i) The nature of the covalent bond
- (ii) Bond polarity
- (iii) Stereochemistry and the importance of molecular shape
- (iv) Functionality

To explore what the students bring with them on these four concepts as they face their first university organic chemistry course, a test was devised, mainly in a structural communication grid format.<sup>32</sup> Their performance in this was related to the students' performance in their class examination.

### Structural Communication Grids

Structural communication grids have been developed and used by several researchers.<sup>33</sup> In a recent study,<sup>34</sup> the strengths and weaknesses of structural communication grids as assessment tools for school pupils have been studied. Structural communication grids involve data being presented in the form of a numbered grid and students being asked to select appropriate boxes in response to set questions. Use of these grids gives an insight into sub-concepts and linkages between ideas held by students, so that understanding can be assessed.

One of the advantages of this technique is that the contents of the boxes can be words, phrases, pictures, equations, definitions, numbers, formulae and so on. The content of the boxes can be varied, so that they can be made suitable for visual as well as verbal thinkers. Numerous questions can be asked and the format almost completely eliminates the problems of guessing, because the student does not know in advance how many boxes are needed for an answer. Credit is also given for partial or incomplete knowledge. Grid questions can be designed to assess a student's degree of understanding of the topic and can be offered as a self-assessment technique that could help pupils identify their weaknesses and strengths. Selected wrong answers can point to particular misunderstandings and the flexibility of the structural communication grids as an assessment and diagnostic tool is enormous. The use of structural communication grids in a research context has been discussed by Reid.<sup>35</sup>

### The Experimental Study

This study had the following two aims:

1. In the light of the organic chemistry taught at school and the way it is presented, the aim is to explore the level of understanding of four underlying concepts just before first year students start their first organic course at

university. Of course, it is recognised that there is a time gap between the school study and the time of the measurement of these conceptual understandings.

- Following this, the second aim is to relate this understanding of underlying concepts to performance in the chemistry examinations used in the first year course at Glasgow.

The study was conducted in two stages:

The first stage of the experimental works consisted of the structural communication grid test. The test involved four main questions, three of a grid nature. The test, therefore, covered only *some* aspects of the four underlying concepts. Care was taken to select the questions so that they related to school syllabus coverage and that language and representations used were appropriate. The test was discussed with experienced secondary teachers and this was followed by consultation with the lecturer in organic chemistry

maximum insight into the strengths and weaknesses of the students understanding of the underlying concepts. Using the spreadsheet, the test was re-marked to give a total mark for each underlying concept. These were then related in turn to the examination performance by each student, using an examination given by the department at the end of the semester. These results are discussed below in detail. It is important to note that the purpose of the examination used by the department was not the same as that of the structural communication grid test. The former sought to test overall performance in the organic course while the latter looked at underlying ideas brought from school.

### Discussion of Results

The patterns of results from the sample for each part of each question are now discussed.

- Look at the boxes below and answer the questions that follow.

(Boxes may be used as many times as you wish)

<b>A</b> 	<b>B</b> 	<b>C</b> 	<b>D</b> 
<b>E</b> 	<b>F</b> 	<b>G</b> 	<b>H</b> 
<b>I</b> 	<b>J</b> 	<b>K</b> 	<b>L</b> 

responsible for the students concerned.

Question 1 mainly explored functional group recognition, question 2 explored stereochemical features, question 3 explored the concept of polarity, while question 4 (which was open-ended) looked at the nature of the chemical bond. The test is shown in full when the results are discussed later.

In all, 367 students completed the structural communication test, representing 82% of this particular first year chemistry class. The test was not timed. The students were mostly from Scottish comprehensive schools, coming to university with a Higher Grade pass in Chemistry at 'A' or 'B'. The test was marked in two ways. Firstly, responses to each item were coded and the data stored in a spreadsheet. The aim was to gain

Select the box(es) which show the structure of:

		Correct responses
(a)	An isomer of the compound shown in box G	B, E
(b)	A secondary alcohol	E
(c)	An aldehyde (alkanal)	F, K
(d)	A compound which reacts with bromine to form 1,2-dibromobutane	I
(e)	An ester	A

In question 1(a), the students had two isomers to identify and 33% were successful, with a further 14% finding one of the two. Another 30% identified both



but added a third option, many selecting an identical molecule that was shown in a different way.

In question Q1(b), students were asked to select the box(es) which contain the structure of a secondary alcohol. 61% could identify it correctly but a further 11% identified a tertiary alcohol in addition. Alcohols are emphasised in the school syllabus and, happily, two thirds were giving the right answers.

In reply to Q1(c), only 29% could identify the aldehydes (alkanals) correctly. A further 14% did not see formaldehyde (methanal) as an aldehyde (alkanal) while other functional groups were confused with

It is perhaps easy to see the confusion between an acid and an ester in that both contain the  $-\text{COO}-$  linkage. However, the ether does not contain this linkage but the  $-\text{C-O-C}-$  linkage. Is this a visual confusion, or is it that the presence of oxygen *in a linkage* which causes the difficulty, or both? It is even possible that the similarity of names (ester and ether) is a source of confusion.

(2) Look at the boxes below and answer the questions that follow.

(Boxes may be used as many times as you wish)

<b>A</b> 	<b>B</b> 	<b>C</b> 	<b>D</b> 
<b>E</b> 	<b>F</b> 	<b>G</b> 	<b>H</b> 
<b>I</b> 	<b>J</b> 	<b>K</b> 	<b>L</b> 

aldehyde (alkanal): ketone 15%; acid 13%; ester 9%; propanol 3%. Over 17% offered no answer at all. Overall, the majority was showing confusion over aldehydes (alkanals).

In Q1(d), only 46% could identify the compound (a 1-alkene). Nearly 23% wrongly identified the alkene that would give a 2,3-dibromo compound, while another 14% identified this alkene compound *and* the right answer. One way of interpreting the pattern of results is to suggest that the students, when school pupils, did not really understand what was happening during such an addition reaction. They would be aware that the bromine solution was decolourised and would have been told that a dibromo compound was formed. The specific features of the addition were, however, not so clearly grasped. Again, this may have significance when further addition reactions are met, and elimination reactions are introduced.

In Q1(e), only 54% identified the ester correctly, 18% incorrectly choosing an acid and 12% incorrectly choosing an ether, with 11% not offering any answer.

Select the box(es) which contain:

		Correct responses
(a)	An isomer of the molecule shown in box A	D, I
(b)	An isomer of the molecule shown in box D	A, G, I
(c)	An isomer of the molecule L	E, K
(d)	A molecule which is identical to the molecule shown in box F	H

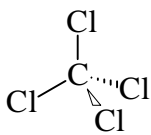
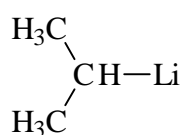
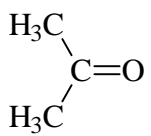
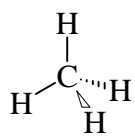
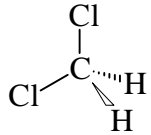
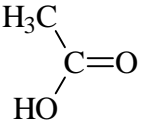
In question Q2(a), 56% were confident about isomerism here with a further 33% with a partial understanding. When the various isomers of the dibromoethene were considered taking account the possibility of cis-trans isomerism (question 2(b)), the number who grasped this fully dropped to 38%. A further 20% demonstrated that they did not see the lack of rotation around a double bond.

In Question 2(c), surprisingly, 44% had difficulty with alkane isomerism. There was confusion, with K often omitted and, sometimes, J added and with straight chain compounds when compared to a branched compound. This may reflect the way the molecules were presented in that the representation at school level

students had not met the idea, it would difficult for them to look for such a stereochemical feature.

(3) Look at the boxes below and answer the questions that follow.

(Boxes may be used as many times as you wish)

<b>A</b> 	<b>B</b> $C_2H_5OH$	<b>C</b> 
<b>D</b> 	<b>E</b> $H_2O$	<b>F</b> 
<b>G</b> 	<b>H</b> $NH_3$	<b>I</b> 

used a different system from that encountered in the test. The system used in the test was chosen to follow the system that students would meet in their organic chemistry lecture course. Informal evidence from school teachers that pupils seem to be able to manage alkane isomerism with few problems would support the argument that the different method of representation might have been a factor causing confusion. This points to a serious problem inherent in all forms of representation; at school level, the molecules are drawn 'flat', with all the bond angles at right angles, while the system used here made some attempt in representing the correct geometrical shape.

