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This is a themed issue on Experiments and the Laboratory in Chemistry Education.

Guest editors: Avi Hofstein and Rachel Mamlok-Naaman

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Indexed/Abstracted in
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Chemistry Education Research and Practice

The journals, *University Chemistry Education*, published by The Royal Society of Chemistry, (http://www.rsc.org/uchemed/uchemed.htm) and *Chemistry Education Research and Practice*, published from the University of Ioannina, (http://www.uoi.gr/cerp/) have merged with effect from January 1st 2005. The new, fully electronic journal is published by The Royal Society of Chemistry under the title: ***Chemistry Education Research and Practice,*** and it will continue to be available free of charge on the Internet**.** There are four issues per year.

The new journal is edited by Georgios Tsaparlis (gtseper@cc.uoi.gr) and Stephen Breuer (s.breuer@lancaster.ac.uk) and intends to maintain the high standards set by its predecessors. Its editorial policy will be the following.

'*Chemistry Education Research and Practice*' is the journal for teachers, researchers and other practitioners in chemical education. It is the place to publish papers on:

- research, and reviews of research in chemical education;
- effective practice in the teaching of chemistry;
- in depth analyses of issues of direct relevance to chemical education

Contributions can take the form of full papers, preliminary communications, perspectives on methodological and other issues of research and/or practice, reviews, letters relating to articles published and other issues, and brief reports on new and original approaches to the teaching of a specific topic or concept.

The new journal welcomes contributions of the type described above; these should be sent to cerp@rsc.org.

Chemistry Education Research and Practice

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Guidelines for Authors

Submission of contributions

Chemistry Education Research and Practice (CERP) is the journal for teachers, researchers and other practitioners in chemical education. It is published free of charge, electronically, by The Royal Society of Chemistry, four times a year. It is the place to publish papers on:

- research, and reviews of research in chemical education;
- effective practice in the teaching of chemistry;
- in depth analyses of issues of direct relevance to chemical education

Contributions can take the form of full papers, preliminary communications, perspectives on methodological and other issues of research and/or practice, reviews, letters relating to articles published and other issues, and brief reports on new and original approaches to the teaching of a specific topic or concept.

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 to cerp@rsc.org, or directly to the editors: Stephen Breuer at s.breuer@lancaster.ac.uk or to Georgios Tsaparlis (gtseper@cc.uoi.gr).

2. Submitted contributions are expected to fall into one of several categories (listed above). 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.

   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"/ 2.5 cm 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 by the name of the author (or the first author, if more than one), followed by the year of publication. If an author has more than one reference from the same year, then it should be given as Smith 2001a, Smith 2001b, etc.

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;
   - keywords identifying the main topics covered in the paper

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.

   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 following practice:

   Books and Special Publications:
   Author A., (year), *Title of the book italicized*, Publisher, Place of publication, page no. if applicable.

   Journal Articles:
   Author A., Author B. and Author C., (year), Title of the article in Roman type, *Full Name of the Journal Italicised*, **Volume no. in Bold**, inclusive page numbers.

   For example:
   Osborne R. and Freyberg P., (1985), *Learning in science: the implication of children's science*, Heinemann, London.

   Jackman L.E. and Moellenberg W., (1987), Evaluation of three instructional methods for teaching general chemistry, *Journal of Chemical Education*, **64**, 794-96.

7. All contributions submitted will be refereed anonymously by two independent referees. In case of a disagreement a third referee will be consulted. The decision of the Editors on

the acceptance of articles is final.

8. Authors grant *CERP* 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 format.

Perspective

The laboratory in science education: the state of the art

Avi Hofstein and Rachel Mamlok-Naaman

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Abstract: For more than a century, laboratory experiences have been purported to promote central science education goals including the enhancement of students' understanding of concepts in science and its applications; scientific practical skills and problem solving abilities; scientific 'habits of mind'; understanding of how science and scientists work; interest and motivation. Now at the beginning of the 21st century it looks as if the issue regarding learning in and from the science laboratory and the laboratory in the context of teaching and learning chemistry is still relevant regarding research issues as well as developmental and implementation issues. This special CERP issue is an attempt to provide up-to-date reports from several countries around the world. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 105-107]

Keywords: Science laboratory, chemistry laboratory, scientific practical skills

Introduction

Laboratory activities have long had a distinctive and central role in the science curriculum and science educators have suggested that many benefits accrue from engaging students in science laboratory activities (Hofstein and Lunetta, 1982; 2004; Tobin 1990; Hodson, 1993; Lazarowitz and Tamir, 1994; Garnett et al., 1995; Lunetta 1998; Hofstein, 2004; Lunetta et al., 2007). At the beginning of the twenty-first century we are entering a new era of reform in science education. Both the content and pedagogy of science learning and teaching are being scrutinized, and new standards intended to shape and rejuvenate science education are emerging (National Research Council, 1996; 2000). The *National Science Education Standards* (NRC, 1996) and also the 2061 project (AAAS, 1990) reaffirm the conviction that inquiry in general and inquiry in the context of practical work in science education is central to the achievement of scientific literacy. Inquiry-type laboratories have the potential to develop students' abilities and skills such as: posing scientifically oriented questions (Krajcik et al., 2001; Hofstein et al., 2005), forming hypotheses, designing and conducting scientific investigations, formulating and revising scientific explanations, and communicating and defending scientific arguments.

Learning in and from science laboratories

Over the years, many have argued that science cannot be meaningful to students without worthwhile practical experiences in the school laboratory. Unfortunately, the terms *school laboratory* or *lab* and *practical* have been used, too often without precise definition, to embrace a wide array of activities. Typically, the terms have meant experiences in school settings where students interact with materials to observe and understand the natural world. Some laboratory activities have been designed and conducted to engage students individually, while others have sought to engage students in small groups and in large-group demonstration settings. Teacher guidance and instructions have ranged from highly structured and teacher-centered to open inquiry. The terms have sometimes been used to include investigations or projects that are pursued for several weeks, sometimes outside the school, while on other occasions they have referred to experiences lasting 20 minutes or less. Sometimes laboratory activities have incorporated a high level of instrumentation, and at other times the use of any instrumentation has been meticulously avoided.

Many research studies have been conducted to investigate the educational effectiveness of laboratory work in science education in facilitating the attainment of the cognitive, affective, and practical goals. These studies have been critically and extensively reviewed in the literature (Hofstein and Lunetta 1982; 2004; Blosser, 1983; Bryce and Robertson 1985; Hodson, 1993; Lazarowitz and Tamir 1994). From these reviews it is clear that in general, although the science laboratory has been given a distinctive role in science education, research has failed to show simple relationships between experiences in the laboratory and student learning. Hodson (1990) has criticized laboratory work and claimed that it is unproductive, and confusing, since it is very often used without any clearly thought-out purpose, and he called for more emphasis on what students are actually doing in the laboratory. Tobin (1990) wrote that: "*Laboratory activities appeal as a way to learn with understanding and, at the same time, engage in a process of constructing knowledge by doing science*" (p. 405). He also suggested that meaningful learning is possible in the laboratory if students are given opportunities to manipulate equipment and materials in order to be able to construct their knowledge of phenomena and related scientific concepts.

