

UNIVERSITY CHEMISTRY EDUCATION

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Editorial Policy for University Chemistry Education (UChemEd)

The journal is aimed at those who teach chemistry in higher education. As a journal for all practising teachers of chemistry at this level, it deals with any topic of practical relevance and use to those involved. It is a place to publish effective methods and ideas for the teaching and learning of chemistry and issues related to the effectiveness of teaching and learning. Contributions are particularly welcome if the subject matter can be applied widely and is concerned with encouraging active and independent learning, with increasing student motivation for learning, with helping them to become effective exploiters of their chemical knowledge and understanding, or with assessment. Contributions should be of clear practical interest to those who teach chemistry.

There are not hard and fast rules for subdividing manuscripts. However, an introduction should provide a clear statement of the relationship of what is described to previous work and opinion (and is likely to include some references to some aspects of educational theory), and also the overall purpose of the article (including, where appropriate, the educational objectives, intended learning outcomes and why these are not satisfactorily achieved by other approaches). Other sections may be equivalent to *methods*, *results*, and *discussion* as used in conventional scientific papers; these sections would describe how the work was carried out, show or illustrate the outcomes (new teaching material etc) which have been created, and critically evaluate how far the original objectives have been met.

Four types of contributions may be submitted:

Full Papers describe a specific method of or approach to teaching, or some teaching material that has been used by the author; papers should explain the educational

objectives that led to the use of the method.

Communications are brief accounts of work still undergoing evaluation and development, but of sufficient interest to merit publication.

Reviews provide for practitioners an up-to-date survey of current methods or approaches to teaching and learning and also show how these relate to our understanding of student learning.

Perspectives provide an opportunity for contributors to present a concise but in-depth analysis of a topic of general interest, with clear conclusions likely to be directly useful to other academics involved in teaching.

Letters: these are a medium for the expression of well-argued views or opinions on any matter falling within the remit of Journal.

All contributions, whether or not they were solicited, are rigorously reviewed. Referees are required to evaluate the quality of the arguments presented, and not to make subjective judgements involving their personal views of what constitutes good or effective teaching. Contributions are judged on:

- (i) originality and quality of content;
- (ii) the appropriateness of the length to the subject matter;
- (iii) accessibility of supporting material

University Chemistry Education

Guidelines for Authors

Submission of contributions

University Chemistry Education (UChemEd) is aimed at those who teach chemistry in higher education. As a journal for all practising teachers of chemistry at this level, it deals with any topic of practical relevance and use to those involved. It is a place to publish effective methods and ideas for the teaching and learning of chemistry and issues related to the effectiveness of teaching and learning.

1. The original contribution should be submitted electronically, preferably in Word for Windows format. Any associated diagrams should be attached in JPG or GIF format, if possible. Submissions should be made by e-mail as a file attachment, or on a floppy disk, to Dr Stephen Breuer at s.breuer@lancaster.ac.uk or at School of Physics and Chemistry, Lancaster University, Lancaster, LA1 4YB, United Kingdom, or to Professor Patrick Bailey at p.d.bailey@hw.ac.uk or at Department of Chemistry, Heriot-Watt University, Riccarton, Edinburgh, EH14 4AS, United Kingdom.

2. Submitted contributions are expected to fall into one of several categories. Authors are invited to suggest the category into which the work should best fit, but the editors reserve the right to assign it to a different category if that seems appropriate. These are the following.

Full papers describe a specific method of or approach to teaching, or some teaching material that has been used by the author.

Communications are brief accounts of work still undergoing evaluation and development, but of sufficient interest to merit publication.

Reviews provide for practitioners an up-to-date survey of current methods or approaches to teaching and learning and also show how these relate to our understanding of student learning.

Perspectives provide an opportunity for contributors to present a concise but in-depth analysis of a topic of general interest, with clear conclusions likely to be directly useful to other academics involved in teaching.

A word count (excluding references, tables, legends etc) should be included at the end of the document.

3. Presentation should be uniform throughout the article.

Text should be typed in 12pt Times New Roman (or similar), with 1" margins, double-spaced, unjustified, ranged left and not hyphenated.

Always use an appropriate mix of upper and lower case letters: do not type words in uppercase letters either in the text or in headings. **Bold** or *italic* text and not upper case letters should be used for emphasis.

All nomenclature and units should comply with IUPAC conventions.

Tables and figures should be numbered consecutively as they are referred to in the text (use a separate sequence of numbers for tables and for figures). Each should have an informative title and may have a legend.

Equations should be written into the text using the word processing program, either as normal text or using the program's equation facility.

Structures should, wherever possible, be treated as a figure and not incorporated into text.

References should be given as superscripts, designated as numbered endnotes.

Footnotes should be generally avoided and important additional information may be referenced and included in the reference list.

4. A title page must be provided, comprising:

an informative title;

authors' names and affiliation, full postal address and e-mail; (in the case of multi-authored papers, use an asterisk to indicate one author for correspondence, and superscript a, b, etc. to indicate the associated addresses);

an abstract of not more than 200 words.

5. Wherever possible articles should be subsectioned with headings, subheadings and sub-sub-headings. Do **not** go lower than sub-sub-headings. Sections should not be numbered. Headings should be no more than 40 characters in length and subheadings and sub-sub-headings no more than 30.

The introduction should set the context for the work to be described; include references to previous related work, and outline the educational objectives.

A concluding section (which need not be headed conclusion) will include an evaluation of the extent to which educational objectives have been met. A subjective evaluation may be acceptable.

6. The formatting of references should follow the general practice in the various titles within the Journal of the Chemical Society range. For example:

Books and Special Publications:

- W.G. Perry, *Forms of intellectual and ethical development in college years: a scheme*; Holt, Rinehart and Winston, New York, 1979. p. 218.
- M. McCloskey in D. Gentner and A.L. Stevens (eds), *Mental models*; Lawrence Erlbaum, New Jersey, 1983, pp. 147-153.

Journal Articles:

- D.C. Finster; *J.Chem.Ed.*, 1989, **66**, 659.
- A.H. Johnstone and K.M. Letton, *Educ.Chem.*, 1990, **27**, 9.

References to articles in *U.Chem.Ed.* on the Web should be identified by paper number until they are incorporated into numbered issues.

7. All contributions submitted will be refereed anonymously. The decision of the Editors on the acceptance of articles is final.
8. Authors grant *U.Chem.Ed.* the exclusive right to publish articles. They undertake that their article is their original work, and does not infringe the copyright of any other person, or otherwise break any obligation to, or interfere with the rights of such a person, and that it contains nothing defamatory.
9. Articles will be published on the Web in PDF and HTML formats as soon as the editorial process is complete. In addition, they will be combined into electronic issues as a PDF file in April and October.
10. **Letters to U.Chem.Ed.** relating to published articles or on any other educational topic should be sent for publication on the U.Chem.Ed. Web Board to its moderator, Dr Paul Yates at p.c.yates@chem.keele.ac.uk. A selection of these letters will be incorporated into the issues of the journal.

At present, there appears to be a dearth of commercially available software for generating written comments to university students on their assessed work. The development of *electronic feedback*, a software package based on MS Excel 97 and MS Word 97, is a response to this recognised need. The programme has an additional advantage in that it allows tutors to distribute feedback via e-mail. The purpose of this paper is to describe this method and to report on its effectiveness when marking chemistry coursework at Liverpool John Moores University (JMU). Given that Excel and Word are applications that have a wide user base and that most institutions have well developed e-mail networks, it is thought that this procedure will be readily transferable.

Method

The electronic feedback software consists of two programs: *Feebac5.xls*, an MS Excel 97 workbook, and *Fb.doc*, a MS Word 97 document. Together, these programmes can be used by tutors to generate individual word-processed feedback reports that can be printed and/or e-mailed to each member of the class. Each feedback sheet details

the student's name and can include the percentage mark, class rank, a general comment, and a series of comments directed specifically at the student. To illustrate the operation of the software, a fictitious set of data has been created. This data set is smaller in size than one that might typically be considered, but is sufficient to convey the essential details of the procedure. An example feedback sheet that has been generated using this data set is shown in Figure 1.

Preparation

The Excel workbook *Feebac.xls* is composed of a series of worksheets; *Configure*, *List*, *Header*, *Annos*, *Numbers* and *Report*, that contain a number of blank cells. The feedback sheets are created using data that is entered into these cells by the assessor. Tutors enter student names, e-mail addresses and registration numbers into the *List* worksheet, Figure 2. Typically, this information is readily transferred from institutional electronic information services. The class list shown in Figure 2 has the format preferred by JMU in which data appears in the order; e-mail address, forename, surname and registration number. Users can configure the software so that it will accept

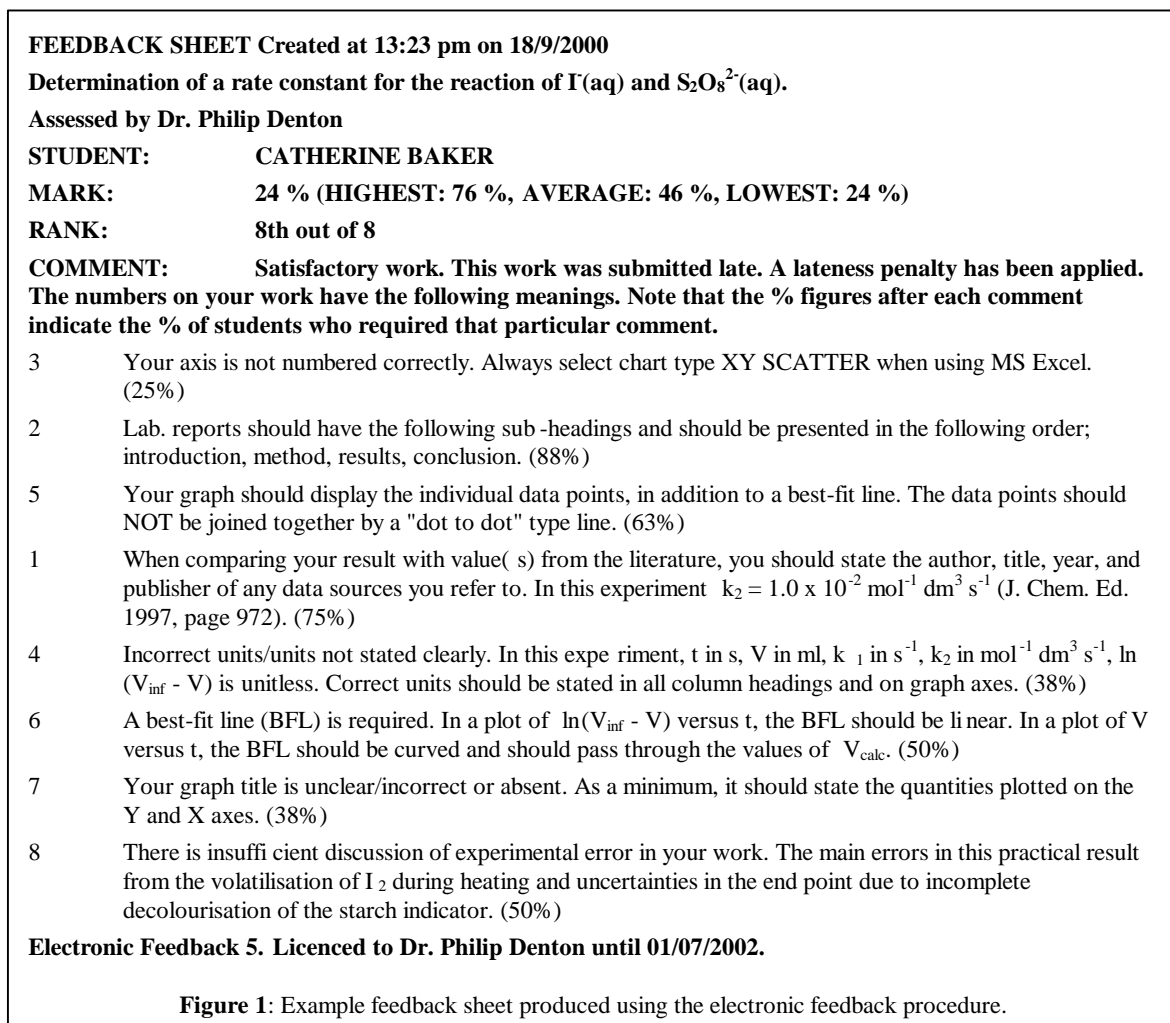


Figure 1: Example feedback sheet produced using the electronic feedback procedure.