Q2(d) moved on to optical isomerism, a topic not specifically covered at school at Higher Grade, the level used as the basis for entry. However, some would have studied at Advanced Higher Grade where this topic is covered. The aim here was to explore whether the students could 'see' this three-dimensional aspect of stereochemistry. As expected, optical isomerism posed problems, with only 30% being successful. The main error for those who responded was confusion between optical isomers and molecules, which were identical but were presented from a different angle, 41% making this selection, with a further 27% including both right and wrong answers. The perception of three dimensions is known to cause problems.<sup>23, 24, 26</sup> This item confirms the need for great care in presenting reactions where such stereochemical features are important. However, if many of the

Select all the boxes:

		<b>Correct responses</b>
(a)	Where the molecules can form hydrogen bonds	B, E, H, I
(b)	Which contain molecules with a carbon atom which is at the <i>positive</i> end of a polar bond	A, B, D, G, I
(c)	Which contain <i>molecules</i> which are polar	B, C, D, E, G, H, I

In Q3(a) the students were asked to identify molecules which can form hydrogen bonds. Only 21% noted all four, but a further 30% managed three of the four, the missing one usually being ammonia. This was a surprising omission in that the school course did deal with ammonia. Hydrogen bonding is taught at school with fairly specific molecules used as illustrations. The concept has clearly not been grasped in an overall sense.

In Q3(b), in seeking to identify molecules with the carbon at the positive end of a polar bond, considerable confusion was observed. Only 7% identified all the

molecules, with a further 15% missing one of them. Many more managed three of the five answers (10%) while large numbers identified one (16%) or two (23%) correct answers. However, 22% offered no answer at all. Clearly, this is an area of very large confusion. One of the problems may lie in the way bonding ideas are developing at school level, with ionic and covalent being taught as a kind of 'norm' and polar covalency then being added later (leaving, perhaps, a suggestion that this is not so normal?).

A similar level of confusion emerged when students were asked in Q3(c) to select and identify all the boxes that contain molecules that are polar, with only 7% being totally successful. 11% wrongly identified tetrachloromethane as a polar molecule and 8% identified methane as a polar molecule. Large numbers offered a limited range of correct answers. 13% offered no answer.

This is an area of major difficulty. Part of it arises because hydrogen bonding is related specifically to water and alcohols – the concept is not presented in a broad sense at school level. There is little emphasis at school (up to Higher grade) on bond polarity in carbon compounds (although the polar bond in general is covered) and this shows clearly in the results. This poses fundamental problems when students are faced with their first university organic course when they will meet mechanisms of reactions in some detail. The failure to grasp the fundamental notion of bond polarity may pose problems to some students in making sense of mechanistic interpretations.

The fourth question was not in grid format. It asked the students to explain what the line between two carbons represented and what the double line between two carbons represented. 57% correctly indicated two and four electrons respectively, with a further 13% specifically referring to electrons without a clear reference to the numbers involved. This underlying idea seems reasonably well established although it has to be noted that 30% did not show any grasp of what a bond line meant.

### Overall Patterns

Four underlying ideas have been explored by means of the structured communication grid test. Specific areas of weakness have been identified, with bond polarity being particularly problematic. Inevitably, as molecular complexity increases, so difficulties increase. Such difficulties may be reduced when students 'see' molecules in a more holistic way, recognising functional groups and structural features with confidence. It is clear that this was not always happening.

It is important to gain a view of organic chemistry through the eyes of incoming students. Some of the

inadequate grasp of key ideas (e.g. bond polarity) is likely to make further learning more difficult. It was also likely that the different ways schools and universities represent structures could be causing problems. It could be easy to suggest that the school presentation should change to be more like that used later. This might be a more ideal situation but it has to be recognised that it would be difficult to achieve.

### Correlation with Class Examination Performance

This comparison involved 295 students, 66% of those enrolled in the class. The 295 were those who completed the structural communication grid test and who had completed *both* [organic] questions in the class examination at the end of the semester, with a choice of questions being offered. Of course, it is recognised that this may have selected those students who were more comfortable with organic chemistry.

The examination was scored by the department lecturers in the normal fashion, following a marking scheme. These marks were compared to the scores obtained from the structured communication grid. Pearson correlation was used to establish the relationship between the scores obtained in the structural communication grid test and the examination used by the department. This examination contained one section on organic chemistry and there were two questions (questions 5 and 6 of the whole examination). Each part of questions 5 and 6 is now outlined very briefly. For the purposes of this study, all the student scripts were examined and their scores for each part of each organic question were recorded on a spreadsheet. It is worth remembering that the student group was an able group, and almost everyone had obtained an 'A' or 'B' pass in Higher Grade Chemistry from school as well as good grades in other subjects.

In Q5(a), students were asked about the systematic name of an alkene (2-methylbut-2-ene); 95% gained full marks.

In Q5(b), students were asked about *cis/trans* isomerism in an isomer of 2-methylbut-2-ene. The responses here were weaker, only 51% giving the correct answer and drawing the isomeric structures correctly.

In Q5(c), students were asked about the reactions of the 2-methylbut-2-ene with bromine, hydrogen bromide, and potassium permanganate. Only 57% offered correct answers.

In Q5(d), students were asked to draw the mechanism of addition of HBr to the 2-methylbut-2-ene, using curly arrows. 63% gave an acceptable answer

In Q6(a), students were asked to draw in all the lone pairs of electrons missing from six given molecules or ions; 69% gave correct answers.

In Q6(b), students were asked about the treatment of a bromoalkane with hydroxide and they were told that a mixture of two products is formed. Many organic concepts were being tested in this question and the students response here was also relatively weak (57%). This is really the area of major difficulty in organic

Nonetheless, nonsignificant values were also obtained. This suggests that the correlations were *not* simply reflecting some kind of overall ability in chemistry. Indeed, many of the variations in correlations values obtained can be related to what was being asked and the underlying ideas specifically developed at school level.

When looking at the performance in questions 1 to 4 correlated with the performance in questions 5 and 6,

**Table 1 Correlation: Structural Communication Grid Questions and Examination Questions**

N = 295	Question 1	Question 2	Question 3	Question 4
<b>Question 5</b>	0.26	0.22	0.34	0.19
	p < 0.001	p < 0.001	p < 0.001	p < 0.001
<b>Question 6</b>	0.21	0.22	0.30	0.20
	p < 0.001	p < 0.001	p < 0.001	p < 0.001

chemistry and new students always find difficulty with reactions and mechanisms of organic chemistry. The astonishing fact observed here is that some students could not identify which of two atoms in a polar covalent bond was the more electronegative! This confirms the poor grasp of bond polarity from school observed in the structural communication test.

A comparison was made between the student's performance in the questions from the structured communication grid, used *before* the students started their first organic course (questions 1-4) and the examination *after* the student had finished their first year organic chemistry course (questions 5-6).<sup>1</sup>

The hypothesis is that the grasp of key underlying concepts from school would predict future success in the mechanistically presented organic chemistry course at university. However, it is possible that any positive correlations can be explained simply by the ability of the students in chemistry or, indeed, their commitment to chemistry.

Correlation coefficient values were obtained for each part of each of questions 1 to 4 compared to each part of each of questions 5 and 6. They were also obtained for the questions overall and the discussion starts by looking at these overall correlations before exploring some of the more interesting details with separate parts of questions.

With a sample approaching 300, even quite low correlation values may be highly significant.

positive highly significant correlations were obtained in each case. These are summarised in Table 1

These correlation values are what might be expected. Of greatest interest is the observation that the *highest* correlations occur with Question 3, where it has already been shown that student confusions are greatest. It could be argued that these statistically significant correlations merely reflect general knowledge of chemistry or even general ability. However, when the correlations involving parts of questions are considered, correlation values approach zero are obtained in quite a number of cases. This suggests that the observed statistically significant correlation values *do reflect something more than knowledge of chemistry or general ability*. For example, Table 2 illustrates some places where low correlations were obtained.