Research on learning in and from science laboratories: looking to the future

Laboratory activities have been used in many natural science disciplines to teach students of many age spans in very different cultural and classroom contexts. In the many studies and varied research settings important issues and variables intersect. However, there have been many substantive differences in the laboratory settings and in other variables reported. To develop research in the field, the science education community and especially the research community must be careful to provide detailed descriptions of the participating students, teachers, classrooms, and curriculum contexts in research reports. Among the many variables to be reported carefully are (based on: Lunetta et al., 2007): learning objectives; the nature of the instructions provided by the teacher and the laboratory guide (printed and / or electronic and / or oral); materials and equipment available for use in the laboratory investigation; the nature of the activities and the student–student and teacher–student interactions during the laboratory work; the students' and teachers' perceptions of how the students' performance is to be assessed; students' laboratory reports; the preparation, attitudes, knowledge, and behaviors of the teachers . What do the students perceive they are supposed to accomplish in the laboratory activity? How do they perceive their laboratory performance will be assessed? How important do the students and the teachers perceive the laboratory activities to be? Studies should clearly report the amounts of time students spend in laboratory activities, and how those are integrated or separated from other work in the science course. They should distinguish clearly between long-term and short-term student investigations, and indicate clearly the numbers and roles of students in each laboratory team. Since substantial differences are often present in different laboratory settings, detailed descriptions of the subjects and contextual details are especially important. To support the development of knowledge that can advance science education by informing curriculum development, teaching and assessment practices, and education policy, it is essential to define technical terms precisely to explicate knowledge in the field; it is also important to use those terms consistently in research reports and in scholarly writing.

This special issue of CERP is totally devoted to the issue of theoretical, practical, and research issues regarding the laboratory in the context of secondary and tertiary education in the chemical sciences. This special issue consists of twelve contributions from seven countries, representing different educational settings and different student backgrounds. The editors of this journal and the guest editors of this special issue sincerely hope that this contribution will provide more insight into our knowledge regarding the laboratory as a unique learning environment.

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Practice

A lesson plan on 'methods of separating matter' based on the Learning Company Approach – A motivating frame for self-regulated and open lab-work in introductory secondary chemistry lessons

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Abstract: This paper describes the use of the learning company approach to lead classroom practice to more cooperative learning and a different style of experimentation. The lesson plan seeks to motivate the students in a cooperative mode to do their experiments self-regulated and self-organised. The approach, originally developed for a lesson plan on acids and bases for 10th grade chemistry lessons (age range 15-16), has been extended to the development of another lesson plan for younger students (6th or 7th grade, age range 11-13) following the same approach on the topic 'Methods of Separating Matter'. The lesson plan and its development by Participatory Action Research are described. Data from teachers' and students' feedback is discussed. The discussion shows how the discourse from educational theory on a different style of experimentation can be put into practice. The evaluation confirms that open experimentation in a cooperative mode can be successfully applied by the learning company approach with such young students, leading to an open and attractive learning environment. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 108-119]

Keywords: Cooperative learning, open experimentation, learning company, participatory action research

Introduction and theoretical background

There seems to be no question that lab-work is an essential part of secondary school chemistry lessons (Nakhleh et al., 2002). In the discourse about chemistry teaching over recent decades, lab-work repeatedly had been described as an essential component to teach scientific method and to learn chemical content (e.g., Blosser, 1983) or to understand the nature of science (Duschl, 1990). Nevertheless, there had also been more cautious remarks that the positive role of lab-work for learning chemistry is not self evident (e.g., Hofstein and Lunetta, 1982). There is evidence from research that the inclusion of lab-work into our classes does not automatically lead to positive results in cognitive achievement and learning about the scientific method (Lunetta, 1998; Nakhleh et al., 2002).

Discussions starting from these not very positive results, e.g. by Bates (1978), Gunstone and Champagne (1990), Tobin (1990), or Herrington and Nakleh (2003), tried to work out why the practice of lab-work in school chemistry lessons is still not very successful. Lunetta (1998) [referring to Champagne et al., (1985), Eylon and Linn (1988), and Tasker (1981)] concluded:

> "*Students often fail to understand the relationship between the purpose of the investigation and the design of the experiment which they had conducted, they do not connect the experiment with what they have done earlier, and they seldom note the discrepancies between their own concepts, the concepts of their peers, and those of the science community. […] To many students, a 'lab' means manipulating equipment but not manipulating ideas.*" (Lunetta, 1998, p. 250)

Within these discussions we can identify several requirements for change in the common practice of school chemistry experimentation. Lab-work in schools should be more than experiments that consist of following a cook-book recipe (Tamir and Lunetta, 1981; Tobin, 1990). They need to turn the lab-work towards a more inquiry-oriented mode, and more student self regulation, and the inclusion of planning, evaluation and documentation of experiments into students' activities (Hofstein and Lunetta, 1982; Gunstone and Champagne, 1990), and linking experiments more carefully to content learning and meaningful contexts (Lunetta, 1998). Additionally, arising from the distributed cognition framework, Nakleh et al. (2002) suggested especially the construction of a cooperative lab learning environment to recognize the dynamic and interactive aspect of knowledge, and Lunetta (1998) argued for taking more thoroughly into account the aspect of communication during lab activities through the cooperative learning and the social constructivist approach. When such cooperation was observed, improvements in achievement, skills development and self-esteem were reported (Lunetta, 1990; Quin et al., 1995). Additionally, Nakleh et al. (2002) urged the development of different forms of assessment with the focus on a good performance as a group, and referred directly to the method of poster presentations.

This paper reports the development and application of a lesson plan that follows explicitly the above mentioned contributions to the discussion of lab-work in science education. The lesson plan deals with the topic 'Methods of Separating Matter' in initial chemistry lessons at lower secondary level. The lesson plan is based on the learning company approach – a cooperative learning method. It leads classroom practice to a different style of experimentation. The lesson plan seeks to motivate the students in a cooperative mode to do their experiments in a self-regulated and self-organised way, starting from inquiry-oriented tasks. The planning, preparation, and evaluation of the experiment become a cooperative student activity, as do the documentation and learning about the theory behind the experiments. Assessment is also done in a cooperative mode on the basis of poster presentations.

The approach was originally developed within a Participatory Actions Research project (Eilks and Ralle, 2002) for a lesson plan on acids and bases for grade-10 chemistry lessons (age range 15-16) in Germany (Witteck and Eilks, 2006). The present paper reports the development of another lesson plan for younger students (6th or 7th grade, age range 11-13) following the same approach on the topic 'Methods of separating matter'. The paper describes the lesson plan, discusses data from teachers' and students' feedback and compares the experiences to those worked out on the lesson plan on acids and bases.

Towards the Learning Company Approach in chemistry teaching

The 'Learning Company' (or 'Learning Office') approach comes from the field of didactics[1] of business and professional education in Germany. According to Paetzold and Lang (1999), the Learning Company is a didactically-constructed classroom structure, analogous to existing or 'ideal' companies. The learning environment is used for the simulation of practical, profession-oriented tasks in business. Through a model based on already-existing or idealised companies, students are supposed to learn how processes in a company occur. They should recognise how businesses are structured, and how differing tasks within the company are related in a cause-effect relationship to one another, to the economy

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[1] The term 'didactics' in Germany is used to define the research and practice field of teaching and learning.

and to the environment. This also incorporates thoughts about functional cooperation within and between different departments.

One might think that teaching how business and industrial structures function is not one of the main goals of chemistry education in schools. However, the possibility of using the above-mentioned thoughts for motivation, the encouragement of cooperative learning and the framing of experimentation in a different style seems to be very promising.