List						
	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
	e-mail		Forename	Surname	Regno	
1	PACBBAKE	MISS	CATHERINE	BAKER	66342	
2	PACJBALE	MISS	JOANNE MA	BALEED	206282	
3	PACABASS	MR	AHMED HAF	BASSI	46634	
4	PACRBERA	MISS	RAMANDEE	BERAHNEG	283599	
5	PACABULL	MR	AMIR	BULLOCK	125146	
6	PACJCAME	MISS	JULIE ELIZA	CAMERON	328365	
7	PACACAVE	MR	ALASTAIR J	CAVE	133879	
8	PACBCHAK	MR	BENJAMIN	CHAKRABO	134667	
9	PACPEVAN	MR	PARTHA PR	EVANS	628045	
10	PACHFAZL	MISS	HAYLEY	FAZLEE	234042	
11	PACMHARR	MR	MOHAMMA	HARRIS	265837	
12	Figure 2: Example <i>List</i> sheet from the spreadsheet Feedbac.xls.					

electronic details in the order favoured by their institution.

The marker enters specific details of the activity that is being assessed into the *Header* worksheet, including the title of the coursework and the maximum mark that can be awarded. The assessor

can also put in statements that they wish to appear in the 'Comment' section of the feedback sheet, Figure 1. Some of these comments will only appear if the student's mark falls within certain boundaries. Thus, the example *Header* worksheet in Figure 3 has been completed so that any student awarded a mark of 60 % or above, but below 70 %, can also put in statements that they wish to appear in the 'Comment' section of the feedback sheet, Figure 1. Some of these comments will only appear if the student's mark falls within certain boundaries. Thus, the example *Header* worksheet in Figure 3 has been completed so that any student awarded a mark of 60 % or above, but below 70 %,

Header	
Enter filename	<input type="text" value="Uchemed"/>
Title of Coursework	<input type="text" value="Determination of a rate constant for the reaction of I<sup>-</sup>(aq) and S<sub>2</sub>O<sub>8</sub><sup>2-</sup>(aq)."/>
<input type="text" value="33"/>	Maximum Mark
Maximum % Mark	Comment
70	Excellent work.
60	Very good work.
50	Good Work.
40	Satisfactory work.
30	Unsatisfactory work.
0	Poor work.
Other Comments	
Top Mark	Top of the class, well done!
Late Work	This work was submitted late. A lateness penalty has been applied.
All Students	The numbers on your work have the following meanings. Note that the % figures after each comment indicate the % of students who required that particular comment.
Figure 3: Example <i>Header</i> sheet from the spreadsheet Feedbac.xls.	

Annotations		
Determination of a rate constant for the reaction of $\text{I}^{-}(\text{aq})$ and $\text{S}_{2}\text{O}_{8}^{2-}(\text{aq})$.		
Dr. Philip Denton		
	Number of scripts marked (to date)	8
	Highest Mark (%)	76
	Average Mark (%)	46
	Lowest Mark (%)	24
	Standard Deviation (%)	16
		% of students with this annotation
Meaning of the annotations		% of students with this annotation
1	When comparing your result with value(s) from the literature, you should state the author, title, year, and publisher of any data sources you refer to. In this experiment $k = 1.0 \times 10^{-2} \text{ mol}^{-1} \text{ dm}^3 \text{ s}^{-1}$ (J. Chem. Ed. 1997, page 972).	75
2	Lab. reports should have the following sub-headings and should be presented in the following order; introduction, method, results, conclusion.	88
3	Your axis is not numbered correctly. Always select chart type XY SCATTER when using MS Excel.	25
4	Incorrect units/units not stated clearly. In this experiment, t in s, V in ml, k_1 in s^{-1} , k_2 in $\text{mol}^{-1} \text{ dm}^3 \text{ s}^{-1}$, $\ln(V_{\infty} - V)$ is unitless. Correct units should be stated in all column headings and on graph axes.	38
5	Your graph should display the individual data points, in addition to a best fit line. The data points should NOT be joined together by a "dot to dot" type line.	63
6	A best-fit line (BFL) is required. In a plot of $\ln(V_{\infty} - V)$ versus t, the BFL should be linear. In a plot of V versus t, the BFL should be curved and should pass through the values of V_{∞} .	50
7	Your graph title is unclear/incorrect or absent. As a minimum, it should state the quantities plotted on the Y and X axes.	38
8	There is insufficient discussion of experimental error in your work. The main errors in this practical result from the volatilisation of I_2 during heating and uncertainties in the end point due to incomplete decolourisation of the starch indicator.	50

Figure 4: Example *Annos* sheet from the spreadsheet *Feedbac.xls*.

receives the comment, "Very good work." Additional comments can be directed to those students who are subsequently identified as having handed work in late, and to the student who secured the highest mark.

Tutors are required to enter a series of feedback statements into the *Annos* worksheet, Figure 4. The statistical information that appears on this sheet will be considered subsequently. Typically, the feedback comments are those which past experience shows are most likely to be needed during marking, e.g. "You have failed to state the correct units". Clearly, the number of written comments required will depend on the nature of the assessment activity. When a large group of students have submitted practical reports on a particular experiment, for example, the same errors and misunderstandings crop up time and

time again, limiting the number of statements that is required. Since Excel does not have the facility readily to format text, comments that contain superscripts, subscripts, line breaks or tab spaces can be entered using a series of special characters. Thus, '^' = convert next character to a superscript, '_' = convert next character to a subscript, '^' = insert line break, '-' = insert tab space. For example, the formula of the persulphate ion is ' $\text{S}_{2}\text{O}_{8}^{2-}$ ' using this system.

Marking

The three worksheets described up to this point, *List*, *Header* and *Annos* can be completed before the students have submitted their work. During marking itself the students' scripts are annotated with digits where each number corresponds to one of the feedback comments on the *Annos* worksheet. In this way tutors can avoid having to write the

Meaning of the annotation (abridged)	% of students with this annotation (7/10/99)	% of students with this annotation (23/9/99)
Lab. reports should be presented in the following order; introduction, method, results, conclusion.	60	36
Your graph axis is not numbered correctly. Always select chart type XY SCATTER when using MS Excel.	36	2
Incorrect units/units not stated clearly.	98	74
Your graph should display the individual data points, in addition to a line.	34	2
Your best-fit line is incorrect and/or absent.	91	31
Your graph title is unclear/incorrect or absent.	57	7
Your graph axis is not labelled correctly or is not labelled at all.	21	0

Figure 6: Assessment profiles from two first year undergraduate chemistry practicals.

School of Pharmacy and Chemistry. This was in addition to three focus groups, each consisting of three students chosen at random. Members of staff were also requested to offer their views on the software after it was presented to them during a JMU training session.

Results

The *electronic feedback* method has been used to assess physical chemistry laboratory reports and worksheet assignments submitted by first and second year undergraduates at JMU. The procedure has been found to work well in practice. Ideally, the bank of feedback statements should be written before the assessor receives the students' work to enable the marking to be completed as quickly as possible. There is no reason, however, why it cannot be gradually built up during marking itself.

When marking laboratory reports, the same initial bank of general feedback comments can be used. These are then edited and augmented so that they are appropriate to each experiment. Typically, about 25 distinct comments are required. Many of the comments relate to core skills such as report writing and the graphical representation of experimental data. The frequency with which particular comments were used when marking two first year undergraduate physical chemistry experiments, conducted two weeks apart, is shown in Figure 6. By the time the students came to undertake the second practical they had already received e-mailed feedback on the first. As is

evident, the ability of the students to present their work in an appropriate scientific manner had improved markedly over this period.

Annotating students' work with numbers in place of comments ensures that marking is relatively straightforward and rapid. Moreover, the *List* and *Header* worksheets of the *Feedbac.xls* file can be filled efficiently if electronic class list information is available. The time taken to complete the *Annos* worksheet will depend on the number and complexity of the feedback comments. As discussed above, however, if the assessed assignment is similar to one that has been set previously, tutors may find that it is possible to use an existing bank of feedback comments that has been appropriately modified. In this way, the time taken to enter the *Annos* worksheet can be considerably reduced. The *Numbers* worksheet can be completed quickly if marked scripts are first arranged in class list order, before the marks and the numerical annotations that appear on the work are entered.

Students reacted positively to the electronic feedback procedure when questioned in the focus groups and in responding to the questionnaire. All the interviewed students felt that the e-mailing of feedback was an efficient way to receive details of their performance in an assessment, as it removed the requirement for them to wait until the next time they met the lecturer. It was evident that students were comfortable with the principle of receiving feedback when they were at a computer

terminal on their own. The focus groups confirmed that they were more likely to pay attention to the electronic feedback that is returned quickly and felt that it was then acceptable to wait 2-3 weeks for marked coursework to be returned.

The questionnaire revealed that 88% of the undergraduates felt that it was useful to have written feedback e-mailed to them in advance of receiving their marked script. The vast majority stated that they appreciated knowing the maximum, average and minimum marks for the activity (91 %) as well as their position in the class (88 %). All questioned students found the comments on their feedback sheet useful and most of the class (81%) felt that they had received more written feedback than they normally obtained from tutors. It became clear that one of the particular advantages of the electronic feedback procedure is its ability to return lengthy, detailed comments on a particular aspect of the assessment. The responses of two students were typical, "*It is a helpful method of marking as it enables you to see how and why mistakes were made...*" and, "*It offers a more in-depth description of how you have gone wrong.*" A number of students also commented that the printed feedback sheets overcame difficulties associated with the legibility of staff handwriting. In response to the question, "*should electronic feedback be used more regularly within the School?*", 100% of respondents said, "Yes".