**Table 2 Some Non-Significant Correlations**

N = 295	Question 1(a)	Question 2(b)
<b>Question 5</b>	0.08	0.09
	Not sig.	Not sig.
	Question 1(b)	Question 1(d)
<b>Question 6</b>	0.09	0.08
	Not sig.	Not sig.
	Question 5(b)	Question 5(d)
<b>Question 1(d)</b>	0.04	0.07
	Not sig.	Not sig.

In looking at the pairs of questions involved in each correlation, it is clear that the questions are testing

<sup>1</sup> It is chance that question numbering worked out this way but, for simplicity, the numbers are used in the discussion: questions 1-4 coming from the structural communication grid and questions 5 and 6 from the departmental chemistry examination.

completely different skills although all are, of course, testing organic chemistry. The nonsignificant correlations show that the different skills are, indeed, *different* and not just reflections of some kind of overall ability. For example, question 1(a) deals with isomers of alcohols and ethers and this is completely unrelated to any parts of question 5.

**Table 3 Question 1(d) and parts of question 5**

N=294	Pearson r	Significance
Q5(a)	0.12	<5%
Q5(b)	0.04	ns
Q5(c)	0.16	<1%
Q5(d)	0.07	ns
Q5(e)	0.13	<5%
Q5(Total)	0.17	<1%

There are also some correlation values, which vary when separate parts of the questions are considered.

In Table 3, performance in question 1(d) in the structured communication grid is related to the five parts of question 5 of the chemistry test. 1(d) specifically relates to bromination across a double bond. Q5(a) and (b) test the name and structural isomerism of an organic molecule and, as expected, correlation values are not high. Q5(c) is testing the mechanistic understanding of bromination and hydrobromination across a double bond and, as might be expected, highly significant correlation is found. Q5(d) is about the concept of drawing the mechanism of the addition of HBr to the double bond of an alkene as a Markovnikov addition using curly arrows. Here, the overall process is different. In fact, in Q5(d) many organic concepts are being tested but these were new to the students, not having been studied at school. It appears that success in the question about hydrobromination is not dependent on a grasp of the bromination process. Q5(e) was about ozonolysis of the double bond and, while not covered in school chemistry, the reaction is somewhat similar to bromination.

The performances in each part of question 2 of the

**Table 4 Question 2 and Question 6**

N = 281	Pearson r	Significance
Q2(a)	0.18	<1%
Q2(b)	0.07	ns
Q2(c)	0.23	<0.1%
Q2(d)	0.14	<5%
Q2(Total Score)	0.22	<0.1%

structured communication grid were correlated with question 6 of the departmental test and the results are shown in Table 4.

Q2 in the structural communication grid test deals with stereochemistry. Q2(a) and Q2(b) both deal with isomerism in alkene molecules. Q2(a) involves simple molecular isomerism (1,1 and 1,2 substitutions) while Q2(b) also involves geometric isomerism. Q2(c) deals with alkane isomerism and Q2(d) tests to see if students could 'see' the idea of mirror images.

Q2(b) is dealing with geometrical isomerism which is not covered at all in Q6 - hence the absence of significant correlation. Q2(a) and (c) both deal with structural isomerism and Q6(b) depends on this and the high correlation might be for this reason. This is confirmed when the correlations of 2(d) with Q6(b) is calculated and found to be 0.22 (sig at <0.1%). Q2(d) deals with chirality and the idea of mirror images. There are no chirality ideas involved in Q6 at all and the observed lower correlation is as expected.

Sometimes, correlation values were higher. For example, the performances in each part of question 3 of

**Table 5 Question 3 and Question 5**

N=295	Pearson r	Significance
Q3(a)	0.15	<1%
Q3(b)	0.29	<0.1%
Q3(c)	0.23	<0.1%
Q3(total)	0.34	<0.1%

the structured communication grid were correlated with question 5 of the departmental test. The results are shown in Table 5.

Q3(a) deals with hydrogen bonding which is not tested explicitly in any way in Q5 of the chemistry test. It is at first sight surprising that there is any significant correlation at all. However, the ideas behind hydrogen bonding involve an appreciation of bond polarity and this is important in answering a mechanistic question like question 5. The very high significance of the correlation values for Q3(b) and Q3(c) are to be expected since most of question 5 depends heavily on an understanding of bond polarity which was tested in these questions. It would appear that understanding bond polarity is a very critical skill and it is very obviously required in many parts of question 5.

### Summary

Significant correlations must be interpreted with caution, but the absence of significant correlations is interesting and, indeed, most of the variations in

correlations values obtained can be related to what was being asked and the underlying ideas specifically developed at school level. Of course, the results could be interpreted by suggesting that those who had understood the underlying ideas at school level were also capable of higher levels of performance in a university course. However, again, the absence of significance in some cases tends to undermine any argument based on some kind of overall ability at chemistry.

The highest levels of significance were observed in the areas related to bond polarity. The problems relating to the way this is presented in the school syllabus order have been discussed and it is very clear that a mature understanding of the nature of polarity and of induced polarity are important in making sense of a mechanistic presentation of organic chemistry.

Functionality is very important in understanding organic reactivity. The school syllabus approach, with its emphasis on the carbon skeleton at early stages, poses some problems in developing confidence in functionality. It may well be that such experience in handling functionality can act as a 'chunking' device, reducing potential overload on the working memory when studying organic reactions and mechanisms.

Structural ideas are also important. There is a problem with the school syllabus expecting molecules to be drawn flat on paper, with bond angles apparently at 90°. The university course represents molecules on paper in such a way that the real stereochemistry is more apparent. In addition, the school syllabus insists that all hydrogens are shown while practising organic chemists rarely show the hydrogen atoms. Three-dimensional visualization is not easy and the use of a working area where students can carry out tasks using models along with paper representations and other visual representations has been shown to help.<sup>16</sup>

Of course, school chemistry courses are not designed simply to prepare pupils to study chemistry at university or they ought not to be. Perhaps only about one fifth of those gaining a Higher Grade in Chemistry in Scotland will actually take any course in Higher Education that contains recognisable chemistry. What this study has shown is that certain ideas in school chemistry are well established and others are not so well established and that performance in a first level chemistry course in specific areas of organic chemistry reflects the grasp of specific underlying ideas gained from school. This emphasises the importance of knowing what ideas pupils bring with them from school courses<sup>36</sup> and how they came to gain these ideas. It also pinpoints some topics that may need to be developed further before introducing new organic chemistry ideas.

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## Introduction

As teachers in higher education, we are increasingly aware that assessment is a (if not the) major driver for students in higher education. Students apply the 'assessment' test. If a concept, skill or knowledge chunk is deemed to be assessable in a way that contributes to the ultimate goal (of degree, diploma etc), then a high priority is accorded in the learning strategy of the student. Given this prevailing culture, we can adopt either of two strategies: to change this culture of assessment-driven learning or to use it as an opportunity to improve learning. Another possibility might be to remove assessment entirely but the arguments for assessment are powerful, embodying ideas of guiding student improvement and progression, diagnosis of faults, providing feedback to teachers and informing employers.<sup>1</sup> Over the last decade and more, there have been many laudable and, to a large extent, successful programmes that have introduced context-based learning,<sup>2</sup> problem solving approaches and holistic perspectives. Nevertheless, even with such approaches, assessment remains a major learning driver for many students. So accepting that there is a strong argument for the retention of assessment, and that changing the

culture of assessment-motivated learning would be difficult if not impossible to achieve, a critical consideration of the quality of assessment should be a feature of every study programme.