About two years ago a group of teachers, developing lesson plans for cooperative learning by Participatory Action Research (Eilks and Ralle, 2002) for the past six years, was looking for new ideas. Being experienced in the creation and evaluation of different forms of cooperative learning, e. g. the jigsaw classroom (Eilks and Leerhoff, 2001), learning at stations (Eilks, 2002), the ball-bearing- (Witteck et al., 2004), or pairs-to-share-method (Witteck and Eilks, 2005), and mixed approaches (Markic and Eilks, 2006), the group sought new approaches to structure cooperative learning settings with more openness and student self-regulation concerning lab-work tasks.

The Learning Company Approach offered some promise, and the group turned their attention to the development of new examples and appropriate materials for it. The focus was set on structuring lesson plans to be integrated into regular classes and fulfilling a part of the government syllabus.

A first learning company lesson plan on the chemistry of acids and bases was worked out by cycles of development, testing, evaluation and reflection within a Participatory Action Research design (Eilks and Ralle, 2002) in grade-10 chemistry lessons (Witteck and Eilks, 2006). The objective was to combine all relevant aspects concerning acid and base chemistry from the syllabus into one learning company lesson plan, theoretical aspects as well as lab activities. As to the methods of teaching, it was intended that all necessary stages of learning should be performed by the pupils on their own, based on small learning groups, starting from open-ended tasks (goal-oriented ‘work orders’ from the ‘manager in the learning company’ (the teacher) towards his departments (the student groups) instead of prescribed ‘cook-book recipes’) and based on experimental work (Witteck and Eilks, 2006).

Teachers’ reports to the actions research group’s meetings, based on classroom observations and reported experiences with the new approach, considered the lesson plan as amazing. The students achieved far better results than the teachers expected – and did this on their own. The teachers described students as showing very high motivation, lively, self-regulated and successful activity, and learning a great deal. Feedback from the students supported the teachers’ view. The students saw the lesson plan very positive, i.e. concerning the cooperative atmosphere, the open and challenging tasks, and the freedom to follow own ideas and interests (Witteck and Eilks, 2006). This led the teacher group to the question, whether such an open approach also is applicable to younger students.

Open experimentation in a Learning Company for introductory chemistry lessons on methods of separating matter

Learning about properties of matter, and using different properties of matter as a basis for methods of separation are typical topics in the initial phase of introductory chemistry lessons in Germany, mostly conducted in grade 6 or 7 (age range 11-13).[2] Typical methods covered are distillation, filtration, or centrifugation. Explanations on the particle level are not always part of the relevant unit. In most cases explanations on the particle level are dealt with later in the respective school year.

The Learning Company ‘Dr Taste’ is a constructed learning environment analogous to a fictitious analytical institute focusing on the analysis of food and drinks. The Learning

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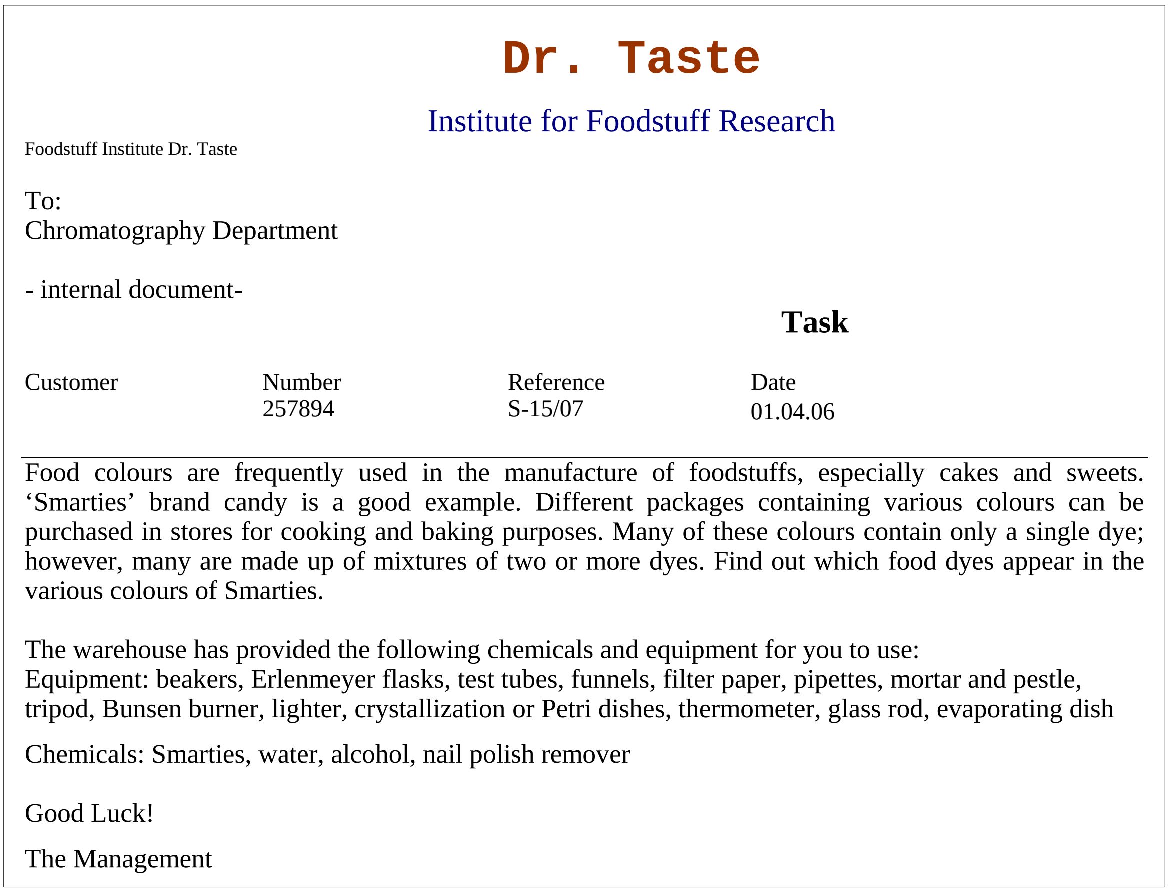
[2] The syllabuses in Germany vary in the sixteen German states (Länder). Nevertheless, the core of the syllabuses is very similar throughout. The grades science and chemistry are introduced in secondary schools and timetables are not the same in the different states.

Company has a managing director (the teacher) and different departments (the student groups). The departments are responsible for the different operations within the learning company; each of them is the expert group for a typical method of separating matter. Dr Taste covers the departments: distillation, filtration, chromatography, extraction, adsorption, centrifugation and decantation.

The departments (the student groups) are getting goal-oriented ‘work orders’ from the managing director (the teacher). The work orders describe a – more or less – open problem, which is embedded in a clear everyday life context from the field of food and drinks, to be solved by the department (Figure 1). The work orders do not prescribe procedures, and are to be organised so that no experimental directions have to be given. Thus, the assigned experimental problems have to be overcome through self-dictated, self-organised, self-responsible learning. A folder of information materials is provided so that the exercise could be solved without having to resort to a prescribed path.

Figure 1. Work order to the Department of Chromatography.



Dr. Taste

Institute for Foodstuff Research

Foodstuff Institute Dr. Taste

To:
Chromatography Department

- internal document-

Task

Customer	Number 257894	Reference S-15/07	Date 01.04.06

Food colours are frequently used in the manufacture of foodstuffs, especially cakes and sweets. ‘Smarties’ brand candy is a good example. Different packages containing various colours can be purchased in stores for cooking and baking purposes. Many of these colours contain only a single dye; however, many are made up of mixtures of two or more dyes. Find out which food dyes appear in the various colours of Smarties.