After the staff training session, 31 colleagues returned written sheets to provide feedback on the session. Those staff who have a familiarity with Excel reported minimal difficulties using the software. One member of staff commented, "*A fairly complex piece of software which I will feel more confident of using once I've tried it out using my own annotations. Educationally, a very sound method.*" Other staff acknowledged that the procedure could become second nature with practice. 5 members of staff said they would definitely not use the software in future, either because they had an existing electronic system that they preferred, or because they had experienced difficulties using the software.

Discussion

Up to now, the electronic feedback technique has been used primarily in the grading of chemistry coursework. The procedure is quite general, however, and can be used for any assessment where it is expected that students will make the same errors repeatedly. It is clear that the electronic feedback approach can make the marking process considerably less onerous as it

removes the requirement to annotate students' work with repeated hand-written comments. The package would be of particular interest to those tutors who find that, using conventional methods, they are unable to return as much feedback as they would wish to. Although this approach is perhaps less personal than traditional marking, there is no reason why tutors cannot supplement their printed feedback with hand-written comments to individual students.

The two files that comprise electronic feedback are password protected to prevent the accidental overwriting of essential subroutines. Thus, there are limited opportunities for customisation. Tutors can have some control over the final appearance of the feedback sheets, however, and may choose to omit details of the maximum, average and minimum marks as well as the student's position in the class. Tutors who prefer to allocate grades instead of marks can choose to hide the percentage marks that are normally displayed on the feedback sheets and can write feedback statements such as 'Grade B+'. Each statement can have a particular number associated with it and these can be allocated to students in the customary manner.

The software need not necessarily be used exclusively when marking assessments where the same errors crop up repeatedly. If they so wish, tutors can write a single, lengthy feedback comment for each student and use the software to generate the corresponding feedback sheets. In this way the software can be used to e-mail feedback to students on highly individual assessments such as project work. If this approach is adopted, the number that corresponds to the feedback comment, and the percentage of students requiring that statement, may be omitted from the feedback sheet.

Acknowledgement

This work was completed as part of the Postgraduate Certificate in Learning and Teaching in Higher Education 1999/2000. I wish to thank all the tutors associated with this course.

Supporting material

Copies of the requisite software and a user guide are available from the author. Interested persons should send a stamped addressed A4 envelope and a formatted 3½" disk. Please include your e-mail address so that you may be contacted subsequently for your opinions of the software. Respondents should indicate how they wish their title and name to appear on the feedback sheet, as this information cannot be changed subsequently. This is a security precaution that is included so as to prevent the unauthorised proliferation of the software.

References

- 1 G. Brown, J. Bull and M. Pendlebury, *Assessing Student Learning in Higher Education*, Routledge, London, 1997, p. 7.
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- 3 G. Gibbs and T. Habeshaw, *Preparing to Teach: An Introduction to Effective Teaching in Higher Education*, Technical and Educational Services, Bristol, 1993, p. 95.
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- 5 T. King, *Using an Optical Mark Reader for Continuous Student Assessment: a Case Study in Higher Education in Computer Assisted Assessment.*, ed.-s, J. Darby and J. Martin, 1994, p. 23.
- 6 G. Gibbs, S. Habeshaw and T. Habeshaw, *53 Interesting Ways to Assess Your Students*, Technical and Educational Services, Bristol, 1986, p. 77.
- 7 B.S. Nicholls, *U. Chem. Ed.*, 1998, **2**, 10.
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- 9 S.L. Helgeson and D.D. Kumar, *Journal of Computers in Mathematics and Science Assessment*, 1993, **12**, 227.
- 10 L. Barnett, D. Brunner, P. Maier and Warren, *A Technology in Teaching and Learning: A Guide for Academics*, Interactive Learning Centre, University of Southampton, 1996, p. 59.
- 11 S. Habeshaw, G. Gibbs and T. Habeshaw, *53 Problems with Large Classes: Making the Best of a Bad Job*, Technical and Educational Services, Bristol, 1992, p. 136.

be completed at different times throughout the class. We looked at other testing systems that include randomised selection of questions (for example Turton⁵), and at commercial systems such as Question Mark Designer,⁶ but found that these were designed for computer delivery of tests, and did not offer any possibility of customisation to meet all our needs. We therefore decided that the best option was to design our own style of test.

The system we designed has now been in operation for three years.^{7,8}

Methods

Creating the questions

The first year laboratory course consists of 20 sessions in each of which each student completes a different experiment. Before leaving the laboratory each student completes a test of 20 questions and hands in a coded answer sheet. Each test paper is unique to the student concerned and is generated on paper for each student from a bank of multiple-choice questions. Students collect their test papers at the start of each laboratory session, and answer the questions at appropriate points during and at the end of the experimental procedures. Because all the tests are different, we are able to allow students to discuss the answers to questions. Students are also encouraged to seek help from demonstrators with questions they find difficult.

The answers to the test questions are entered directly onto a copy of the University's standard, machine-readable form for marking by an optical mark reader; this form simply lists the question number and offers the choice of five boxes corresponding to the alternative responses provided (five boxes are always provided even though some questions are only provided with three or four responses). Individual test papers, each of which is prepared as a Microsoft Word document, are created by the computer from the bank of questions. Typically the question bank for each experiment consists of 24 different basic questions, but the variety is considerably increased because many of these basic questions have a number of variants (2–8). Variants are generated in several different ways. Sometimes it was possible to devise equivalent questions that were totally different, or (in the case of dummy calculations) to provide different data for the same calculation. Sometimes it was possible to use a fixed set of responses, but different question stems, one corresponding to each response. However, in some cases, the only acceptable variation was to change the order of the possible responses. With such questions, it is obviously easier for students to collaborate, but we were satisfied that they would at least have to read the question and its responses carefully — it would not be possible just to find out from a neighbour that the answer to question 3 was B.

The provision of a machine-readable test of observations made and of results was tackled in two ways. The first is used in experiments where all students should in theory obtain the same answer. The style of question used here is:

- **From the calibration graph, in which of the following ranges was the concentration of potassium ions in the riverwater?**
- A **Less than 8mg l⁻¹**
- B **8–9 mg l⁻¹**
- C **9–10 mg l⁻¹**
- D **10–11 mg l⁻¹**
- E **More than 11mg l⁻¹**

We tried here to avoid making the middle response the correct one, so that students could not use our ranges to guess the answer that we were expecting. The evidence we have from student queries is that they are very keen to code their results correctly, rather than attempt to cheat the system. The correct response is awarded a full 1 mark, but other responses may be awarded partial marks, based on our knowledge of the errors of the experiment.

The second method is required for experiments where students are expected to get different results, and where the mark is to be awarded for aspects of experimental work that involve human judgement. For these questions, the student is informed what the marks are awarded for but is instructed not to provide an answer. Instead, responses to be coded on the machine-readable answer sheets are decided by demonstrators after examining the laboratory manual and checking calculations where necessary. This is done throughout the class and does not usually cause delays. Examples of these questions are:

- Has the mass of the iron compound been recorded correctly?**
- Are the titration volumes in good agreement?**
- Has the percentage yield been calculated correctly?**
- Has the graph been drawn neatly and correctly?**

Demonstrators have a key for each experiment, which details the appropriate response for these questions, which we define as 'demonstrator-marked'. For each question, the key provides a letter that corresponds to the full mark of 1; the other letters correspond to fractions of a mark. Thus, if the key letter is C, students awarded response C receive a mark of 1, but other responses receive 0.75, 0.5, 0.25, or 0. The letters corresponding to the correct result are different for the different experiments, are kept secret from the students, and are changed from time to time. Amongst other characteristics of student work, these demonstrator-marked questions require demonstrators to check calculations, to examine

graphs for neatness and correct plotting, and to examine the appearance of organic products. Marking guidelines leave as little room as possible for personal interpretation so that postgraduate demonstrators are able to assist the staff with marking. Demonstrator-marked questions are included in the same format and in the same place on all the test papers for a particular experiment. They are therefore designated as 'fixed'.

Questions dealing with other aspects of the experiment (for example, calculations with dummy data, and questions dealing with background theory) are of a more conventional style. For the purposes of creating test papers these questions are designated as 'fixed' (one of the variants appears in every test paper, always in the set position), 'compulsory' (one of the variants appears in every test paper, but in any available position) or as 'optional' (a question which need not be selected).

Depending on the experiment, a test paper will contain 3–20 fixed questions, 0–10 compulsory questions, and 17–20 optional questions selected from a bank of up to 30 (basic questions) with a total of up to 80 variants.

Creating the test papers

The test papers are created from the question banks and the corresponding Questionnaire Definition Files, by using the Creator program, which is written in *Delphi* (like the others in the suite). The program reads a set of daily *Excel* spreadsheets (giving lists of student names, laboratory numbers, and class codes), another spreadsheet giving the rota of experiments (which relates student laboratory numbers with experiments for each week), and a file, which defines all the experiments. The program uses the student's laboratory number together with a 'day code' defining the day of the week and the week number to set the rules by which the algorithm selects the questions for each student in a manner that appears to be random. Each test will include all the fixed questions, in their defined positions, along with the Compulsory questions and enough Optional questions to give a total of 20; the positions of the "c" and "o" questions are different for each different test. The algorithm also determines which of the optional questions are selected and (for questions with variants) it also determines which variant is selected.

To simplify the handling and distribution, the font size and margins for the questionnaire are set to

permit each test to be printed on a single sheet of paper. An example of a test is shown in Figure 1. Once the student names are available, laboratory numbers have been allocated, and the daily *Excel* spreadsheets prepared, questionnaires are simple to produce. Normally they are generated for all students for a given day and week number in a single batch (although if necessary a single form can be printed). This is repeated for other days and week numbers. The limiting factor in the process is the printer — but with a fast printer, tests for 20 lab sessions (for 5 weeks, with 4 lab classes each week; up to 3000 tests) can be printed in a single day.

Marking program

The laboratory technicians scan the completed machine-readable forms by using a Scanmark 2000 (<http://www.scantron.com/scan/sm2000.htm>) optical mark reader (omr). The machine is set to reject forms if marks are missing or not dark enough to be readable; it can also reject some invalid codes. Any rejected form is returned at once to the student, with advice to make marks darker, or insert or amend codes and then the form is rescanned. We bought our own reader for this project, but use the University's standard printed forms. The omr software writes the data to an ASCII text file.

Each week, the four daily files are processed by the Marker program, which uses the same algorithm as the Creator program to determine, for each student, which questions have to be marked. It then checks the answers in the answer file, and awards the appropriate mark. It has not proved possible to make the marking process fully automatic, because students sometimes make errors in entering their laboratory numbers and/or day codes, but the program attempts to flag these, and the flagged entries are corrected manually. When all corrections have been made, the program is instructed to insert the marks into the *Excel* spreadsheet, which also serves as the register for the class. At the time of marking, the responses are recorded in a text file for later analysis, if desired, for example to calculate the fraction of the class with the correct answer to every variant of every question (the facility value).