The vital role of learning outcomes in the design of an assessment strategy is recognised both by teachers and government agencies. The United Kingdom Quality Assurance Agency<sup>3</sup> enshrines this link in both recommendation and legislation relating to the programmes of higher education institutions in the UK. The Agency defines learning outcomes as 'statements that predict what learners have gained as a result of learning' and the '...achievement of which a student should be able to demonstrate'. So providing we are able to define learning outcomes competently, students should have a clear idea of what may be assessed and how it is to be assessed. Note that the competent definition of learning outcomes must include information on both the assessment criteria and the mode of assessment. The UK Chemistry Benchmark Statement<sup>4</sup> identifies a range of assessment media. The list includes formal examinations, laboratory reports, problem solving exercises, planning and presentation of oral reports, and the conduct and reporting of individual and

**Table 1 Comparison of aspects of formal examinations with non examination-based assessment**

Formal examinations	Non-examination-based assessment
Allow for verification of student work	Can be less certain that it is the student's own work
Performed in limited time (time management)	Time is student-limited
All skills and knowledge may be tested at the same time	Skills and knowledge tested over a longer time but wider range of skills tested
Relatively easy to administer	Skills tested more effectively
Good discriminator on certain criteria	Time for reflection
Relatively easy to grade consistently	Synoptic
Disadvantages some students (poor recall, panicky disposition etc.)	Can be more difficult to administer
Unable to test some important skills well (selection, organisation, communication etc.)	Reasonable discrimination (but tendency to low standard deviation)
Tests at a particular point in time, no measure of retention	Difficult to grade consistently
Choice of questions can mean that some areas not tested	Not so memory dependent
Tests memory	Perhaps a more even playing field



collaborative project work, with the possibility of poster displays. There is no shortage of recognised assessment media within the chemistry establishment.

All institutions use a subset of these assessment media and it is important to look at the total learning package in terms of outcomes and assessment. Each medium has its particular strengths in testing specific learning outcomes. One categorisation of assessment media is based on the degree of 'openness' and of 'time constraint'.<sup>5</sup> At one end of the 'spectrum' is the open project with an indefinite (or at least extended) completion date and the other end features the closed book, fixed time, formal examination. Between, there are assessments such as open book examinations, fixed time essays and short projects. However, assessment by formal examinations is distinctive as compared non-examination assessments as can be seen from Table 1.

The following analyses and discussion are directed by three questions:

"Are we teaching what we think we are teaching?"

"Are students learning what we think they are learning?" and

"Are we assessing what we think we are assessing?"

The aim of the study is to determine how well we are using examinations as a measure of our claimed learning outcomes.

### Examination and learning outcomes

In this part of our studies, we are focussing on the closed-book, fixed-time examination. Although this is just one of several media, it features in almost all institutions and, with chemistry-based programmes, it makes a significant contribution to overall assessment. Also this assessment medium is generally accessible.

Whilst realising that some learning outcomes are inappropriate for testing by examination, we

embarked on a detailed look at first-year university, chemistry-based examination papers and the relationship of questions to learning outcomes. Papers used were from 22 UK universities (58 papers), 6 state universities in the USA (13 papers) and 4 Australian universities (11 papers). The selection of papers from the USA state universities included some early, year-2 module papers, as there is a lower level of subject specialisation at university entrance in the USA than there is in the UK. (An additional 31 examination papers were received but not used, as specific learning outcomes were not specified.)

The first task was to assign the appropriate learning outcomes to the individual questions on the papers. The assignments were carried out in duplicate and the assigning pair of teachers was asked to negotiate over any discrepancies in their question/learning outcome assignment. Very few discrepancies arose (less than 2 per cent) and these were resolved by discussion between the assigning pair, apart from one instance when a third party was brought in. There were many differences in the papers in terms of the numbers of questions, choice of questions and time allocated to questions. The learning outcomes claimed by the institution for the examination and those actually tested by the questions in the examination were tabulated for each paper. The overall learning outcome totals are shown in Table 2.

The following exemplar (Table 3) is typical of an individual paper analysis, representing neither the best correlation between the learning outcomes claimed and those actually tested, nor the worst. The paper comprises a three-hour examination paper with two sections. Students were asked to complete two questions from four from Section A and three questions from five in Section B, a total of five questions to be completed from the nine on the paper. The claim made by module assessment information provided by the institution to the student was that there were seven learning outcomes (which we have designated A-G) tested by the examination.

**Table 2 Learning outcomes tested and claimed in examination papers.**

Institutions	Number of papers	Total number of questions	Total learning outcomes claimed	Total learning outcomes tested	Outcomes tested/outcomes claimed
4 Australia	11	76	68	39	0.574
22 UK	58	455	179	81	0.452
6 USA	13	96	121	42	0.347

**Table 3 Examination questions analysed by learning outcomes.**

Learning outcome	Question								
	1	2	3	4	5	6	7	8	9
A	✓	✓		✓					
B			✓			✓		✓	
C		✓			✓		✓		✓
D									
E				✓					
F					✓	✓			✓
G									✓

## Learning outcomes A-G

- A Use given spectroscopic and other data to deduce the structure of molecular species.
- B Select appropriate reaction sequences to effect specific structural changes in molecules.
- C Describe all mechanistic steps in functional group transformations.
- D Interpret kinetic data in terms of reaction mechanisms for some organic transformations.
- E Assign R, S notation to chiral carbon.
- F Identify and account for reaction product outcome that is affected by chirality of starting material.
- G Identify the main features of drug receptor sites explain how selection and specificity is achieved.

This simple analysis indicates that, although there is a claim to test the seven learning outcomes in the examination paper, one outcome, D, is not tested at all. Outcomes E and G are tested in just one question, with the other outcomes being tested in three questions except for outcome C which is covered by four questions. Well, this could be worse as we do have all but one of the outcomes being tested in at least one question.

However, students are not asked to attempt all nine

questions. There is a choice. Take a student who attempts Questions 1 and 3 (two from four in section A) and Questions 5, 6 and 8 (three from five in Section B). How does the analysis look now (Table 4)?

A rather less satisfactory pattern now emerges. Although outcomes B and F are tested in three and two questions respectively and A and C are tested in one question each, we now have three learning outcomes, D, E and G, that are not tested at all. This illustrates the need to consider the range of student question selection as well as the totality of the questions actually appearing in the paper. As suggested earlier, the exemplar featured in Tables 3 and 4 is typical of the analysis and certainly by no means is the worst case.

A further major consideration is that of student performance. Threshold pass marks in examinations generally fall in the range 40-45 per cent. With the examination paper structure illustrated, it would be possible for a student to gain a pass with just three of the seven learning outcomes achieved. The point is that we do need to be mindful of what we *claim*. "This examination tests learning outcomes X, Y, Z etc." should not be translated as "Students who pass this examination have achieved learning outcomes X, Y, Z etc.". We might be reluctant to fly if we knew this to be case for the assessment of the training of the pilot of our

**Table 4 Examination questions attempted by a student analysed by learning outcomes.**

Outcome	Question								
	1	2	3	4	5	6	7	8	9
A	✓	✗		✗					
B			✓			✓		✓	
C		✗			✓		✗		✗
D									
E				✗					
F					✓	✓			✗
G									✗

aeroplane.

The main findings from these simple analyses of examination papers are that:

- There is a mismatch between outcomes claimed and outcomes tested (Table 2 data).
- Some outcomes are tested several times in the same paper and some omitted. This situation is made worse where the paper embodies a choice of questions (Table 3 data).
- In the worst cases, students are able to achieve a pass grade with less than twenty per cent of the learning outcomes fully achieved (Table 4 data).\*
- Questions that are easy to set and easy to mark tend to predominate (see next section on problem solving in examinations).

### Problem solving in examinations

The predominance of the 'easy to set, easy to mark' questions led to a further line of enquiry. These questions tend to be either of the regurgitation of information variety or involve a 'problem' of some sort, often a calculation. This latter type can run from year to year with just a change in the input data. The frequent claim, that the examinations address problem-solving, needs to be looked at in this context.

Many of the calculation-type questions masquerading under the problem solving banner are of the type: calculate the mass of sulfur dioxide produced by burning 1.00 tonne of coal containing 0.700 per cent by mass of sulfur. Certainly this type of question does test a range of skills and knowledge but is it a *problem*? The answer is obtained by applying a simple, standard algorithm: find the mass of sulfur, convert to moles, use in balanced equation to find amount of sulfur dioxide then use relative molecular mass of sulfur dioxide to find the mass of sulfur dioxide. The input data are given, the method is familiar and the output is given.

Problem types have been categorised by Johnstone<sup>6</sup> and others in terms of these parameters and the above can be seen to be a Type 1 'problem'. The 'problems' in Table 5 become more 'problem-like' and less 'exercise-like' further down the table.