The warehouse has provided the following chemicals and equipment for you to use:
Equipment: beakers, Erlenmeyer flasks, test tubes, funnels, filter paper, pipettes, mortar and pestle, tripod, Bunsen burner, lighter, crystallization or Petri dishes, thermometer, glass rod, evaporating dish

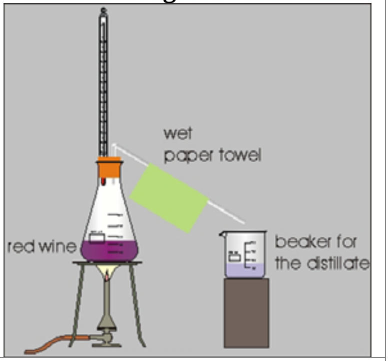
Chemicals: Smarties, water, alcohol, nail polish remover

Good Luck!

The Management

The framework for the students’ activities is set up by regulating the chemicals and equipment offered to the department by the teacher (Figure 1). Within this framework the students are asked to find out about the task, its background and possible strategies for solving the problem. Intentionally, within this example all groups are offered the same equipment, which comprises standard tools to be used in early secondary school chemistry lessons. In this early phase the students are asked to make themselves familiar with these tools and their functions. There are more lab tools offered than are necessary to solve the individual problem. The learning about the function of the lab equipment is essential for any further learning in the lab (Miller and Nakleh, 2004). ‘Playing’ with these tools and trying out their use is one of the objectives of the open experimental tasks within this unit.

Table 1. Overview on the departments, tasks and solutions.

Department	Open task	Chemicals and equipment	Possible solution
Distillation	There are many kinds of alcoholic drinks, for example wine, beer, champagne, schnapps, grain alcohol and sherry. All these drinks contain alcohol. But what does alcohol look like? Separate the alcohol from a sample of red wine. Describe the properties of the alcohol that you extract.	*Equipment*: beakers, Erlenmeyer flasks, test tubes, funnels, filter paper, pipettes, mortar and pestle, tripod, Bunsen burner, lighter, crystallization or Petri dishes, thermometer, curved glass rod, evaporating dish, perforated stopper, paper towels *Chemicals*: red wine, water, alcohol	One distillation apparatus should be set up as per Figure 1. Heat the wine carefully. Cool the glass tube by laying a wet paper towel on it. The paper towel should be kept wet with cold water. Collect the distillate in a beaker. Compare a few drops of the distillate with the red wine and with pure alcohol, then place each in an individual evaporating dish and ignite them. **Figure 1** 
Extraction	Potato chips taste good, but are viewed as an unhealthy sort of food because they contain so much fat. But what does this fat actually look like? Your task is to separate the fat out of a potato chip sample and describe its properties.	*Equipment*: beakers, Erlenmeyer flasks, test tubes, funnels, filter paper, pipettes, mortar and pestle, tripod, Bunsen burner, lighter, crystallization or Petri dishes, thermometer, curved glass rod, evaporating dish *Chemicals*: potato chips, nail polish remover, water, alcohol	Grind a fresh portion of potato chips in the mortar with the pestle until the pieces become extremely fine. Place the potato chip crumbs into an Erlenmeyer flask and add 30 mL of nail polish remover. Stir the mixture for 10 minutes after placing the flask in a warm water bath that does not exceed 40°C. (Preheat the water with the heating coil in a beaker before adding the Erlenmeyer flask.) Filter the liquid into a second Erlenmeyer flask using a funnel and filter paper. Evaporate the nail polish remover under an exhaust hood and examine the fat from the potato chips.
Filtration	Apple juice is not just a popular drink among children. However, if you pulp an apple, you get a mixture which doesn't seem to have much juice. If you press this mixture through a cloth, you are left with cloudy apple juice. The apple juice you can purchase in the store is no longer cloudy; it is clear. This is the most popular type of apple juice and sells better than the cloudy sort. Grind up an apple and squeeze out the juice. Make clear apple juice from the cloudy juice and describe its properties.	*Equipment*: beakers, Erlenmeyer flasks, test tubes, funnels, filter paper, pipettes, mortar and pestle, tripod, Bunsen burner, lighter, crystallization or Petri dish, thermometer, evaporating dish, knife, fork, kitchen towel *Chemicals*: apples, naturally cloudy apple juice	Place the naturally cloudy apple juice into a beaker and filter it very carefully. Do not place too much of the apple mixture into the funnel at one time, since the juice will run through the filter only very slowly.

Chromato-graphy	Food colours are frequently used in the manufacture of foodstuffs, especially cakes and sweets. Smarties brand candy is a good example. Different packages containing various colours can be purchased in stores for cooking and baking purposes. Many of these colours contain only a single dye; however, many are made up of mixtures of two or more dyes. Find out which colours appear in different colours of Smarties. Some contain only one single dye; other colours use several dyes to achieve a particular candy colour.	*Equipment*: beakers, Erlenmeyer flasks, test tubes, funnels, filter paper, pipettes, mortar and pestle, tripod, Bunsen burner, lighter, crystallization or Petri dish, thermometer, evaporating dish, glass rod *Chemicals*: Smarties, water, alcohol, nail polish remover	Place a Smartie in the middle of a piece of filter paper. Very slowly and carefully place a single drop of water onto the Smartie with a pipette or glass rod. Add a further single drop of water after the colouring of the candy dissolves in the first drop of water. Keep adding 1-2 more drops singly until the coloured solution drips onto the filter paper and starts to expand outwards. It is crucial that the work be carried out slowly!
Adsorption	Nowadays you are able to buy soft drinks with very intensive and unusual colours, for example blue. We have purchased a bottle of the blue soft drink “Powerade”. Remove the colour from the blue soft drink and describe its properties.	*Equipment*: beakers, Erlenmeyer flasks, test tubes, funnels, filter paper, pipettes, mortar and pestle, tripod, Bunsen burner, lighter, crystallization or Petri dish, thermometer, evaporating dish *Chemicals*: ‘Powerade’ (blue), active charcoal	Place 50 mL of ‘Powerade’ into a beaker. Add kernels of active charcoal to the solution and stir for a while. Filter the solution through filter paper.
Centrifuging	Orange juice is a popular drink which appears in many varieties, for example with or without orange pulp. Your task is to make pulp-free orange juice out of orange juice with pulp. How much pulp does 100 mL of orange juice with pulp contain?	*Equipment*: beakers, Erlenmeyer flasks, test tubes, funnels, filter paper, pipettes, mortar and pestle, tripod, Bunsen burner, lighter, crystallization or Petri dish, thermometer, evaporating dish, centrifuge *Chemicals*: orange juice with pulp	A) Place the orange juice with pulp into a test tube and wait until the pulp settles to the bottom. Carefully pour the orange juice into another container, so that the pulp remains in the test tube. B) Place the orange juice with pulp into a centrifuge und separate the juice from the pulp. Decant the juice from the pulp after the separation is complete.

For each task, the students are asked to plan and implement their own ideas of how to solve the given problem. The students have to search for theoretical information and ideas of how to solve the problem experimentally. A specially constructed multi-media learning environment (Dr Taste's intranet) is offered as a help, as well as the use of the textbook. The multi-media learning environment offers information about the methods of separating matter and gives ideas on how to do the experiments. Nevertheless, neither the textbook nor the multi-media tool contains clear descriptions of how to conduct the experiment in every case using the available equipment. Such a description is only available from the teacher and can be given to the students according to the teacher's decision. Initial ideas also can be found on the Internet but have to be searched for by the pupils. Table 1 gives an overview on the open tasks, framing conditions and possible solutions.