A special arrangement had to be made for the "Unknown Samples" that students have to identify in the Inorganic part of the laboratory class. There are 47 different samples, so it was not considered necessary to generate fully randomised tests.

- 2071 JOHN SMITH Cations part 2 Day code: 0321
- Q1.** The colour of the solid and the stock solution of compound T is?
 A Colourless / white B Pink / red C Green D Blue
- Q2.** With which of the following pairs of cations are the colours of the solid and stock solution of compound T compatible?
 A Cu^{2+} and Cr^{3+} B Cu^{2+} and Fe^{2+} C Cr^{3+} and Co^{2+} D Ni^{2+} and Fe^{2+}
- Q3.** On heating the precipitate a change in colour was noted. What was the final colour observed?
 A Blue B White/colourless C Green D Black
- Q4.** Which of the following is the only cation to fit the result obtained when sodium hydroxide solution (dilute then excess) was added to the compound?
 A Ni^{2+} B Cu^{2+} C Cr^{3+} D Fe^{2+}
- Q5.** Unknown T was copper sulphate 5-hydrate. Which of the following is the formula for this compound.
 A $(\text{CuSO}_4)_5 \cdot \text{H}_2\text{O}$ B $\text{Cu}(\text{SO}_4)_2 \cdot 5\text{H}_2\text{O}$ C $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ D $\text{Cu}_2\text{SO}_4 \cdot \text{H}_2\text{O}$
- Q6.** Which of the equations below represents the formation of the precipitate of copper hydroxide?
 A $\text{Cu}^{2+}(\text{aq}) + 2\text{OH}^-(\text{aq}) \rightarrow \text{Cu}(\text{OH})_2(\text{s})$ B $2\text{Cu}^{2+}(\text{aq}) + \text{OH}^-(\text{aq}) \rightarrow \text{Cu}_2\text{OH}(\text{s})$
 C $\text{Cu}^{2+}(\text{aq}) + \text{OH}^-(\text{aq}) \rightarrow \text{CuOH}(\text{s})$ D $\text{Cu}^{2+}(\text{aq}) + 2\text{OH}^-(\text{aq}) \rightarrow \text{CuOH}_2(\text{s})$
- Q7.** What is the formula of the compound formed on heating copper hydroxide?
 A CuS B CuO C CuOH D $\text{Cu}(\text{NO}_3)_2$
- Q8.** The precipitate redissolved on adding excess ammonia solution owing to the formation of a complex. Is the complex
 A An anion B A cation C A neutral molecule
- Q9.** What is the name given to this type of complex?
 A Hydroxo B Ammine C Amine D Hydrate
- Q10.** Which of the following equations represents the formation of the copper complex ?
 A $\text{Cu}^{2+}(\text{aq}) + 6\text{NH}_3(\text{aq}) \rightarrow [\text{Cu}(\text{NH}_3)_6]^{2+}(\text{aq})$ B $\text{Cu}^{2+}(\text{aq}) + 4\text{NH}_3(\text{aq}) \rightarrow [\text{Cu}(\text{NH}_3)_4]^{2+}(\text{aq})$
 C $\text{Cu}^{2+}(\text{aq}) + 4\text{NH}_3(\text{aq}) \rightarrow [\text{Cu}(\text{NH}_3)_4]^{4+}(\text{aq})$ D $\text{Cu}^{2+}(\text{aq}) + 6\text{NH}_3(\text{aq}) \rightarrow [\text{Cu}(\text{NH}_3)_6]^{6+}(\text{aq})$
- Q11.** On addition of excess of concentrated hydrochloric acid to a solution of unknown T a colour change was observed. Which of the following changes in colour best fits your observation?
 A Blue to greenish yellow B Blue to violet C Blue to red D Green to blue
- Q12.** The change in colour is due to the formation of a complex. Is the complex
 A An anion B A cation C A neutral molecule
- Q13.** What is the name given to the type of complex formed with hydrochloric acid?
 A Hydroxo B Chloro C Amine D Hydrate
- Q14.** Which of the following represents the formula of the complex formed?
 A $[\text{CuCl}]^-$ B $[\text{Cu}_2\text{Cl}]^{2+}$ C $[\text{CuCl}_4]^{2-}$ D $[\text{Cu}_2\text{Cl}_4]^{2-}$
- Q15.** Which of the following is the correct formula for the precipitate formed when sodium sulphide was added to T?
 A CuS_2 B Cu_2S C CuS D Cu_2S_2
- Q16.** From the colour of compound U and its solution, which of the following groups of cations can you say are definitely not present in the compound?
 A Mg^{2+} , Ca^{2+} , Sr^{2+} , Ba^{2+} , Cd^{2+} B Cr^{3+} , Fe^{3+} , Co^{2+} , Ni^{2+} , Cu^{2+}
 C Zn^{2+} , Al^{3+} , Pb^{2+} , Sn^{2+} , Sn^{4+} D Cd^{2+} , Mn^{2+} , Fe^{2+} , Ag^+
- Q17.** Which of the following groups of cations is compatible with the result from the reaction between compound U and sodium hydroxide solution?
 A Mg^{2+} , Ca^{2+} , Sr^{2+} , Ba^{2+} , Cd^{2+} B Cr^{3+} , Fe^{3+} , Co^{2+} , Ni^{2+} , Cu^{2+}
 C Zn^{2+} , Al^{3+} , Pb^{2+} , Sn^{2+} , Sn^{4+} D Cd^{2+} , Mn^{2+} , Fe^{2+} , Ag^+
- Q18.** Which one of the following cations can be eliminated because it would have given a precipitate if the solid was tested with nitric and sulphuric acids?
 A Ca^{2+} B Mg^{2+} C Cd^{2+} D None
- Q19.** Unknown U was magnesium sulphate 7-hydrate. Which of the following is the formula for this compound?
 A $(\text{MgSO}_4)_7 \cdot \text{H}_2\text{O}$ B $\text{Mg}(\text{SO}_4)_2 \cdot 7\text{H}_2\text{O}$ C $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ D $\text{Mg}_2\text{SO}_4 \cdot 7\text{H}_2\text{O}$
- Q20.** Which of the following is the formula for the precipitate formed when sodium hydroxide was added to a solution of U?
 A $\text{Mg}(\text{OH})_2$ B $\text{Mg}_2(\text{OH})_3$ C MgOH D Mg_2OH

Figure 1. An example of a questionnaire

Instead, a limited number of tests were prepared for each of the samples used. The pre-prepared questionnaires are associated with the samples rather than with individual students. These tests are identified to the Marker program by special codes printed on the test forms in place of the normal day codes. Different students complete different numbers of unknown samples, so all the marks achieved by one student are summed in a single spreadsheet cell.

Providing students with feedback

Feedback to the students is provided in two ways. In the first, marks are made available by the Laboratory Mark Reader program, which runs on two low-specification computers in the laboratory. This program reads copies of the main Excel spreadsheets, and allows students to see the mark achieved in the previous week(s), and also to find out the numbers of the questions they have answered incorrectly. Students are advised to retain their questionnaires so that they can review these questions; they are advised to consult a demonstrator if they do not understand their error.

The second form of feedback is provided only to students who get marks below a given threshold (usually 12 out of 20). These students are offered a printed report showing their incorrect responses and they are particularly recommended to consult a demonstrator for advice about their errors. The printouts include the full text of questions answered incorrectly, but questions related to the student's experimental data are normally labelled in the answer file so that they are excluded from these reports. (The same applies to the first form of feedback.)

Results

The facility value calculated for each question (and each variant) provides evidence that no questions appear to be either so easy or so difficult that they provide no useful discrimination between students. Typically, the facility values fall between 0.6 and 0.8, which we regard as satisfactory here. In a normal exam, an 'ideal' question would have a value of 0.5, because half the class got the question correct; but a test should include a range of facility values in order to discriminate across a range of student abilities (1).

Furthermore, the facility values for variants of the same basic question are essentially the same. These results provide reassuring evidence that the tests are discriminating effectively. A point of particular interest arises from our examination of the facility values for questions, which differed only in the order of the distractors. We observed considerable variation in the numbers choosing the various wrong answers, but we found only two for which the correct answer had a higher facility when the

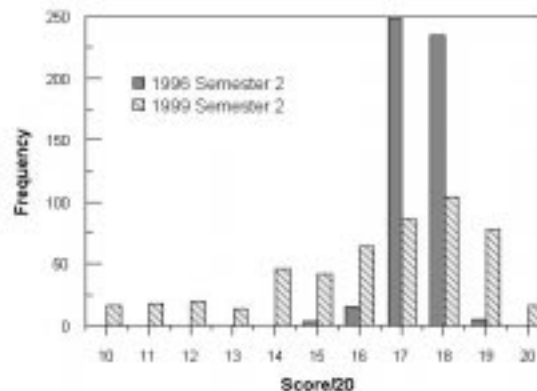


Figure 2. Comparison of laboratory marks awarded by the old and new systems

nearest distractor immediately preceded it. In view of the large number of questions we examined, this was not statistically significant and our observations are therefore inconsistent with the suggestion that the relative locations of the correct answer and 'nearest' distractor can have a significant effect on the facility of questions.⁹ A useful reminder that 'objective testing' is not fully reliable and reproducible was provided by a question with only 3 responses (A, B and C), but for which 6% (1998) and 4% (1999) of students marked response D.

Figure 2 shows a comparison of the marks awarded during a single semester (1999, semester 2) using the new system with those awarded during the last semester in which the old system was used (1996, semester 2). The distribution of marks is still skewed towards the top end of the marking scale, but the new system has resulted in a much fuller use of the total mark scale. Table 1 provides a comparison of the marks obtained in all the semesters since 1996 (2) and shows that 1999(2) is typical of semesters since the introduction of the new system. (Although there is no statistical justification for calculating a standard deviation for data, which are clearly not drawn from a Normal

Semester	96/2 (Old)	97/1	97/2	98/1	98/2	99/1	99/2
Mean	17.7	16.0	15.7	16.0	15.9	16.5	16.2
Standard Deviation	0.5	2.6	1.8	2.5	3.0	3.0	2.7

Table 1. Statistics for Laboratory Marks

Population, it is a convenient way of providing a crude comparison between semesters).

Using the new system, the distribution of marks for laboratory work is similar to the distribution for closed examinations. This is illustrated in Figure 3, which shows a plot of lab marks vs. exam marks for

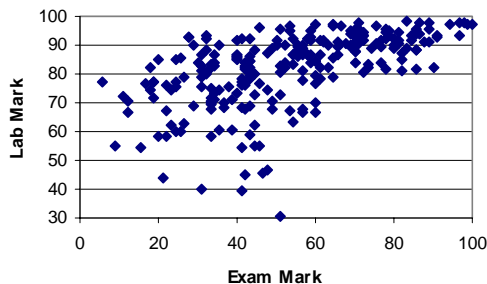


Figure 3. An example of correlation between laboratory and examination marks

semester 1999(2). Almost every student obtained a higher mark for lab work than for the closed examination. However the correlation coefficient is highly significant ($R = 0.57$, $n = 243$, $P < 0.001$).