\* A few examination papers contained compulsory sections where there was no choice of questions. Others clearly embodied norm-based and criterion-based sections. With these structures, more of the claimed learning outcomes have to be achieved to obtain a pass grade.

**Table 5** Categorisation of problem types.

Type	Data	Method	Output
1	G	F	G
2	G	U	G
3	I	F	G
4	I	U	G
5	G	F	O
6	G	U	O
7	I	F	O
8	I	U	O

F = familiar, G = given, I = incomplete, O = open, U = unfamiliar.

An example of a Type 4 problem might be 'How many sugar residues are added per second to a blade of grass as it grows?' or 'How many amino acid residues are added per second to a human hair as it grows?' The inexperienced student, faced with this type of problem might panic but with a little thought it is possible to start confining the broad question. Certainly the input data are incomplete. The method is not immediately familiar but the output is defined by the question. To take the latter problem, how much does hair grow in a second? In a month it probably grows 1-2 cm. People are familiar with roughly how often they have their hair cut. How thick is a human hair? It is certainly less than 1 mm. Would ten hairs side by side cover 1 mm or would it be rather more? So we can get a range for the volume of hair produced in a month (and in one second). What is the density of hair? Probably around  $0.8 \text{ g cm}^{-3}$  like many organic materials, so we can estimate the mass produced per second. What is the mass of an amino acid residue? Easy, via relative molecular mass, and we thus have the number of residues per second. A bit of thought enables a seemingly impossible problem to be broken down into manageable parts. The answer is a staggering number of around  $10^{11}$  per second. So the slow growing hair on the macro scale is a frenzy of activity at the molecular level!

We analysed the questions in all 82 of the examinations papers according to the categories outlined in Table 6. All questions that embodied problem solving (in part or as the whole of the question) were included in the analysis (432 of 627 questions in total), the results featuring in Table 6. Whilst there is an interpretive element into the assignment of questions to problem type, only in very few cases (less than 3 per cent) were there inconsistencies in the allocations recommended by two independent academics and these were resolved by discussion.

**Table 6** Categorisation of problems in examination papers.

Type	Number of questions analysed	Proportion/percent
1	409	94.7
2	13	3.01
3	9	2.10
4	0	0.00
5	1	0.20
6	0	0.00
7	0	0.00
8	0	0.00

The claim that ‘examinations test problem solving’ could be defended if one were to accept that the straightforward, algorithmic type exercise is indeed a ‘problem’. However, current interest in problems and problem-solving<sup>7</sup> suggests that the term ‘exercise’ is more appropriate for type 1 ‘problems’. Our observation that 94.7 per cent of the questions analysed were of Type 1 (data given, method familiar and output given), the standard algorithm type, again suggests a danger in making claims that cannot be substantiated.\* From this analysis, it does appear that questions that are essentially the same from year to year in which the only change is in the data and not in the structure are very common, easy to set and easy to mark. There are other media that are better suited for the testing of problem-solving but we should not be claiming what we are not doing.

#### Problem solving and educational background

We have some experience of non-Type 1 problem solving in chemistry with Open University (OU) students. The student body of the OU is diverse, spanning extremes of ranges of age, education and background. An intriguing notion was to see if we could determine whether formal educational experience paralleled the ability to solve problems. Overall, there is evidence that OU students with recent experience of higher education study tend, at least to begin with, to perform to a higher standard overall than those without that recent experience<sup>8</sup> but would this be reflected in problem solving?

We divided a cohort (totalling 305 students) into three categories based on the England, Wales and Northern Ireland educational qualifications (Table 7). The Group 1 division separated the students

\* As with any formal, closed-book examination, it is not appropriate to test skills that have not been developed prior to the examination. Any move to include problem solving (Type 2 or higher) in the examination should be preceded with a familiarisation of problems of this type.

with no formal educational qualifications from those with any GCSE\* or higher. The *same* cohort was divided differently to produce Group 2 which had as its lower educational population those students at least one GCSE grade and the higher educational population had specifically GCSE chemistry or chemistry within science or more advanced qualifications. The final Group 3 had the divide such that only Advanced-level (or higher) was included in the top division.

**Table 7** Grouping of Open University students according to educational background.

Group	Lower educational population	Higher educational population
1	None	GCSE and higher
2	None plus GCSE	GCSE (chem) and higher
3	None plus GCSE plus GCSE (chem)	Advanced level and higher

**Table 8** The relative performance of Open University students of different educational background on Type 4 problems.

Group	Low		High	
	% Score	Standard deviation	% Score	Standard deviation
1	63	14.0	65	13.2
2	63	12.6	62	13.7
3	66	12.2	63	13.9

The variations of student performance in Table 8 are statistically not significant. The performance on Type 4 problems does not seem to be affected by prior educational qualifications. (However, the initial performance of students shows significant variation on Type 1 problems with a correlation between prior educational level *and* how recent was that experience. These findings are consistent with those of Macpherson<sup>9</sup> who investigated the link between problem solving ability and cognitive maturity.)

\* The General Certificate of Secondary Education is a UK national examination. Students are normally aged 16 years and take up to 10 subjects.

## Conclusions

This overview of first-year, university, chemistry examination papers embodies a number of limitations such as:

- The somewhat crude analysis of problem types and the ignoring of question types that cannot be categorised with this system.
- The semi-subjective mapping of questions to learning outcomes.
- The learning outcomes themselves, not all of which were defined clearly and related to the mode of assessment.

Nevertheless, the survey has thrown up a number of common features of examinations

- There is a mismatch between outcomes claimed and outcomes tested.
- Some outcomes are tested several times in the same paper and some omitted. (This situation is made worse where the paper embodies a choice of questions.)
- In the worst cases, students are able to achieve a pass grade with less than twenty per cent of the learning outcomes fully achieved.
- Questions that are easy to set and easy to mark tend to predominate.
- Claims for the assessment of problem solving should be viewed with suspicion without a clear idea of what constitutes a problem.
- Experience with simple algorithmic exercises is not an indicator of success with problem solving.

All the above findings effectively arose from our attempts to check that assessment was firmly embodied in our learning outcomes. The findings indicate that we have in some cases a way to go before we achieve a tight mapping between what we teach, what the students learn, and what we assess. A step forward would be to ensure that examination papers are subject to a simple learning outcomes analysis, which is then seen to be part of the total assessment of each module and programme. Learning outcomes, once defined, are capable of informing what we teach, what students learn and how it is assessed.

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## Experimenting with undergraduate practicals

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### Abstract

This article provides an account of a practitioner's experiences and observations in a transition from the use of traditional (expository) style practicals to problem-based practicals in undergraduate chemistry laboratories. Specific examples are used to illustrate the principal features of the different styles of practical used and a representative selection of student and demonstrator comments on their initial experiences of problem based practical work is also included.

### Introduction

Only a minority of chemists would challenge the view that laboratory work is an essential and desirable component of a chemistry degree course<sup>1</sup> and this is reflected in the criteria for the accreditation of chemistry degree courses by the Royal Society of Chemistry (RSC), which states a minimum requirement of 400 laboratory hours exclusive of the major research project.<sup>2</sup> However, whilst many espouse the importance of laboratory work in chemistry degree courses, it may be argued that, too often, insufficient consideration is given to the purpose these 400 hours fulfil and the reality on the ground is often a lack of clarity of purpose in much of what the students actually do. Given the very considerable resources (time, money, space, equipment etc.) devoted to support undergraduate laboratory work in chemistry it is unfortunate that the findings of Johnstone and Wham<sup>3</sup> in 1979 "...that in the midst of an apparently active learning situation, it is possible for the student to be passive with his brain in neutral" still strikes a resonance.

In 1995, Meester and Maskill<sup>4</sup> reported the results of a survey of first year practical classes from seventeen universities in England and Wales. They concluded:

*"The aims of the course are stated in only half the manuals. The aims for the experiments are mostly contained in the experiment descriptions. Useful learning objectives are mentioned just once. The scientific level of the experiments does not exceed that of controlled, predictable experiments. Changes that have taken place in the style of practicals in secondary education are hardly reflected in tertiary education"*.