Starting from this information, the students have to negotiate about the groups' strategy and may try out different approaches. The students can adjust the way and speed of their working according to their own capabilities. Strategies of structuring the groups' cooperative activities can be used to help the students in their self-organisation if required. One way of such help may be giving single students individual roles within the group, e. g. the speaker, the time manager, or the minute taker. The final objective of the groups' work is the presentation of the activities, results and theoretical background on a poster.

The lesson plan consists of seven steps:

1. In the Learning Company, students are divided into small groups ('departments'). Each group is composed of 4-5 children, and it is very important that the groups should comprise a thorough mix of high achieving and no so high achieving learners. Each group receives a department I.D. tag upon which they can write their names. Each group can choose a speaker, materials collector, time manager, minute taker and/or public relations person.
2. The students receive their tasks as a group. The memos contain instructions for the task at hand and list the chemicals and equipment available.
3. Pupils should be given 1-2 hours of preparation time for the experiments. This time is spent learning on the computer and uses the learning environment created for this purpose. Planning the experiment should be discussed with the teacher in advance of starting the hands-on activity. If no computer resources are available, hard copies of the learning environment, textbooks and relevant working materials can be provided to the students.
4. After discussing and planning the procedures, the students must carry out their experimental work and carefully document all activities. It is helpful if access to the computer-based learning environment is also available in this phase. If a department cannot find a solution, the teacher can provide the pupils with ideas or, in the worst-case scenario, a descriptive procedure for the experiment. The students must carry out their experiments and carefully document all activities.
5. The presentation should be carefully set out on a poster, so that students in the other 'departments' can absorb and understand the contents and the experimental results presented.
6. The pupils' experimental results are presented on posters to the whole class at the very end. At each presentation, one of the students has to be present at his/her own group's poster for clarification. Students receive a worksheet, with which they must document the results of the other 'departments'. Furthermore, the pupils must fill out an evaluation form to evaluate and critique the results and presentations of the posters from the other groups.
7. In the final stage after the presentation, the students can strengthen their knowledge of the various procedures from the other groups. They can actively review on the multimedia learning environment those procedures which they either did not understand the first time around, or where they still have questions about the experimental procedures or end results.

Development and evaluation of the lesson plan

The above lesson plan was developed by a team of about fifteen teachers within a Participatory Action Research Project conducted in cooperation with the University of Bremen (Eilks and Ralle, 2002). The action research group existed for about six years before undertaking this project. The group meets at the university every four weeks for a whole afternoon, when lesson plans are developed and feedback is discussed. In the past, the group developed various lesson plans for dealing with the particulate nature of matter (e.g., Eilks et al., 2004) and for applying more open and cooperative methods in secondary chemistry teaching (e.g., Eilks, 2005).

The entire process of structuring the lesson plan and associated materials is a cyclical process of development, testing, evaluation and reflection involving university researchers in chemistry education and classroom practitioners. Structuring this lesson plan was done over a period of about half a year, led mainly by one practitioner (TW) from the group.

To date, the lesson plan has been tested in three cycles by practitioners from the research group within their regular classes in 3 German Realschule (middle school) and 6 German Gymnasien (grammar school) grade-7 learning groups, with a total of about 250 students (age range 12-13). The first cycle of testing accompanied the last stages of structuring the lesson plan. The second cycle took place about 3 months later, with the third cycle occurring 12 months later. Nevertheless, all groups were taught using nearly the same lesson plan and working materials.

The views of the teachers were collected through open group discussions in the regular meetings of the Participatory Action Research group. Additional data came in the second cycle from two written student questionnaires, which in three learning groups asked for the students’ experiences and criticisms (N = 82). A combination of an open- and a Likert-type questionnaire was used. The questionnaires were structured similarly to those used in Leerhoff and Eilks (2003), Witteck et al., (2004), or Eilks (2005). The students were first asked in an open questionnaire to evaluate which aspects of the lesson plan were important (from the students’ point of view), either in a positive or negative sense. After the open questionnaire, they were asked to fill out a Likert-type questionnaire, in order to gather information on the points considered important by the teachers and researchers.

Teachers’ and students’ views

The teachers’ view

The teachers noted that the Learning Company Approach on methods of separating matter generated high motivation in the students. Starting form the presentation of the idea of the Learning Company by the teacher the students became very curious. From the beginning the students were very focused on the problem to be solved, which suggested to the teachers that the framework offered a quasi-authentic and very challenging situation. The teachers reported that the students seemed to identify themselves with their group or ‘department’.

One of the most important impressions repeatedly mentioned, concerned the intense and content-focussed discussions aimed at the question of how to structure promising experimental activities to solve the given problem. All the groups found appropriate ways to solve their problem. The strategies differed greatly and ranged from trial-and-error approaches to well thought and planned procedures. The offer of sheets with specimen solutions by the teachers was used only in some middle school classes for control. They were not used in the grammar school classes.

Another important issue the teachers commented upon concerned the combination of different elements within the learning environment. The teachers ascribed great advantages to this approach because of the openness concerning the sequence and self-directed emphasis of students’ activities. The students moved backwards and forwards between their hands-on activities and the search for information. A networked activity of searching for theoretical information, practical help in the written resources, communication and negotiation within the group, and hands-on activity was described by the teachers. The teachers identified this self-directed and networked activity between theory learning and hands-on activity as a totally new experience during lab-work exercises, both to them, and to the students. The teachers considered this self-regulated combination of different activities focussed on a content problem in chemistry lessons as being very challenging and demanding to the students. But, according to the teachers, the problems were solved well and with few unexpected problems.

The results from the students' groups – their minutes and posters – met the demands set up by the teachers in advance of the lessons, based on their long experience as teachers at these age levels. Difficulties were only observed with chromatography and adsorption, but were reduced in the later cycles of testing by expanding the explanations and help within the multi-media learning environment.

In the view of the teachers, the main benefit of the jointly developed lesson plan was the high motivation and intense, self-regulated, content-focussed engagement of the students with theoretical topics from chemistry within a lab environment.

The students' view

The positve feedback from the teachers' perspective is supported by the students' view. Some of the aspects are parallel, but the focus is different. Within their questionnaire the students mentioned especially positively the fun they had and the openness (to have freedom to follow own interests, ideas and pathways). The independent activity, the cooperative atmosphere (to be allowed to do things together as a group) and the experimental activities without the teachers' close guidance and control was mentioned as being very positive (Table 2). Some of the students also recognized the importance of first making themselves familiar with the intended hands-on activities in advance to carrying them out:

> *"I liked the Learning Company because we first developed the write-up of the experiment and later on we had to conduct the experiment (exactly in the way* ***we*** *planned it)."*

Table 2 gives an overview of the frequency of selected aspects mentioned by the students in their comments in the open questionnaire. It asked the students what they thought of the lesson plan, their ideas on what worked well and what should be improved. Table 3 reports some selected student answers for illustration.