We are satisfied that the distribution of marks obtained with the new system is a better reflection of our students' performance in the laboratory classes. We find it hard to accept that the data shown in Figure 2 for semester 1996(2) really mean that all our students truly deserve marks in the top quartile of the scale. And we are neither surprised nor concerned that most students achieve a higher mark for lab work than they do in examinations because it is possible in the laboratory to compensate for mistakes or lack of aptitude by perseverance and hard work. Furthermore, we have noted a marked improvement in student attitude to laboratory work since the introduction of the new system; the great majority actively strive to achieve high marks and keen to learn how they have lost marks, to the extent that there have been many requests for the feedback printouts to be made available for all students. In official Student Course Evaluation Forms, over 90% of respondents said that they thought the practical work was well organised. In addition, around 85% said they found the laboratory work interesting (in contrast to Johnstone's report¹⁰ that the majority of young lecturers interviewed by him had, as students, found labs boring).

Staff and demonstrators also report favourably on the new system. The laboratory is now able to close at the advertised closing time. The automation of the recording of attendance and mark has significantly reduced the administrative work associated with the running of the class.

Discussion

There can be no doubt that we achieved our first objective of removing the problem of queues with the consequent advantage that the students do not stop work earlier than is justified by their progress.

There are other advantages. The system for marking and recording of marks operates very efficiently giving demonstrators more time to teach in the laboratory. The use of paper tests means that, for some kinds of experiment, we can completely integrate the tests with the experiments so that they are in-lab rather than post-lab tests. The Master *Excel* spreadsheet allows us to monitor student attendance and take action if necessary. Our comparisons of the new lab marks with old ones and with examination marks have convinced us that we now have a much more reliable mark for the laboratory work than we did in the past so that we now have no worries about the weighting of 20% given for this mark in the end-of-module degree examinations, and indeed we are giving thought to increasing this.

The original version of the Reader program gave only the mark, and comments from students obtained from course evaluation forms resulted in many requests for the feedback printouts to be made available for all students instead of just those who obtained low marks. We take this to be a positive indication of a genuine wish to improve, and to comply with this request, we have very recently introduced the enhanced version of the Reader program, which informs students of the questions that they answered incorrectly.

The suite of programs we have developed is generic in that it can be readily adapted for a variety of uses. This is illustrated by our use of the Questionnaire Generator Program to create homework assignments for level 2 students doing the analytical lab course. Because this is timetabled for the end of the session, students face a conflict between their perceived need to revise and the requirement to prepare lab reports. It was therefore decided to separate the calculations from the experimental work, and issue the calculations early in the semester. We had not felt able to do this previously because of the prevalence of copying when all students receive the same homework tests, but the opportunity to create randomised tests overcame this objection.

For each experiment, six sets of "good" but not perfect data were selected from those obtained by students in previous years, and the Creator program was used to generate randomised tests for each student. There was no intention of using machine marking, so no multiple-choice responses had to be created. The students are no longer required to prepare lab reports at the end of term, because the evidence of their ability to carry out the calculations is measured from their calculations using dummy data, and their actual data is entered into a Visual Basic program which calculates and records the final answers for subsequent assignment

of marks for accuracy. The course evaluation forms show that this is appreciated.

As far as the staff are concerned, there is a considerable saving in workload. Although the marking of the calculations is done manually with the help of a key indicating the data given to each student, this is much faster than marking real laboratory data because the answers are already known. More time is saved by the automated calculation of results even though it requires some human intervention, since there is no need to check the calculation itself. This procedure also serves to prevent students from trying to "fudge" their results.

Our system is an example of the power of computers in teaching with no pretence at being Computer Assisted Learning. We see this as a very positive aspect since we have long observed that the majority of our students are not very enthusiastic about the use of computer-assisted learning.

Acknowledgements

We are grateful to the University Information Services Committee for providing the original funding which allowed us to develop the database of questions and the software, to Dr Simon Heath of CLUES for provision of programming support, and to Aberdeen University Learning Technology Unit for support for recent enhancements to the software.

The programs that make up the Random Questionnaire Generator suite are completely generic in nature, although they do require the user to be running Windows 95/98/NT, together with Microsoft *Word* and *Excel*. We are willing to make them available at a modest price to anyone who is interested in using them.

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*The first key to wisdom is constant questioning...
By doubting we are led to enquiry, and by enquiry we discern the truth.*

Peter Abelard (1079-1142)

An attempt has been made to remedy some of the deficiencies of the traditional didactic lecture by enhancing student involvement and learning through the use of focussed questioning within the lecture format. The potential benefits of questioning are considered and the effectiveness of the approach is evaluated through classroom observations, peer observation, an end of module questionnaire and student discussions. Some limitations of the approach are identified and suggestions for future improvements are made. The paper concludes with a brief consideration of the importance of thinking time to the promotion of meaningful learning.

Introduction

30 years ago when I started teaching I believed that I had knowledge to impart and that the better I taught the more my students would learn. When I, like many others,¹ came to realise that what my students were learning was not always what I was trying to teach them, I tried to teach better. What I then found, however, was that the better I taught the better my teaching was rated by students but not, alas, the better they learned. It was only when I encountered *constructivism*^{2, 3, 4} and Alex Johnstone's *Information Processing Model of Learning* (Figure 1)^{5, 6} that I started to think about the learner and realised that I needed to teach not just better but differently. Knowledge, alas, can't simply be transferred from the teacher to the learner, much though we might wish that it were otherwise, but meaning must be constructed in the mind of the learner.² I see an analogy with digestion where even for a

cannibal, ingested proteins are not incorporated directly into body structures but rather are broken down before being reassembled into useful biomolecules. Learning involves the linking and interpretation of incoming information with what is already known by an individual. As we all have different stores of knowledge in our long-term memories (Figure 1) we may all interpret incoming information differently.

If we look into the black box between teaching and learning it seems reasonable that where new information can be satisfactorily linked to pre-existing knowledge and interpreted this will be likely to happen. Piaget^{2, 7} referred to this process as *assimilation* and under low resolution it is indistinguishable from simple information transfer. However, this will not always be the case, particularly throughout the education process; confusion

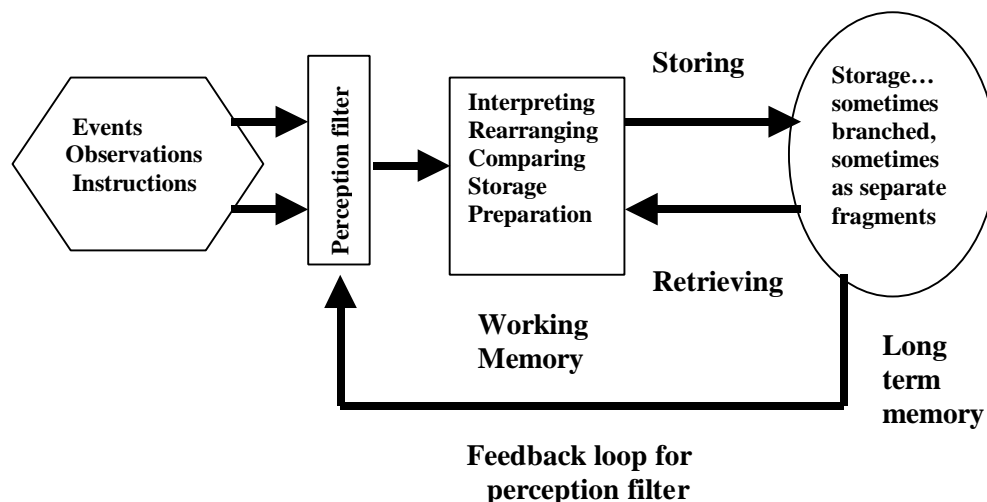


Figure 1. Information processing model for learning

(disequilibrium) will occur whenever new information can't readily be assimilated into existing schemes. What happens now? Such input can simply be ignored, and it is my belief that this is exactly what our students are increasingly choosing to do, it can be linked and interpreted incorrectly leading to so called alternative frameworks⁸ or the learner may resort to rote memorisation and try to save the information without linking it to existing knowledge. None of these, of course, represents an acceptable learning outcome from the perspective of the teacher. The possibility also exists however, that the learner will modify the pre-existing schemes until any discrepancies can be resolved. Piaget referred to this process of modifying and developing pre-existing schemes as *accommodation*.^{2,7} Education surely involves learning not just more but better and I believe that the promotion and facilitation of accommodation is of pivotal importance in this.⁹ The better we organise information and link it to what we already know, the more easily it is likely to be recalled and applied to new situations in the future. However, Herron recently postulated that learning operates on a principle of minimum effort.¹⁰ This suggests that whenever possible the learner will resist restructuring cognitive schemes, preferring to ignore data that don't fit, or to make false connections. Only when the learner becomes really dissatisfied with existing structure will modification start to occur. One can go so far as to suggest that a bad lecture, whatever that may be, followed by peer group discussion or outside reading represents a much richer learning experience than a good lecture, whatever that may be, with minimum student follow-up. Anything which produces active involvement of the learner is therefore likely to enhance the quantity and in particular the quality of learning.

Research by Anderson in 1980 found that questions interspersed in text were amongst the most effective aids to help understanding.¹¹ I therefore decided to use focussed questioning to try to promote learning within a lecture format. The aim of questioning was not to assess current knowledge or understanding; though undoubtedly some misconceptions, which need to be rectified quickly, will be identified. Rather, the questions sought to promote active learning through the stimulation of thinking and the creation of disequilibrium. Questions can contribute positively in at least four ways:

- (a) They may promote both variety in the presentation and more active student involvement during lectures.
- (b) They may stimulate learning by relating new information to knowledge already stored in long-term memory (Figure 1).
- (c) They may help to identify what is particularly important to concentrate on, *i.e.* they may 'tune the filter' (Figure 1).
- (d) They may indicate to the learner where further width or depth of knowledge is needed and help stimulate thought by generating disequilibrium in the learner's mind. Over the years many unsuccessful students have told me that they had expected to do much better in my

examinations than they did and that they had understood the material when I covered it in my lectures.¹² They hadn't of course, but like passengers in a car who see no problems with the journey because the driver knows the way, they are incapable of retracing the journey on their own at some future date. It therefore seemed particularly important to break through this complacency.

A question that contributes positively in any of these ways can be considered successful, but I was particularly interested in promoting learning through forcing students to reassess their current knowledge and understanding by creating dissatisfaction with current thinking.