Meester and Maskill's study indicates that, at the time of their study, much undergraduate laboratory work in chemistry involved recipe style experiments with little opportunity for development of skills. Has the situation changed significantly since then? Alternative approaches to laboratory teaching have been published, such as problem-based learning,<sup>5</sup> but it is not clear whether such alternative approaches are significantly represented in undergraduate chemistry courses in the UK. In the US, recommendations made by the National Research Council for more inquiry-based learning in science education have clearly stimulated activity in the development of inquiry-based learning.<sup>6,7</sup>

Johnstone and Al-Shuaili<sup>8</sup> recently reviewed the literature on the relationships between practices in undergraduate laboratory work and student learning. Their review includes an examination of types of laboratory work, which is based on Domin's<sup>9</sup> analysis. Domin<sup>9</sup> identifies four distinct styles of laboratory experiments (expository (or traditional/verification), inquiry, discovery and problem-based) that are distinguished in relation to 'outcome', 'approach' and 'procedure'.

The purpose of the present article is to relate the factors that stimulated a practitioner to alter the style of laboratory practical from traditional (expository) to a more problem-based style and to highlight some of the principal differences in terms of what the students do and experience with these different styles of practical work. A representative selection of student and postgraduate demonstrator comments on their experiences of problem-based practicals is included and serves to highlight some of the challenges associated with their use in undergraduate chemistry courses.

## Discussion

When I commenced full time teaching of chemistry in HE in 1993, the laboratory manuals/courses within my remit were rather dated and entirely of the traditional expository style described by Domin.<sup>9</sup> Improvements to the laboratory manuals included attention to clarity in descriptions of procedures, rigour in equations, quantities and units and clarity in stating the purpose of the experiment. Post-lab activities, in the form of assessed questions designed to probe students' understanding of the experimental procedure and the background theory, were also included. Pre-lab work amounted to "please ensure that you have read the laboratory script before coming to the laboratory".

In the process of marking some 2<sup>nd</sup> year physical chemistry laboratory reports about three years ago, I realised that the prescriptive way the practical work had been designed was generating 'good' reports with 'correct' data analysis and 'correct' results from most students. I found myself awarding first class marks to reports by students who I knew (from tutorials and other evidence) didn't really understand what they had done, why they had done it or what the results meant. Intuitively, I realised this was a poor learning experience for many students. Instead of the students doing the experiments, effectively I was trying to do the experiments (and much of the data analysis) through the students by providing them with increasingly precise instructions. I started to consider an alternative approach, recognising that the only way to learn certain aspects of experimental chemistry is for the student to design the experiment herself, reflect on any shortcomings of her design, make improvements and learn from her mistakes. This concurs with the *QAA Chemistry Benchmarking document*,<sup>10</sup> which states that graduate chemists should have developed "Competence in the planning, design and execution of practical investigations, from the problem recognition stage through to the evaluation and appraisal of results and findings; this to include the ability to select appropriate techniques and procedures".

I therefore developed a number of undergraduate chemistry practicals that are predominantly characterised by a problem-based approach in tandem with the use and development of transferable and subject-specific skills. I developed a number of practicals in physical chemistry (some from existing traditional style practicals<sup>11, 12</sup> and some adapted from or inspired by the literature<sup>13, 12</sup>), which feature clearly formulated and explicit objectives, but which omit detailed instructions to a

greater or lesser extent. An additional, implicit feature in the design of some of these experiments is an attempt to encourage students to de-compartmentalise their subject knowledge (e.g. handling organic reaction mechanisms in a physical chemistry practical). The practicals have been used successfully across several modules at levels 1 and 2 during the past three years at Keele and some have been disseminated via the LTSN<sup>12</sup> and elsewhere.<sup>14</sup> Other practitioners at Keele have adopted similar approaches to the design of chemistry practicals and an account of one such experiment was published recently in this journal.<sup>15</sup>

To illustrate the principal features of the different practicals styles, aspects of two 2<sup>nd</sup> year physical chemistry practicals are discussed in more detail below:

### The Influence of Ionic Strength on the Solubility of Barium Iodate Monohydrate

This experiment is used in a second year physical chemistry practical course and relates to lecture material on ion-ion interactions and Debye-Hückel theory. By the time the students commence this experiment they have covered much of the relevant material in the lectures.

This experiment is concerned with the influence of ionic strength on the solubility of barium iodate monohydrate and the use of experimental data to obtain the solubility product and mean activity coefficients of the barium and iodate ions. This practical ran in traditional prescriptive style at Keele up until 2000-2001 before being transformed into a problem-based practical. It should be noted that the time allocation for the traditional style experiment was around five hours but for the problem-based style it is closer to ten hours, which reflects increased time demands of problem-based practical activities.<sup>9</sup>

The traditional script describes a colorimetric method in which the concentration of iodate in solution is determined by quantitative conversion of the iodate to iodine using iodide, with the ionic strength being varied using KCl. The introduction to the practical covers the background theory and provides references to background reading. The experimental procedure and data analysis are detailed and prescriptive and implicitly address the student as a passive instrument. The main pitfalls in the experimental procedure and data analysis are spelled out explicitly so that most students negotiate a smooth path from experiment to report. To illustrate the style of the traditional script, the main parts of the experimental section of this practical are reproduced in Figure 1.

Figure 1. Extract from traditional prescriptive laboratory script.

<i>Solubility of Barium Iodate Experimental Section (Traditional Practical)</i>								
<p>The solubility of <math>\text{Ba}(\text{IO}_3)_2 \cdot \text{H}_2\text{O}</math> is measured by determining the concentration of <math>\text{IO}_3^-</math> in equilibrium with the solid for a range of solutions of differing ionic strengths. This is done by removal of an aliquot of the supernatant liquid followed by quantitative reduction (using iodide, <math>\text{I}^-</math>) of <math>\text{IO}_3^-</math> to <math>\text{I}_2</math>. As <math>\text{I}_2</math> is coloured (<math>\text{IO}_3^-</math> is colourless), its concentration can be measured conveniently by visible absorption, and this can then be used to deduce <math>[\text{IO}_3^-]</math>. The apparatus used is a colorimeter, which is an instrument that measures absorbance at selected fixed wavelengths.</p>								
<p><b>(i) Apparatus</b>            Digital colorimeter, 1 cm cuvettes, stoppered bottles, 25°C constant temperature water bath, volumetric glassware, solid <math>\text{Ba}(\text{IO}_3)_2 \cdot \text{H}_2\text{O}</math>, solid KCl, <math>\text{I}_2</math> solution (<math>0.05 \text{ mol dm}^{-3}</math> in <math>0.1 \text{ mol dm}^{-3}</math> KI solution), KI solution (<math>0.1 \text{ mol dm}^{-3}</math>), HCl solution (<math>2 \text{ mol dm}^{-3}</math>), de-ionised water.</p>								
<p><b>(ii) Beer-Lambert Calibration Plot</b>            Prepare a series of <math>\text{I}_2</math> solutions containing KI (iodide ions (<math>\text{I}^-</math>) enhance the solubility of <math>\text{I}_2</math> by forming the <math>\text{I}_3^-</math> ion) using the solutions provided, such that the <math>\text{I}_2</math> concentrations span the range, <math>[\text{I}_2] = 10^{-4}</math> to <math>5 \times 10^{-3} \text{ mol dm}^{-3}</math> (~8-10 solutions should be sufficient - use the stock KI solution for dilutions). <b>Prior to each absorbance measurement</b>, place a cuvette, containing KI solution only, in the sample chamber of the colorimeter and <b>set the reading to zero</b>. Using the most concentrated solution, select the optimum wavelength (~500 nm) for the absorbance measurements (consult a demonstrator for advice if you are unsure about this step). Next, measure the absorbance of each solution and construct a Beer-Lambert plot from the data. It is essential that you have a satisfactory calibration plot before proceeding further.</p>								
<p><b>(iii) Solubility Measurements</b>            Using volumetric glassware, prepare a series of KCl solutions (<math>100.0 \text{ cm}^3</math> in stoppered bottles) with similar concentrations to those shown in the table below, using <b>de-ionised</b> water (<b>the concentrations of the solutions you prepare must be known accurately</b>).</p>								
$[\text{KCl}]/10^{-3} \text{ mol dm}^{-3}$	0	2	4	7	10	15	20	50
<p>To each solution, add about 0.1 g of <math>\text{Ba}(\text{IO}_3)_2 \cdot \text{H}_2\text{O}</math>. Warm each of the bottles to about 40°C, shake well and then allow them to equilibrate in a 25°C constant temperature bath for ~30 minutes, shaking periodically. Monitor the temperature of the bath to ensure it remains constant (<math>\sim \pm 1^\circ\text{C}</math>).</p> <p>To estimate the <math>\text{IO}_3^-</math> content of each solution, take a <math>25.0 \text{ cm}^3</math> aliquot using a pipette fitted with a short piece of PVC tubing containing a plug of cotton wool (to prevent extraction of un-dissolved solid) and place it in a <math>50.0 \text{ cm}^3</math> volumetric flask. Add <math>1 \text{ cm}^3</math> of HCl (<math>2 \text{ mol dm}^{-3}</math>) and make the solution up to <math>50.0 \text{ cm}^3</math> with <math>0.1 \text{ mol dm}^{-3}</math> KI. Mix well and measure the absorbance as before (remember to zero the colorimeter). Repeat each determination with a second <math>25.0 \text{ cm}^3</math> aliquot.</p>								