Table 2. Frequency of comments made in the open questionnaire (N=86).*

Positive comments (what worked well)	
The more intense and effective learning.	18
The cooperative atmosphere for learning.	39
Being more independent,	
- because of being more active.	44
- because of responsibility for my actions.	2
- because of being allowed to make our own decisions about the activity.	31
- because of the possibility of self-regulated and self-organised experimentation.	24
The lesson plan was really attractive and we had more fun in the class.	38
Negative comments (what should be improved)	
There should be less control by the teacher.	4
The demands were too high because of the limited time.	1
There were problems within individual groups.	4
We were disturbed by too much noise.	2

* N = 86, 3 students did not give answers to the open questionnaire, most students responded to more than one category.

Figure 2. Selected student answers from the open questionnaire.

> *“The biggest difference for me was that we had to do everything ourselves and that we weren’t as strictly controlled as in other experiments in class. I especially liked the fact that we had to get to the results all by ourselves and were allowed to simply forge ahead as we liked. That was really fun.”*
>
> *“The difference was that we had to work out everything for ourselves, for example putting the experiment together, etc.”*
>
> *“I liked the work with the computer learning environment because we could work more independently than normal. In addition, we had to devise the experiment by ourselves. I really liked having to work independently and having to carefully think out how to perform the experiment.”*
>
> *“I liked the group work. It was independent work. We had to do all the work ourselves without the teacher helping us (well, maybe a little)... I really liked the Learning Company because we could perform experiments. You could do experiments with the things and materials that were given to us and some were pretty cool.”*
>
> *“With this method of teaching I could be a lot more active and think and act more freely. I understood almost everything better than in ‘normal’ lessons. I find that independent work is much more demanding and more interesting than normal teaching methods.”*

Table 3. Data from the Likert-questionnaire (N=86).*

	I totally agree	I pretty much agree	I scarcely agree	I don’t agree
1: I worked much more independently in the Learning Company than I normally do during our lessons.	45 (54,9 %)	34 (41,5 %)	3 (3,7 %)	4 (4,9 %)
2: I missed the direct control of my work by the teacher after each step.	4 (4,9 %)	19 (23,2 %)	35 (42,7 %)	28 (34,1 %)
3: I worked much more intensely in the Learning Company than I normally do during our lessons.	37 (45,1 %)	32 (39,0 %)	11 (13,4 %)	6 (7,3 %)
4: I prefer it if the teacher discusses all topics with the whole class than to work in small groups.	11 (13,4 %)	12 (14,6 %)	19 (23,2 %)	43 (52,4 %)
5: I think that I learned a lot in the Learning Company.	54 (65,9 %)	25 30,5 %)	7 (8,5 %)	0 (0,0 %)
6: I don`t like the Learning Company because my work is too dependent on my classmates.	1 (1,2 %)	15 (18,3 %)	20 (24,4 %)	50 (61,0 %)
7: I found the Learning Company confusing and lacking in structure	2 (2,4 %)	9 (11,0 %)	24 (29,3 %)	51 (62,2 %)
8: I like the Learning Company because I could work out something with the other students.	65 (79,3 %)	16 (19,5 %)	2 (2,4 %)	3 (3,6 %)
9: It was difficult for us to organize the Learning Company by ourselves.	5 (6,1 %)	10 (12,2 %)	23 (28,0 %)	48 (58,5 %)
10: I think I learned a lot by working with the computer.	29 (35,4 %)	35 (42,7 %)	10 (12,2 %)	12 (14,6 %)
11: I like the Learning Company because we could carry out our experiments independently in our group.	75 (91,5 %)	6 (7,3 %)	4 (4,9 %)	1 (1,2 %)
12: I like the Learning Company because we were allowed to carry out experiments without a given recipe.	56 (68,3 %)	19 (23,2 %)	5 (6,1 %)	6 (7,3 %)
13: Using different teaching methods makes our lessons more fun and less boring.	55 (67,1 %)	22 (26,8 %)	7 (8,5 %)	2 (2,4 %)

* Numbers and percentages of the students who answered to the Likert-items whether they totally, pretty much, or scarcely agreed, or didn’t agree.

The answers from the open questionnaire are supported by the Likert-questionnaire (Figure 3). The students mentioned that they had the feeling to have worked very intensely and to have learned a lot (item 3 and 5). The structure was considered very motivating and attractive (item 13). The positive consideration was based on two aspects. One is the cooperative learning atmosphere (items 4, 6, and 8), and the other was the highly self-directed activity (items 1 and 9), and especially the chance for self-regulated lab-work activities without being given a cook-book recipe that got the highest support (item 11 and 12). The demands were high, but were considered by the students as not being too high (item 2, 7 and 9).

Conclusions

The experiences described by the teachers and the students' feedback from the questionnaires support the findings concerning the Learning Company's evaluation on the topic acids and bases (Witteck and Eilks, 2006). The results support the idea that opening up a chemistry lesson's lab-work towards self-regulated learning by the Learning Company Approach is possible, and that it leads to a different learning atmosphere. The described lesson plan leads towards a different style of lab-work which promotes more student activity and involvement in the process of experimentation. The present report on Dr Taste's Learning Company offers the additional conclusion that similar processes, as documented on the example on acids and bases (Witteck and Eilks, 2006), are also possible with younger students. The approach is highly motivating and welcomed by the students, especially on account of its cooperative character and the chance to find one's own methods and to follow one's own ideas during the performance of the lab tasks.

Current practice in German science teaching is different. The amount of lab-work done is low, and in those cases where the students are asked to do lab-work, the activities in most cases are over-directed (Fischer et al., 2005). The positive experiences gained in the two examples of the Learning Company Approach linked to open experimentation should lead to science teaching being more open and cooperative, particularly in lab activities.

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Practice

The project CHEMOL: Science education for children - Teacher education for students!

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Abstract: The project CHEMOL (CHEMistry in Oldenburg) has developed a structure that integrates laboratories for primary-school children into the university education of teachers, both as in-service and teacher training programmes. The CHEMOL lab is visited once or twice a week by different classes. Supported by members of the team and teacher-training students, the children investigate phenomena about fire, water, air, and solids in small groups and they develop and carry out simple experiments themselves. For the visiting children, CHEMOL aims to develop a general understanding of basic concepts of science (with a special focus on chemistry) and basic experimental skills. For student teachers, the project offers the possibility to plan and carry out experimental work with young children and to observe and discuss the children's ideas. Thus, the CHEMOL project gives the students a chance to transfer their theoretical knowledge about teaching and learning science into practice already during their study time at university. The conceptual approach and results of a small accompanying interview study is discussed in this paper. **[***Chem. Educ. Res. Pract.***,** 2007**, 8** (2), 120-129]

Keywords: teacher education, university science labs, primary school

Introduction and background of the teacher education project

In most countries, the balance between practice and theory is a perennial issue in teacher education. Although teacher education programmes may vary in different countries, there is a tendency that university education is mainly responsible for theoretical education, while pre-service teacher training in schools offers the practical experience (e.g. Ball, 2000). The situation in Germany exemplifies this statement: teacher education comprises a first component at university followed by a training-on-the-job for one and a half or even two years at school. Many student teachers and practising teachers complain that they are not able to see the relevance of the pedagogical theories they learn at university; instead, they rather assume teaching as being mostly common sense and learned through experience. This may be a consequence of the way teacher education is organised.