The Study

A 12 week, one hour a week sequence of lectures on bioinorganic chemistry was used to evaluate this approach. The lectures, supported by 12 hours of associated laboratory time, represented one third of a final year honours degree module. The module was taken by 36 full-time students on the BSc (Hons) Applied Biochemical Sciences degree and by 10 part-time students studying for Chemistry or Life Sciences degrees. All students had previously studied some biochemistry as well as chemistry modules, all were well known to me and all but three had been taught by me previously. I started the course with a brief introduction to my ideas about how meaningful learning can take place and to metacognition.¹³ The importance of active engagement with new information and participation in class activities was stressed. This occupied about 20 minutes at the start of the first lecture. It was gratifying to note subsequently, that during informal discussion with several students in individual studies advice sessions, students both understood and appeared to support the approach being taken.

Each lecture commenced with a brief synopsis of what was to be covered and one *Big Question* that would be developed and considered during the course of the lecture. The aim of these questions was to prompt students to think about a key problem. Examples of such questions included: *Why are only certain elements used by life?* and *How are ion gradients produced and maintained in the body?* A significant number of questions, about ten each lecture, were also posed during the lectures. These were either targeted at individuals or the class as a whole but were to be answered directly. Research has clearly identified that waiting time must be adequate if questioning in the classroom is to be productive.¹⁴ Care was therefore taken to ensure that adequate time was available and multiple contributions from the class were encouraged. Examples of questions used included: (1) *What is a Lewis acid?* (2) *Given the solubility product of $\text{Fe}(\text{OH})_3$ as 10^{-38} what is the maximum concentration of free Fe^{3+} available in aqueous media at pH7?* and (3) *If copper is the catalytic site what is the likely role of zinc in superoxide dismutase?*

While the first of these questions does appear to require only simple factual recall, its purpose is not to find out that most students on hearing the word acid immediately think of hydrogen ions. Rather it is used to alert the individual that knowledge in long-term memory (Figure 1), which relates to polarisation will be needed. Lewis acidity is a major and recurring theme on the course and related questions used in subsequent lectures included: *Why are metal ions needed when the proton is so effective as a polarising cation? When would 'life' choose to use Mg^{2+} rather than Zn^{2+} as a Lewis acid catalyst? and Why do you think 'life' chooses Zn^{2+} rather than Cu^{2+} as a Lewis acid catalyst?*

Question 2 is more complex, requiring both conceptual understanding and a 'back of the envelope' calculation. Given time most students should have been able to solve this problem, but in the lecture context progress was only made after some prompting on how best to proceed. In many ways the final question might be considered the most demanding of the three. Here some students had little difficulty in deciding that the most likely role would be structural. Although this question predated any detailed discussion of the biological roles of zinc, a general consideration of roles undertaken by metal ions had previously taken place.

In their own way each of these three very different questions can be thought to show that what is being presented is more complex than it might at first appear and hence create a learning opportunity.

Four approaches were used to evaluate the effectiveness of the approach just described:

- Classroom observations.
- Peer observation in week 10.
- An end of module questionnaire.
- A group discussion with three students (four were invited but one was unable to attend) conducted in week 10.

Results

(a) Classroom Observations

Having explained the importance of active participation at the onset, I had hoped that willingness to contribute would improve rapidly once students became familiar with the process. However, while five or six students were regularly prepared to contribute, the vast majority avoided answering unless directly challenged. The lullaby effect¹⁵ was apparent with many answers being shallow and not indicative of deep thinking. For example, to the question "Why is lead not an essential element?" the answer "because it is toxic" seemed to be accepted by all the students. Only after I pointed out that oxygen had been extremely toxic to the earliest forms of life did the class appear to be willing to refocus on cause and effect. Although the level of student contributions fell below what I had hoped for, perhaps it was unreasonable to expect to obtain

evidence of meaningful learning concurrent with the teaching (*vide infra*). As an optimist, I can still hope that the stimulus/disequilibrium resulting from the questions may still initiate active engagement with the information over a more appropriate time scale.

(b) Peer Observation

As it was the process rather than the content that was of interest, I decided against using a fellow chemist and asked the Coordinator of Learning and Teaching for the Faculty of Business and Management if she would sit in and observe one of my teaching sessions. We met some 15 minutes prior to the lecture and I briefed her on what I was trying to achieve in the session; she made a series of notes throughout the lecture and we met up for a debriefing session later on the same day. Although much good practice was identified, the key observation as far as I was concerned was that I eventually answered all the questions myself. The students knew that I was going to do this and were happy to wait for my answers.

(c) Student Questionnaire

The questionnaire asked students to assess the helpfulness of six aspects of the teaching on a six-point scale and then invited free responses relating to the best aspects of the teaching, the worst aspects of the teaching and any suggestions as to how teaching might be improved. The questionnaire was handed out at the end of the last lecture. One student was asked to collect and return the completed questionnaires to me; 34 were subsequently returned. The questionnaire and responses to the six Likert-scale questions are shown in the Appendix.

All six aspects of the teaching, which were evaluated, appeared to be well supported by the class with a significant majority assigning one of the two top grades for each feature. The course booklet, which contained gaps (many of which related to the questioning) to be filled in during the lecture, received outstanding ratings from students returning the questionnaire. They were familiar with the use of structured incomplete handouts as I use this approach throughout my teaching.¹⁶

Although no textbook was recommended, students were informed that any modern inorganic text was likely to contain a relevant chapter well worth reading. 16 references to original papers were provided and the lecture to which each related, was indicated. Five complete compilations of the 16 references were made available to the class to be used and shared throughout the semester. Several students chose to make their own copies. My discussion on how learning takes place was also generally well received and, as noted above, discussion with students led me to believe that they both understood and supported the ideas outlined.

The usefulness of both the *Big Question* and *frequent questioning* appeared to be highly rated. Hopefully

this suggests that even where students were reluctant to voice their opinions they were still thinking about the questions. The free response questions (7, 8 and 9) did provide some interesting information. All respondents identified a best aspect of the teaching. A clear majority (19 students) identified the course booklet, which is primarily a simple information transfer technique, as the best aspect of the teaching. Only four students out of 34 returned questionnaires opted for the questioning. Few students listed any worst aspects though two suggested that there was a lot of material to cover and this led to things being rushed. A further two suggested that starting the lecture at 9.15 on Monday mornings was the worst aspect. Only the following suggestions for improvement were made:

- (i) More marks for coursework.
- (ii) Review answers to past examination papers to enable students to know what will be required.
- (iii) Supplement references with appropriate web page addresses.

While these suggestions all seem reasonable, (i) and (ii) provide further evidence for the assessment-driven motivation for learning which we continue to encounter¹⁷ and (iii) would be more justified if there was evidence that the 16 references provided had been well studied.

(d) Group Discussion

A number of issues, mirroring the questionnaire, which I wanted discussed were considered by three of the students. I was there introducing the topics but I took no part in the discussion. The students talked about each issue for some minutes and one student wrote a summary of the consensus view. The group considered that the discussion on learning was a good way to start the course and was useful because it prompted students to think about how they learned. The students thought that the introduction of frequent questions during lectures was beneficial because it helped them to realise how well, or how little, they understood the topics being discussed. The *Big Questions* were also considered useful because they helped to unify each lecture. It was, however, suggested that more active discussion of these questions would help.

Reflective Discussion

Though the approach appeared to attract widespread student support, it clearly did not produce the increased levels of student participation that I had hoped for. It is tempting to suggest that the assessment-driven motivation which directs the behaviour of most students probably means that they did not want to answer my questions, they merely wanted to know my answers. However, perhaps on reflection, my aims were rather ambitious. A majority of students appear likely, initially, to resist any innovative approach to teaching,¹⁸ so an attempt to introduce the questioning approach was

unlikely to meet instant success. Clearly, however, if progress is to be made students must be coerced into contributing more effort towards developing their own answers and hence, enhancing their knowledge creation.

Unfortunately it seems likely, as recently suggested by Bahor *et. al.*¹⁹ that learning does not occur simultaneously with but after the teaching. This suggests that more success might be encountered if students were required to answer the questions at some time in the future. I have in fact tried to finish lectures with a question, which the class will be required to answer at the start of the next lecture but it was evident that only a few students thought about these questions in the meantime. I believe that I have had success with the use of buzz groups¹² but this is a very time demanding process and thus has to be used sparingly. A recent paper by Hutchinson²⁰ suggests that awarding some marks for participation will encourage interaction. However, I suspect that Hutchinson's success can probably be attributed to the fact that their students are required to study appropriate chapters before coming to the classes. As this approach was common throughout the general chemistry teaching programme, the students appeared comfortable with the requirements and complied with them. My use of questioning, however, differed from what students encountered in other lectures and more familiarity with the approach is probably needed before progress could be expected. Any attempt to promote more interactive learning will not be straightforward and, unless innovations are introduced with care, may even be counterproductive. I recently heard of a Management module in the third year of an engineering degree where the lecturer asked students to prepare information for oral presentation to the next class. The next class was attended by only 11 of the 110 enrolled students.

The use of student questionnaires for both teaching quality assessments and the evaluation of teaching innovations is now widespread. The present study supports my own experiences over many years that these questionnaires need to be interpreted with caution, particularly the quantitative aspects. I believe that many unwarranted conclusions continue to be drawn from the indiscriminate use of such data.

Peer observation was employed as an assessment tool almost as an afterthought, yet this clearly provided an extremely useful insight into what was actually happening. Perhaps I should have seen what was happening, perhaps I eventually would have; it was certainly clear once the suggestion was made. The experience certainly convinced me that we could all benefit from sympathetic and constructive peer observation and support.

Throughout the course there was constant conflict between time required for questioning and the demands of the curriculum. I can only agree with the two students who suggested that the course was rushed in parts. It seems certain that increased student interaction will require more time than simple didactic teaching. It is therefore perhaps

instructive to consider the importance of time to learning.

Some Thoughts on the Relevance of Time to the Learning Process

It is clear from earlier comments that meaningful learning requires effort and is therefore likely also to require time. However, the information-processing model (Figure 1) which has been so useful to understanding how we learn, is, at least in the way that I have viewed it, a time independent model. Yet time is clearly a key variable in determining the quality of learning that can take place. It is surely much easier and therefore quicker merely to transfer information to the learner than for meaningful learning to occur. In fact I suggest that getting the information into the mind of the learner is really the first step towards meaningful learning. This corresponds to what is usually called rote memorising or surface learning. Time and effort are then required to link, interpret, possibly correct (if initially misconstrued) and then accommodate this new information to produce deep or meaningful learning. So, far from being alternatives, rote memorising and meaningful learning may be considered as different stages within the learning process (Figure 2). The second step requires both effort from the learner and time for meaningful learning to develop. The model is clearly consistent with recent suggestions that teaching less, *i.e.* reducing the rate of information transfer, can actually lead to more learning taking place.^{21, 22, 23, 24} The model thus predicts that where new concepts are being taught, sufficient time as well as

effort is required to enhance cognitive schemes through accommodation, and therefore questions the pedagogical soundness of the recent move towards wide-spread semesterisation in UK universities. Students all too often treat each module as an isolated unit and do not have, or do not take, the time to reflect on what they memorised. It would indeed be tragic if current benchmarking exercises served to increase curricula rather than to embrace and scaffold learning outcomes.