In the problem-based script, detailed instructions are replaced with clearly stated objectives and some useful information (see Figure 2). The students have to decide how to do the experiment and draw up an experimental plan. In the problem-based practical, different groups of students used different methods in different ways and for different reasons; some used colorimetric methods, while others used titrimetric methods. Within the boundaries of available resources, safety and time limitations, students have control over the number, range and type of measurements they make. They

have the opportunity to carry out preliminary trial experiments, encounter problems, 'go back to the drawing board' and review their preliminary efforts in the light of unforeseen practical difficulties. In short, they have the opportunity to be scientists.



Figure 2. Extract from problem-based laboratory script.

<i>Solubility of Barium Iodate Experimental Section (Problem-based Practical)</i>	
<b>Objectives</b>	
➤	Determine the solubility product ( $K_s^0$ ) for $Ba(IO_3)_2 \cdot H_2O$ .
➤	Determine mean activity coefficients ( $\gamma_{\pm}$ ) for $Ba^{2+}$ and $IO_3^-$ over a range of ionic strengths.
➤	Test the validity of the Debye-Hückel limiting law (DHLL).
<b>Useful Information and Equations</b>	
➤	Iodate may be converted to iodine by iodide in acid solution.
➤	The solubility product, $K_s^0$ of $Ba(IO_3)_2 \cdot H_2O$ is given by equation 2.
	$K_s^0 = a_{Ba^{2+}} a_{IO_3^-}^2 = [Ba^{2+}][IO_3^-]^2 \gamma_{\pm}^3$
➤	The solubility ( $s$ ) is the number of moles of $Ba(IO_3)_2$ that dissolve per $dm^3$ of solution. Therefore, equation 2 may be re-written in terms of $s$ (equation 3).
	$K_s^0 = 4s^3 \gamma_{\pm}^3$
➤	The Debye-Hückel limiting law and the expression for ionic strength are given below.
	$\log_{10} \gamma_{\pm} = -A  z_+ z_-  \sqrt{I}$
	$I = \frac{1}{2} \sum_i c_i z_i^2$
<b>Experimental</b>	
You will work in pairs. Prepare an experimental plan that outlines how you are going to perform the experiment and how you are going to analyse the data in order to extract the desired information. Bear in mind the availability of materials and equipment in the laboratory when planning your experimental approach. You must have your plan reviewed by a laboratory demonstrator before you start your experimental work.	
➤	Formulate plan.
➤	Discuss plan with demonstrator before proceeding
➤	Complete COSHH risk assessment
➤	Perform experiment
➤	Analyse results (individually).

### The Influence of Ionic Strength on the Rate Constant for the Reaction of Crystal Violet with Hydroxide ion:

This experiment is used in the second year physical chemistry practical course and also relates to the lecture material on ion-ion interactions and Debye-Hückel theory. The students commence the practical before they meet the material on ion-ion interactions in the lectures, but this is covered as they progress through the experiment. However, the first objective depends only on knowledge of first year kinetics. This experiment was introduced in problem-based style and had not been used previously at Keele.

### Objectives

- Establish the rate law for the reaction
- Determine reaction rate constant over a range of ionic strengths
- Establish whether results support reaction mechanism by appropriate analysis
- Suggest a molecular mechanism for the reaction

The reaction between crystal violet and hydroxide ion is used widely in various guises as an undergraduate practical in many teaching laboratories. Under appropriate conditions, the reaction is accompanied by loss of the intense colour of the crystal violet and may be conveniently monitored by spectrophotometry. At

Keele the experiment is presented as a problem-based exercise in which the students, working in teams, have to establish the rate law for the reaction and study the influence of ionic strength on the reaction rate constant. They then have to propose a molecular mechanism for the reaction that is consistent with their experimental data.

A traditional prescriptive approach to this experiment would take decision making out of the hands of the students by, for example, detailing all concentrations to be used as well as the number and sequence of experimental runs. Assuming a colorimetric method, the traditional practical would likely prescribe a crystal violet concentration in the region of  $10^{-5}$  M and specify a suitable wavelength to be used to monitor the reaction.

In the problem-based approach the students do not know how fast the reaction is; they need to try it out. It comes as quite a shock to students when enquiring about the whereabouts of the 'sodium hydroxide solution' to be told that they have to decide what concentration they require and then prepare it themselves. The students need to learn that crystal violet is intensely coloured and if the crystal violet concentration is too high it is possible for the reaction to be taking place without any apparent change in colour, as a number of Keele students have discovered. In the problem-based practical, students can find themselves in situations where, monitoring absorbance as a function of time, they obtain a sigmoidal curve because for the first ten minutes the absorbance reading is too high for the instrument to discriminate between the transmitted light levels. In such a situation the student can learn about instrumental limitations in absorbance readings and the consequences of the non-linear relationship between absorbance and transmittance at high absorbance values. It is unlikely that such situations and opportunities for learning will arise in a traditional expository style practical. The students also come to learn (rather than being told) that for practical reasons it is easier to determine the rate law by working under pseudo order conditions with hydroxide ion in excess. The students have to negotiate their way towards a suitable experimental approach in much the same way as researchers do.

Although all students end up using a colorimetric method in this practical, they adopt a variety of approaches in terms of, for example, the range of ionic strength used, the means of varying the ionic strength and temperature control. Indeed one particular group of students decided to work at a higher temperature ( $\sim 40$  °C) in order to increase the reaction rate. The change in temperature affects the dielectric properties of water and the value of the constant in the Debye-Hückel limiting law and

with a little prompting these students were off calculating the value of 'A' at 40 °C, an outcome that is extremely unlikely in a traditional prescriptive practical.

It is interesting to note that during the first run of the crystal violet experiment some students immediately resorted to the Internet to find a procedure. I did not object to this because I made it clear that they would have to justify their method in any case and therefore they couldn't just follow it passively. These students became entrenched trying to reconcile various procedures from the Internet with the objectives of the experiment in front of them. They also learned quickly that they needed to be more critical of the material they were downloading rather than just accepting it as authoritative. So even in situations where students try to resort to a recipe and adopt a passive approach, the nature of the problem-based practical makes it difficult for them not to start thinking about what they are doing and why they are doing it. It is also interesting to note that the students who resorted to the Internet for a ready-made recipe made the slowest progress. Also, the demand on students to explain what they're doing and why they're doing it that way makes it perfectly possible to use the same experiment from year to year. Students may pick up some useful advice from the previous year's students, but the nature of the design of the practical class and the assessment methods makes this of only limited use. If it's not the student's 'own' approach, it will stand out in the laboratory discourse and in the assessment.