The development of pedagogical content knowledge (pck, as described by Shulman, 1986) is promoted by the use of content knowledge and (just beginning) pck in pedagogical contexts (Van Driel et al., 2002). Possible pedagogical contexts are classroom experiences or, for example, microteaching approaches. Some findings indicate that school placement is not always as successful as assumed. For example, sometimes there is a great pressure to cover a given curriculum and no time for reflection on the experience gained. Furthermore, cooperating teachers are strong role models, and in some replies there is a mismatch between their teaching practice and the goals of teacher education programmes (Hewson et al., 1999). Studies on the effectiveness of microteaching show varied results. The investigated approaches include different strategies, which makes it difficult to compare the results. In all, microteaching seems to facilitate the acquisition of teachings skills, but it is not clear if there are transfer- and long-term effects, nor which features of the approaches are crucial for effectiveness (Klinzing, 2002).

The impact of teacher training programmes on the quality of classroom activities is not easy to study. However, several studies indicate that the initial knowledge of young teachers based on their own positive and negative school experiences is very stable, and represents an important base for classroom practice, especially in situations where fast decisions are necessary (e.g. Ball et al., 1999, Van Zee et al., 2001). If teachers change their initial teaching and their attitudes during their first years, they often do not shift towards a more sophisticated insight into learning and teaching, but rather towards the well-established practices of the school where they now teach (Müller-Fohrbrodt et al., 1978). Theories students have once learned at university courses are kept merely for examination purposes, but not actually to guide their teaching. Hence, there is no apparent need for further theories and professional learning.

In recent years reflection became a key concept in teacher education for making changes in teaching (Yerrick et al., 2005). Reflective practice is an integral part of professional practice and fundamental for life-long professional development (Hewson et al., 1999). Some teacher education programmes integrated action research projects (Tabachnik et al., 1999) or comparable projects (Kleickmann et al., 2005), where prospective teachers engage particularly in reflective practice. For example, these approaches helped student teachers to understand and elicit students' thinking and their prior knowledge, but do not guarantee that they employ their knowledge in the classroom (Hewson et al., 1999). Factors that hindered the teaching to effect conceptual change in this example included their own beliefs, the scarcity of school placements and their fragmented content knowledge (Tabachnick et al., 1999).

Currently in Germany and in the Netherlands, as in some other countries, teacher education is changing towards a Bachelor- and Master-system. In this process of developing new curricula, the goal of a better integration as described above has moved centre stage again; the enhancement of the integration of (university) theory and (classroom) practice seems to be a common trend in the recent development of teacher education programmes (De Jong et al., 1998). In Germany, for example, several new approaches integrate a half-year field training in school at the beginning of the training course, although the results of the effect of those approaches are not yet clear. A simple transfer from theoretical knowledge into classroom activities is surely not possible (Kolbe, 2004), even though some students have this expectation.

In this paper, we discuss an approach for prospective primary and secondary teachers that provides small group and short duration teaching and learning activities. Here student teachers can use their beginning pck in a pedagogical context and reflect on their experience together in groups of different backgrounds. The project called CHEMOL (CHEMOL an acronym from CHEMistry in OLdenburg) is part of the teacher education in Oldenburg and Lüneburg. To get an insight into the effects of this integrated module, we are carrying out several research studies; here we discuss the results of the first explorative and qualitative interview-study.

Context of the study

The project CHEMOL for children and teachers

Primary school classes visit the CHEMOL labs in Oldenburg and Lüneburg for half a day. The project began in 2002 and more than 9000 children have visited the CHEMOL lab since then. In the lab, classes are divided in groups of three or four children, which investigate chemical and physical problems, supported by staff members and student teachers. The lab visit is organised as learning cycles: phenomena about water, air, fire and solids are presented to the groups of children and are meant to raise questions. These questions are investigated by the children following their suggestions, or other ideas from the programme and from our former experiences. Normally, each group will have investigated two or three areas during the half-day visit. The schoolteachers, who organise the visit, receive the material in advance and are asked to prepare the children, for example about safe behaviour in lab.

The idea to offer science labs to schoolchildren and to invite them to visit a university has become popular in Germany during the last few years. Many universities give lectures for children, so called ‘Kinderuniversität’ (kids’ universities). Some have designed special lab-work activities for children. One reason for this development was the decreasing numbers of students in sciences, especially in the ‘hard sciences’, such as physics, chemistry, or engineering (Gago et al., 2004). Accordingly, most projects are aimed at students who will decide their career pathways in the near future, students of A level-type courses, for example. The CHEMOL project starts at the other end; we try to foster the interest and motivation of young children and to enhance their background knowledge about the sciences very early on.

There are many reasons to start such activities with young children. Firstly, empirical studies show that primary school children are highly motivated for (simple) scientific investigations and questions (Martin et al., 1997). We can also observe this motivation in the CHEMOL lab as reported by the children and their teachers in questionnaires and by the letters we receive from the children. Secondly, research studies show that young students are well able to develop basic ideas and explanations about scientific phenomena and inquiry (e.g. Metz 1998, Bullock et al., 1999).

Nevertheless, chemistry, physics, or technology topics often get little attention in primary schools in Germany, as in other countries, as shown in several analyses of syllabuses and teaching protocols (e.g. Einsiedler, 2002; Appletown, 2003). This situation cannot be ascribed to the students but rather to the teachers. Primary-school teachers usually have no science background. Even though many of them are interested in science, they admit that they do not feel able to teach sciences (with the exception of biology) (e.g. Harlen, 1997; De Jong et al., 2002).

The aim of the project to foster the interest of young children can only be achieved if teachers take up the new ideas from the CHEMOL visit and continue the work in school. Otherwise, the visit is a single event, and its effects are not very lasting. Therefore, CHEMOL also offers special in-service training workshops, where primary teachers can acquire the necessary knowledge and skills by carrying out the experiments themselves, supported by university staff members. The CHEMOL laboratory shows teachers experiments (Jansen, 2005) they can integrate into their normal lessons at school. For the experiments, only simple, everyday materials such as soda and vinegar are needed, special laboratory equipment is not required and, of course, none of the materials is harmful. The additional (supplied) teaching material includes possible connections to the syllabuses or to optional subjects, and more information about the experiments. Hence, the CHEMOL project is not only for children; it is also designed to improve teacher education.

Nevertheless, a questionnaire study shows the difficulties of incorporating science teaching into the teachers’ own routines at school, although primary teachers evaluated the project positively and consider the motivation and the learning achievement of their pupils as high (for more details see Steffensky and Wilms, 2006). Missing knowledge was most often named as a reason for not carrying out such activities in school. This indicates that the integration of scientific work with children into teacher training for primary schools is important both at the university level and in professional development courses for in-service teachers.

Integration of the CHEMOL project into teacher training

Those students in this project, who aim to teach in secondary schools, study chemistry, biology or physics, while those heading for primary schools usually study biology if they study sciences at all. The concept of 'learning communities' (Eilks et al., 2004) suggests an opportunity for the students to exchange their specific expertise and learn from those of the other groups, since primary-school student teachers often have a better pedagogical background, while the secondary school student teachers have a better command of concepts and skills in sciences. This can also help to establish future patterns of cooperation with colleagues in school.