Acknowledgements

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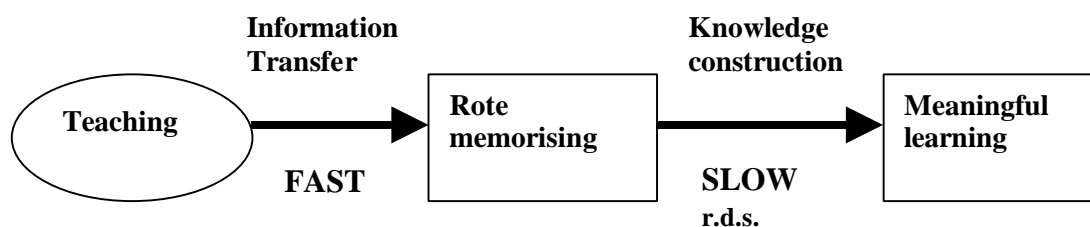


Figure 2. Model showing the time dependence of learning

Appendix**Bioinorganic Chemistry****Student Opinions on Teaching Approach**

Please indicate by ticking appropriate box how helpful you have found each of the following features of the teaching (stating with 0 to indicate useless rising to 5 where you would consider the feature indispensable).

	0	1	2	3	4	5
1. Course booklet					9	25
2. Recommended references		1	5	10	11	7
3. Discussion on how learning takes place		2	3	10	13	4
4. Big question		1	1	13	13	6
5. Frequent questions during lectures			1	10	15	8
6. Prelab session		4	4	6	13	3

Number of responses for each option were as shown above

7. Please indicate what you consider to be the best aspects of the teaching.

8. Please indicate what you consider to be the worst aspects of the teaching.

9. Please indicate how you believe the teaching could be improved for you.

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Why Lecture Demonstrations Are ‘Exocharmic’ For Both Students And Their Instructors

Perspective

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A theoretical model is proposed to explain why lecture demonstrations are often popular among both students and their instructors. This model provides hints about selecting demonstrations that are most likely to enhance the learning of chemistry. It also suggests ways in which demonstrations can be used more effectively.

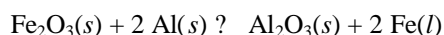
Introduction

There are many reasons for doing lecture demonstrations.

- They are fun to do.
- Students like them.
- They grab the students’ attention.
- They provide breaks that help students recover from the deluge of information in a typical class.
- They provide concrete examples of abstract concepts.
- Most importantly, they can teach chemistry.

Demonstrations are so attractive they are sometimes done under conditions where neither the students nor the instructors are adequately protected against injury. In an earlier paper we collected examples of accidents and near accidents that might remind chemists of the need to pay more attention to safety when doing demonstrations, hopefully without frightening them away from demonstrations.¹

Some demonstrations are so much fun for both the students and their instructors that the term *exocharmic* has been used to describe these demonstrations that are so inherently fascinating they “exude charm”.² The thermite reaction might be an example of an exocharmic demonstration.



In a lecture manual developed for use at Purdue University, we describe various ways in which this popular demonstration can be used.³ We argue that it can be used as the basis for discussions of the

chemistry of the elements; to demonstrate what we mean by the term *exothermic*; to convince students that aluminum is not ‘inert’, regardless of their experience with sandwiches wrapped in aluminium foil; or to help students develop an appreciation of what we mean when say that a reaction gives off approximately 800 kJ/mol.

This paper is based on the assumption that none of these uses satisfactorily explains the enormous attraction that demonstrations of the thermite reaction have for both students and their instructors. Furthermore, it assumes that it might be useful to understand the fascination of ‘exocharmic’ demonstrations such as the thermite reaction, so that demonstrations can be used more effectively to teach chemistry. It therefore proposes a model based on a theory of motivation, which assumes that these demonstrations fall into the category of phenomena known as *discrepant events*.

A Theory Of Motivation

When I was a student, the most hated words in the English language were ‘intuitively obvious’ because they were invariably used to describe things that were never obvious to me. When I became a teacher, the most hated words became: “Is this going to be on the exam?” Often, but not always, students’ use of this phrase stems from their questioning the value of material we ask them to learn because they don’t think it is important. We’ve seen this behavior with students of all ages, from elementary school through the final stages of graduate work. It is frequently a sign of the instructor’s failure to motivate the

students to *want to learn*.

Motivation is a complex topic.⁴ One aspect of motivation, however, can be understood in terms of the theory of optimal arousal.⁵ This theory assumes that we try to attain a state in which we experience *some* arousal of our senses — not too little, nor too much. At times, we devote considerable effort to raising our arousal level by reading exciting stories; by going to scary movies; by riding roller-coasters; and so on. Other times, we escape situations where too much is happening to seek peace and quiet. It isn't just the frequency and intensity of the input our senses receive that determines arousal. The *content* of this sensory input is also important. Consider what would happen if you put down that fascinating document on household contents insurance and picked up a novel you found interesting. There would be no change in the frequency or intensity of the input your senses would receive. (No more light would reach your eyes, for example.) But it is likely that there would be a change in your level of arousal.

What makes us respond to an object or event isn't the physical input of our senses as such, but a difference between what we experience and what we expect. In other words, we respond to situations that have an element of *surprise*.

We tend to like mild surprises, not severe ones. If there is no surprise, there is too little arousal and we feel bored. If there is too much surprise, we feel shocked and disoriented. With due apologies to the author of the story of Goldilocks and the Three Bears, this theory assumes that we avoid extremes of either too much or too little surprise, and tend toward an intermediate stage in which the amount of surprise is 'just right.'

There is abundant evidence that we become habituated to events that occur in a regular schedule to the point that we ignore them. (We no longer respond when the event occurs.) One of the most common occurrences of this phenomenon in the classroom involves rhetorical questions. It has been shown that many teachers fail to give students enough time to develop answers to questions they ask.⁶ The students soon become habituated to the teacher's tendency to ask questions for which answers aren't expected — rhetorical questions —

and from that point on, they don't even notice that questions are asked.

Educators have long recognized the role of the unexpected in motivating students.⁷ Curiosity, for example, has been shown to be an important component of learning, particularly among children.⁸ But what is curiosity if not a drive to investigate and understand situations that evoke surprise? Individuals in all age groups show a marked preference for objects or situations that are novel; that have an element of surprise or incongruity; that generate uncertainty. One of the simplest ways of introducing surprise into the classroom — and therefore take advantage of students' natural curiosity — is through a phenomenon known as a *discrepant event*.

Discrepant Events

Discrepant events have two characteristic properties: They are contrary to what we intuitively expect and they are events we experience for ourselves. Being told something that is counterintuitive doesn't constitute a discrepant event because we can resolve the conflict between what we hear and what we expect by questioning the validity of what we are told. This is harder to do when we observe the event ourselves.

The thermite reaction can be a discrepant event. Students know that chemical reactions give off energy. (They might even know how to calculate the amount of energy liberated.) But the magnitude of the energy given off in this demonstration and the speed with which it is liberated are counterintuitive. Even those of us who should know better are still surprised by the vigor with which two seemingly 'inert' solids react.

Young children are often surprised by iodine clock reactions⁹ when they first encounter them because of the speed with which the solution turns from colorless to deep blue. The 'Old Nassau' demonstration⁹ — in which the solution first turns orange and then black — is even more surprising because students don't expect the contents of a beaker to change color twice. Oscillating clock reactions,¹⁰ however, are better examples of discrepant events. Regardless of the extent to which students have been exposed to the concepts of

reversible reactions, equilibria, kinetics, thermodynamics and so on, there is nothing in their prior experience that prepares them for a reaction that cycles between states in which the solution is colorless, then gold, and then blue.

Implications Of This Model Of Exocharmic Demonstrations

The notion that some of the fascination of lecture demonstrations results from the fact that they may be discrepant events has an important implication: Demonstrations don't have to be spectacular to be effective. They should, however, contain an element of the unexpected.

Let me offer an example, from my own experience. When I took chemistry for the first time, I was told that equal volumes of different gases contained the same number of particles. Until I took physics, this was the most absurd thing I had heard a teacher claim to be true. I knew that gases contained empty

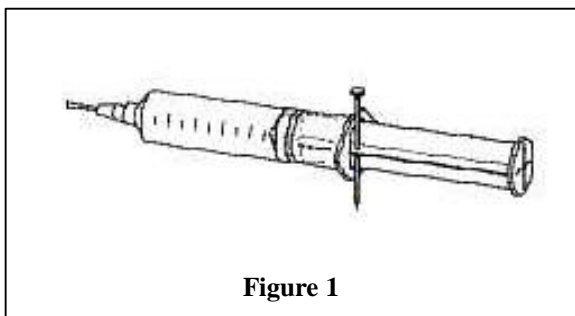


Figure 1

space, but I seriously underestimated the fraction of the space that is empty. It therefore seemed reasonable to expect that equal numbers of gas particles of different size would occupy different amounts of space. I now know I was in good company; Dalton rejected Gay-Lussac's data on combining volumes for the same reason. To me, and to many of my contemporaries, Avogadro's hypothesis was just as counterintuitive as it was to John Dalton.

I am reasonably confident that I could have stated Avogadro's hypothesis, if asked to do so on an exam. I am equally confident that I couldn't have used Avogadro's hypothesis to solve a problem because I didn't really believe it to be true.

About 15 years ago, I learned a lecture demonstration that provides a discrepant event that

gas	Weight of 50 ml of gas	Number of particles In 50 ml of gas
H ₂	0.005 g	1 x 10 ²¹
N ₂	0.055 g	1.2 x 10 ²¹
O ₂	0.061 g	1.2 x 10 ²¹
Ar	0.081 g	1.2 x 10 ²¹
CO ₂	0.088 g	1.2 x 10 ²¹
C ₄ H ₁₀	0.111 g	1.15 x 10 ²¹
CCl ₂ F ₂	0.228 g	1.14 x 10 ²¹

Table 1

confronts the intuitive model of gases I brought to my first chemistry course.¹¹ Start with a plastic 50-mL Leur-lok syringe, a syringe cap, and a 10-penny nail. Pull the plunger out of the barrel until the volume reads 50 mL. Now drill a small hole through one of the veins of the plunger into which the nail can be inserted, as shown in Figure 1.

Push in the plunger until no gas remains in the syringe, seal the syringe with a syringe cap, pull the plunger back out of the barrel of the syringe, insert the nail into the hole, and weigh the 'empty' syringe to the nearest 0.001 grams with an analytical balance. Fill the syringe with different gases * and determine the weight of 50 mL of each gas. Now use the molar mass of each gas to calculate the number of gas particles in each sample.

Typical data obtained with this apparatus are given in Table 1. Within experimental error, the number of gas particles in each sample is the same. It might still seem strange that equal volumes of different gases contain the same number of particles, but it is no longer possible to avoid this conclusion. Although this demonstration isn't as spectacular as the thermite reaction, or one of the oscillating clocks, it can still be exocharmic because it contains an element of surprise for many students.