### Assessment

In terms of reporting laboratory work for problem-based practical work at Keele, a variety of methods are used, including for example, team poster presentations with an element of peer assessment, individual laboratory reports and individual PowerPoint presentations. The principal difference in the student 'reports' based on problem-based work compared with 'reports' based on traditional practicals is that there is, by default, more variety in content and style, and because of this, instances of plagiarism are fewer than with reports on traditional practicals.

Assessment of the problem-based practicals is detailed and structured and is linked to achievement of objectives and explanation of the rationale for the experimental approach adopted in addition to other generic elements. In order to obtain a first class mark, the students need to demonstrate understanding of their specific experimental approach, data processing and the theoretical background to the experiment, rather

Figure 3. Assessment criteria for a problem-based practical

**THE INFLUENCE OF IONIC STRENGTH ON THE SOLUBILITY OF BARIUM IODATE MONOHYDRATE  
POWERPOINT® PRESENTATION ASSESSMENT CRITERIA**

Criteria	Mark
<b>Quality of slides</b> (is there a title slide? are the slides clearly presented and structured? are they too busy or too thin? are results clearly presented and graphs and tables clearly labelled? is the experimental method concise and clear? are sources acknowledged and references cited?).	/15
<b>Structure</b> (is the material delivered in a logical and clear manner, including an introduction and conclusions?)	/15
<b>Style</b> (is the presenter audible and clear? is there eye contact with the audience? are key points emphasised?)	/15
<b>Content (Results and Data Analysis)</b> (what was the rationale for the experimental approach? were the objectives (see below) achieved? are statements, quantities and units accurate? is the quality of the data good or poor? are errors taken into account? are the conclusions drawn from the results justified? have errors been taken into consideration in arriving at the conclusions?)  <b>Objectives:</b>  ➤ Determine the solubility product ( $K_s^0$ ) for $\text{Ba}(\text{IO}_3)_2 \cdot \text{H}_2\text{O}$ . ➤ Determine mean activity coefficients ( $\gamma_{\pm}$ ) for $\text{Ba}^{2+}$ and $\text{IO}_3^-$ over a range of ionic strengths. ➤ Test the validity of the Debye-Hückel limiting law (DHLL).	/40
<b>Response to Questions</b> (Does the presenter understand the specific details of his/her experimental approach, data acquisition and analysis? Does the presenter have an understanding of the meaning, significance and limitations of the results and of the background theory to the experiment? Can the presenter apply their general chemistry knowledge within the context of this experiment?)	/15
<b>Total</b>	/100

than, in the case of a traditional practical, successfully negotiating a prescribed algorithm in much the same way as every other student in the class. As an example, current assessment criteria for the barium iodate experiment are shown in Figure 3.

#### Student and Demonstrator Feedback

Written feedback was sought from students and demonstrators on their experiences of problem-based practical work and it is apparent from the feedback (written and oral) that students had never encountered this approach to practical work. A representative selection of comments from individual students and demonstrators is

reproduced below. The first set of comments relates to the crystal violet experiment, which the students carried out first, and the second set relates to the barium iodate experiment.

#### Comments 1 (Crystal Violet).

- *I find this type of experiment much harder and more frustrating when things don't go to plan. However, it is a weaker part that could be improved if people did them more often.*
- *I found it quite hard to know what I was doing was actually right. Maybe you could have references to other similar experiments so that you could look at these and see how they did the experiment.*

- *The timing of the lecture material was out of step with the lab sessions, so the first week of the lab was spent being confused about what to do.*
- *Need more guidance – lots of contradictory advice.*
- *I do like the experiment but we need more background information as a lot of time is taken up from dry runs.*
- *More help needed with the design of experiment. A lot of different advice given which contradicted each other, therefore confusing. Designing an experiment did help understand what was going on a bit.*
- *This would be a good idea with more guidance given. A lot of help given was contradictory, which was very confusing.*
- *This technique of study is useful and more applicable to a work situation so it may be useful in the future even if it is not easy to get into this style of lab.*
- *Didn't really understand what the experiment was about until we finished it.*
- *The lecture material came too late – we don't really know what we're doing in our first few lab planning sessions. If we are on the wrong lines a hint should be given, as time is short. However, it is a refreshing approach. As it is group work, a group write up might have been a good idea.*
- *Demonstrators and lecturers need to be clearer in their explanations. There was too much 'see how it goes' and there was not enough time to take that approach. There should be more references, as recommending whole chapters of books can also be time wasting. There should be a starting point outlined, as when working in groups there is a lot of discussion and it takes time to start.*

#### **Comments 2.**

- *The second mini-project was much better than the first, as I had more idea as to what to do because we'd had more lectures so better understood the material, and had better guidance at the start of the project when it is most needed.*
- *This was the second mini-project, went better than the first, but I still find it tough, although it was stimulating.*
- *Try this out on the 1st years. More time was needed to work as a team to finalise plans.*
- *A little more time is needed to adjust to the new style of laboratory experiment, as we have never designed our own experiments before. Also, there seems to be a lot of deadlines in the last week or two of the module with assigned problems, oral presentations, lab reports and two workshops in for the last two weeks.*
- *Needed more time, and more guidance. More time is required to prepare.*
- *Please do not make us work in groups of four again – these groups are too large and it leads to too much faffing about and not enough work being done. More time was needed to complete these mini-projects as so much time was spent messing around making sure that the whole group understands what is going on.*

#### **Postgraduate Demonstrator Comments**

- *A good idea and good preparation for final year projects.*
- *Made students think and question why they were doing things.*
- *Harder for demonstrators because unpredictable and don't have a lab script to refer back to.*
- *Worried that I was misleading the students or giving the wrong advice.*
- *They need to know they should plan!*
- *Once they got into it they seemed to enjoy it and it makes them think.*

The feedback reveals that students find the problem-based style of practical work intellectually demanding, time-consuming and often frustrating. Also, it is clear that some students were confused, and therefore it could be argued that the problem-based approach is not an improvement on the traditional practical. However, this was the first time this style of practical had been used in chemistry at Keele, and it is evident from some of the comments that the students are not used to this style of practical. The problem-based style of practical has now been in use in several modules (principally level 2) for a number of years at Keele, alongside other more traditional practicals, and students, staff and demonstrators are now quite accustomed to them. It is apparent that the students became frustrated by contradictory advice and/or a perceived lack of advice and this is supported by a demonstrator's comment relating to anxiety about giving the 'wrong advice'. This highlights one of the main pre-requisites in managing this type of practical work: the tutors/demonstrators need to be very familiar with the material at a theoretical and practical level and they must proactively engage with the students to facilitate their learning. This style of practical work is certainly more demanding on student and staff demonstrators in the laboratory and consumes more laboratory time than that required for a traditional practical. Many of the comments above reflect the initial tendency of staff and demonstrators, in their first experience of this style of practical, to let the students find everything out for themselves, which coupled with instances

of conflicting and contradictory advice did cause confusion and did not always support learning. However, with more experience in the supervision and management of problem-based practical work the teacher acquires a better understanding of what to expect from students according to their level and experience and learns above all to focus on student learning during laboratory discourse.

### Conclusions

An account of a transition from expository style practical work to problem-based practicals has been described and discussed in the light of a practitioner's experiences and student feedback.

There are many challenges (for both students and teachers) associated with the use of problem-based practicals in laboratory teaching, but as well as being more demanding and frustrating they can also be more interesting, flexible and stimulating than the traditional style of laboratory practical, where inflexibility ensures that concept of the 'correct' answer and the 'correct' way of doing things prevails.

However, elimination of expository laboratory experiments from the undergraduate chemistry laboratory is not necessarily desirable, since such experiments fulfil different purposes. Indeed, there may be a synergistic effect in that students may learn more from individual types of experiments provided that they engage in a logically sequenced and balanced variety of laboratory work encompassing a range of experiment styles. For the student who has experienced other styles of laboratory work and has developed a capacity to think critically about experiment design, a traditional prescriptive script has the potential to become a different animal altogether; no longer a passive exercise but a further opportunity for critically evaluating how experiments are done. It is only a concern if the student adopts a passive approach; if a more critical approach is fostered then there is a place for this sort of practical as a

learning tool.<sup>6</sup> As Carnduff and Reid<sup>14</sup> argue, 'to change the experience, you don't need to change the experiment, just what you do with it'.

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