Some demonstrations, such as the hydrogen whistle,¹² are such excellent sources of surprise that

* A simple way to handle gases for lecture demonstrations starts with a 1 or 2 inch length of 3/4-inch diameter plastic tube. Plug one end of the tube with a rubber septum and secure the septum to the tube with copper wire. Fill a balloon with the appropriate gas from a gas cylinder and insert the open end of the plastic tube into the mouth of the balloon. A sample of the gas can now be collected with a syringe by inserting the syringe needle through the rubber septum

nothing has to be done to enhance their status as discrepant events. The hydrogen whistle is based on the apparatus in Figure 2, which consists of a pair of metal funnels welded together so that there is a small hole at the top and a somewhat larger hole in the bottom. The apparatus is filled with H_2 , the hole at the top is plugged with a match, and a rubber stopper is used to close the hole at the bottom. The lights are then dimmed, the stopper and match are removed, and the match is used to ignite the H_2 that escapes through the hole at the top. Attention is drawn to the small flame at the top of the apparatus and the students are told to listen carefully. As the H_2 is consumed, air rushing in through the hole in the bottom makes the apparatus vibrate, and a clear 'whistle' can be heard.

The frequency of the whistle changes with time, as the average molecular weight of the gas in the apparatus increases. With the lights dimmed, and the students paying careful attention to the change in the frequency of the low-intensity whistle the apparatus emits, the demonstration becomes 'striking' when the gas in the container reaches one of the explosive mixtures of H_2 and O_2 — and a loud detonation is heard as a flame shoots out of the bottom of the apparatus.

Demonstrations And The Theory Of Cognitive Change

Some might argue that demonstrations, by themselves, are sufficiently powerful as a teaching device that all we have to worry about is simply doing them. Sarason, however, suggested the following rule for curriculum development or curriculum reform: "A good idea, whose time has come, is no guarantee of success".¹³ We'd like to propose a corollary to Sarason's rule: An ideal demonstration, done 'properly', is no guarantee that students will learn what we thought we demonstrated.

Instead of having the students play the role of passive observers of a demonstration, we might use the demonstration as the basis of a phenomenon that White and Gunstone describe as a POE task — from *Prediction, Observation, and Explanation*.¹⁴ The first step in a POE task is to ask students to predict the outcome of some event, such as what might happen during a demonstration. They are then

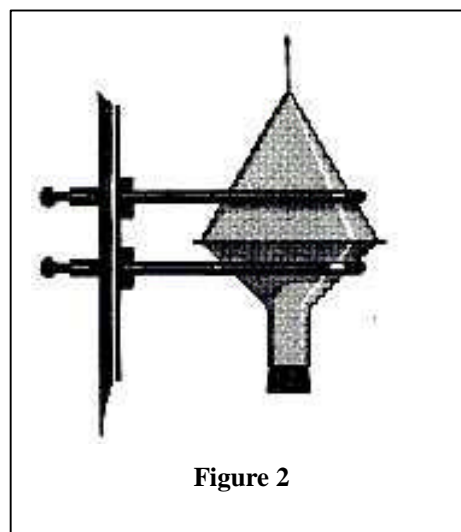


Figure 2

asked to describe what they observe, and finally asked to reconcile any conflict between what they predict and what they observe. Much has been written in recent years about the misconceptions students bring to chemistry¹⁵ and the fact that these misconceptions are difficult to change.¹⁶ Demonstrations, by themselves, won't overcome misconceptions, but they can provide the basis on which conceptual change is built.

Strike and Posner¹⁷ have proposed a model of conceptual change that begins when students become *dissatisfied* with their present concept. They argue that dissatisfaction is necessary for conceptual change to occur, but not sufficient to induce the change. The student must *understand* the new concept they have been asked to learn. The new concept must also seem *plausible* to the students. And, the new concept must seem *fruitful* — it must seem worth learning. The demonstration of Avogadro's hypothesis in Figure 1 provides the basis for the first step in this model, the stage at which students begin to question the conceptual understanding they bring to the course.

Conclusion

If you accept the arguments in this paper, you can think about demonstrations in terms of the following guidelines.

- There is no evidence that students learn from demonstrations, by themselves.
- There is some evidence that students remember the visual images of a demonstration long after

they forget the words.

- Good demonstrations provide a basis on which learning can be built.
- Demonstrations don't have to be spectacular — or dangerous — to be useful.
- Demonstrations that contain an element of surprise, which don't behave the way students might expect, are often the most charming.
- Demonstrations that are the most charming are those that students remember.
- Demonstrations that are charming can therefore facilitate both the learning of chemistry and the retention of this knowledge.
- Demonstrations that students find 'exocharmic' might therefore be those that best teach chemistry.

You might also note that the spectacular (and often dangerous!) demonstrations that attract some students to chemistry might be driving others away by giving students an unrealistic image of what chemists do.

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to chemistry, such as work in business and finance sectors. Where science relates to issues of public interest, such as in the examples given earlier, individuals in all three employment areas may be involved. Research chemists generate new findings and are asked to report on these to their peers, their funders and the public. Science journalists, spokespeople for commercial companies and pressure groups, and science policy makers provide their reactions to the findings of the scientists. Those not professionally involved in science react to the findings by making choices as consumers, protesters and/or voters. In many contexts public response can have a significant impact on the direction of future science research as commercial and governmental organisations react to consumer and voter pressure. In this way all graduate chemists have a role to play in public debates about science. Given the crucial role of knowledge *about* science in such debates, its incorporation into the curriculum would be a service to all chemistry undergraduates.

Additional impacts of knowledge about chemistry

Aside from the science and public policy rationale outlined above, there are additional, perhaps more immediate, reasons for developing students' ideas about how chemistry works. There is growing evidence that encouraging students to think about the structure and purposes of scientific knowledge can support their understanding of science concepts. For example, one study² designed and evaluated an upper secondary course that included teaching about the general relationships between theory and phenomena in science alongside the teaching of energy transfer in electrical circuits. For many students an understanding of the nature of scientific knowledge enhanced their ability to apply their developing understanding of the concept of energy in electrical circuits in experimental situations. To my knowledge, the interaction between knowledge about science and science concept learning has yet to be examined within university science courses. By contrast, the interaction between ideas about science and university science students' experiences of investigative work has been examined. A study involving chemistry undergraduates found that naïve views about how data and theoretical models interact in science can act as a barrier to students' progress during investigative project work.³ It is likely that emphasising knowledge about chemistry within university courses will enhance students' understanding of chemistry concepts and their actions during investigative work.

Knowledge about chemistry in the curriculum

Associated with continuing concern about the nature of the interaction between science and those not professionally involved in science^{4, 5} there have

been a number of initiatives to emphasise knowledge about science within pre-university science education.⁶ For example, the current National Curriculum for Science in England has a new section entitled 'ideas and evidence in science' that focuses on 'how science works'. At the post-16 level there is a new AS course 'Science for Public Understanding';⁷ a group supported by the Royal Society has begun investigations towards an AS course on the 'History and Philosophy of Science'; and a project funded by the Nuffield Foundation has recently published materials for teaching about science *within* A level science courses.⁸ Similar projects have been pursued outside the UK.⁹ Against this background, new entrants to university chemistry courses will increasingly be aware of discussions about how knowledge in chemistry is developed, how disputes in chemistry arise and are resolved and what chemistry knowledge can and cannot contribute in complex problems outside the laboratory whenever chemistry interacts with issues of public concern. In part this article aims to contribute to a debate about whether/how university chemistry courses should respond to these developments.

University students' knowledge about chemistry

It might be said that 'how chemistry works' is addressed already in university courses. Indeed any course that requires students to apply chemical knowledge in problem solving tasks, and to undertake science investigations of their own, is inevitably raising issues of knowledge about chemistry. However, many of the areas in which students are asked to solve problems or conduct chemical investigations are far removed from the ways in which chemistry impacts on public policy. For example, many first and second year courses involve investigations in the laboratory in which the answer is already known and the detailed guidance notes limit the chances of things going wrong. Of course such activities provide a legitimate way of developing students' ability to use established empirical techniques. However, they are unlikely to communicate the uncertainties and complexities of applying chemistry to issues of public concern.

Furthermore, despite the inevitable presence of knowledge about chemistry in university courses, several studies have shown that students often leave university with very naïve views about how science works.^{10,11} Many students see science as capable of providing 'hard facts', that it is always possible to obtain data that will provide a single, incontrovertible interpretation. The presence of uncertainty and multiple interpretations, particularly in complex settings, is often not recognised.

Teaching knowledge about chemistry

So how can knowledge about chemistry be communicated within undergraduate courses? The strongest message coming from the few studies that have been conducted to date is that knowledge about how chemistry works needs to be taught *explicitly*. It is rarely sufficient for students to engage in chemical investigations or chemical problem solving activities for them to develop their knowledge about chemistry. For example, we followed the experiences of 11 undergraduate science students (including 2 chemists) as they undertook final year research projects over a period of 8 months.¹² These projects gave students the experience of engaging in authentic research that addressed complex issues. Gathering reliable data was often a real challenge and in most cases only tentative conclusions could be drawn. However, experiencing authentic research was found not to be a sufficient condition for being able to articulate an appropriate view about 'how science works'. Many of these students persisted with their view of science as always involving 'hard facts'.

To make knowledge about chemistry explicit students need to be encouraged to ask questions about the structure, purpose and limitations of chemistry knowledge. How sure can we be about our conclusions? Do our findings enable us to make any generalisations outside the context of the study? What can our laboratory study tell us about the chemistry of materials in contexts outside the laboratory? What additional issues would need to be considered? Are there other possible interpretations of the data? If so, what should chemists do next in order to resolve the dispute? It might be said that add-on courses on the History and Philosophy of Science/Chemistry could serve this function. I would argue that whilst such courses do serve legitimate aims, they are not best placed to develop students' ideas about science with a view to supporting their consideration of public policy issues and their learning of science concepts and investigative activities. The teaching of knowledge about chemistry needs to be an integrated part of a university chemistry course, with discussions about how chemistry works running through lecture courses, problem solving classes, investigative work, and (critically) assessment activities.

Conclusion

Not everyone would agree that a strengthening of knowledge about chemistry within university courses is desirable, particularly given the other pressures on curriculum time. This perspective aims to contribute to a debate about how/whether university chemistry courses should respond to the increasing focus on knowledge about science within pre-university education. Secondly, lecturers themselves have limited experience in explicit

teaching about chemistry and few resources are available to support such teaching. This perspective is also a plea for university chemistry teachers who recognise the need for knowledge about chemistry teaching to develop such teaching and to communicate to others what works and what doesn't work and there are signs that this is beginning to happen.¹³ Finally, there has been little, if any, research into the impact of knowledge about chemistry teaching on students' ideas about chemistry within university courses. Such studies would provide insights into how students develop new ways of thinking about the practices of chemistry both within chemistry research and also in matters of broad public concern.

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