Student teachers carry out the CHEMOL project normally for four months; at first, participants get an introduction into the theories of children's learning (science) and to the experiments and corresponding basic concepts, the latter is especially important for non-chemistry students. The next step is to observe school classes during their visit at the CHEMOL lab. Thirdly, the student teachers work with groups of children themselves. During these weeks of practical work with the children, there are regular meetings of the students, where they analyse and discuss their experiences and observations. Within the whole learning community, the students form pairs so they can observe each other and consider the learning and teaching situation from two perspectives. Supervising science lecturers also provide feedback. Additionally, some groups are videotaped; these tapes are also used for individual feedback and group discussions. Finally, for their term paper students are asked either to develop an experiment or series of experiments that can be integrated in the course in the future, or to investigate a small research topic. The research questions can be specific ideas or learning difficulties children have, for example. During the phases of reflection, and for their term paper, students have to connect their own experiences and observations to their pedagogic content knowledge. The results are used to optimise the CHEMOL project, which can therefore be regarded as a research based developmental project (Eilks et al., 2004), integrated into the teacher training at university level.

Compared to their future school experience or internships in school, the student teachers have the opportunity during the CHEMOL project to concentrate on teaching and learning sequences, as they do not have to worry about classroom management or preparation of lessons and courses. This reduction of complexity in a teaching situation seems advantageous for the learning of the prospective teachers, especially at the early stages.

Data collection and analysis

Participants of the study (N = 15) were interviewed individually six months after they had participated in the project about their experiences during the course. All the students were in the last third of their university studies. They joined either a chemistry-teaching or physics-teaching programme (3 male, 7 female) or a primary teaching programme (5 female). The interviews lasted on average 40 minutes; they were conducted at the university and were audio taped. The interviews were semi-structured, and allowed the respondents to introduce new issues and tell 'their own stories'. They were based on five open-ended questions:

1. What motivated you to participate in the course?
2. What difference do you see between this course and other practical training courses in school?
3. On which specific aspects of the teaching and learning process did you focus during the course?
4. Did your chemistry content knowledge increase during the course? If so, to what extent?

5. Could you use the acquired knowledge (content and pedagogical content knowledge) and experiences in other courses at university?

The interviews were transcribed for analysis, which involved a process forming categories emerging from the data, categorization of the data, and paraphrasing and summarizing of the coded parts of the transcript. The main aspects (qualitative and quantitative) of the categories are described in the following part. For illustration, some quotations are used, which we translated from German into English, here we tried to strike the right note. This is an additional problem of interpretation; therefore, we made less use of quotations than in some other research reports. The following results refer to the interviews. The videotapes and other observations were not used for deeper analysis, because not all of the interviewed participants were recorded and even when they were, it was not necessarily at the same phase of the project, which makes comparison difficult.

Results

As is known from many research studies, student teachers and in-service teachers criticise the lack of practice orientation in most teacher programmes (e.g. Bohnsack, 2000). Consequently, courses in which teaching practice plays a central role should be popular among teacher students. Indeed, all fifteen student teachers interviewed named this as their main motivation to participate in the course. Working with ‘real’ children is such an attraction that even chemistry is accepted (“*I can’t stand chemistry, but I liked the idea of working with kids, so I decided to put up with it.*”). Besides, student teachers were interested to find out about new experiments for children and to be better trained in handling experiments.

As expected, all teacher students named several organizational aspects, which differ between an internship in school and the CHEMOL project. The main difference participating student teachers mentioned was the focus of interest. In the CHEMOL course, the children and their learning are the focus of interest (11 replies), whereas the preparation of lessons and learning arrangements (7 replies) as well as classroom management (14 replies) were indicated to be the major foci of school practice. Differences between the types and process of reflection are described, too (9 replies). The responses from the in-service teachers centred more on the content, for example on the chosen materials or experiments, or on class management. Particularly in the latter areas, much practical advice can come from the experienced in-service teacher. Reflection on the CHEMOL project refers more to subject-oriented theoretical and empirical findings and teaching behaviour/behaviour patterns and is seen as being more general and abstract. In contrast, reflection and feedback in a training course in school concentrates on the concrete situation, where it is usually the planning and the execution of teaching programmes that are discussed and not teaching behaviour. At least this is what student teachers feel. (“*In school we hear about many tricks, for example how to get a class to be quiet; in the CHEMOL project attention is much more on the principles. In CHEMOL I started to think about teaching, learning, and myself in the teacher role; I know that is important, even if it does not lead to clear advice how to do things*”). Only one student saw no difference at all.

A very important difference in the two settings, as thirteen of the interviewed participants pointed out, is a higher sense of security the CHEMOL project provides. Therefore, these factors are important

- a small group of children is involved instead of a whole class (13 replies)
- the teaching and learning sequence is repeated several times (13 replies)
- there is not somebody (with years of teaching experience) watching the whole time (8 replies)
- the children in the CHEMOL are mostly highly motivated (5 replies)

- there is greater confidence in being able to handle the situation (4 replies).

Correspondingly, the respondents explained that the aspects they focused and reflected on changed over the time of participating in the project (12 replies). At first, the handling of the experiments, the theories behind the experiments, the concern about using the correct terms (both mentioned only by the students of the primary-school programme), and the organisation of the programme itself captured much attention. After repeating the learning sequence four to six times with different groups and gaining confidence, the students became more aware of pedagogical or pck aspects. Some aspects mentioned were

- letting the children plan and do the experiments more on their own (11 replies)
- reducing the need for explanations by the teacher (11 replies),
- changing the sequence of experiments, for example, because the children have less or more experience and/or knowledge than expected (6 replies),
- taking up new ideas from the children to lead the investigation (5 replies),
- asking the children more precisely about their ideas and mental models (4 replies),
- using appropriate language consistently (4 replies).
- comparing different approaches (2 replies)
- anticipating mistakes and trying out different patterns of response to those mistakes (2 replies),
- differentiated and adapted behaviour towards less gifted and more gifted students (1 case).

All five students at the primary-school teacher programme reported a great increase of subject matter knowledge, which is expected, considering the poor knowledge in the ‘hard’ sciences primary teachers often have or are assumed to have (e.g. Asunta, 1997). Although they still assessed their general content knowledge as poor, they were persuaded to introduce the experiments into their own school practice later on. Two of them have meanwhile written their master’s thesis on chemistry topics in primary schools. Additionally, eight of the secondary trainee teachers reported a moderate increase of their subject-matter knowledge, whereas two other students reported only a small increase, if any at all.

The student teachers used their experiences from the CHEMOL project to a great extent in other (school) experimental courses, as well as in their teaching practice (9 replies). Not only was the additional experience in experimentation felt to be helpful, but also the experience in arranging a teaching and learning situation that incorporates an experimental approach.

Besides, in so-called theoretical courses on general or science education the knowledge developed in the CHEMOL project was considered to be helpful. It seems as if the episodic knowledge developed in the CHEMOL project can lead to theoretical knowledge. Student teachers get to know a variety of examples, particularly of children’s ideas and informal concepts and strategies in (experimental) learning situations (5 replies) as well as typical patterns of teacher behaviour (7 replies), they had recognized in their own behaviour. These examples and their reflection illustrate theoretical knowledge. One student explained: “*I can picture a bit better what theories can mean for practical classroom work, because I have more examples in mind*”.

Discussion

The numbers of student teachers participating in the project, as well as their responses to the project, indicate the interest for such activities. Within teacher training, CHEMOL offers student teachers the possibility to acquire practice or experience in theory-based analysis of and reflection on teaching and learning processes and on lab work. An important feature of this project is the possibility of repeating learning sequences with different groups. On average, student teachers repeat a learning sequence with twelve different groups during a term. The more students feel comfortable with the experiments and the new teaching situation, the more they start to try out different things, for example to change the order of experiments or to let the children do more work on their own, so the learning processes of the primary school pupils become more important. The experiments are not very complicated, either in the required experimental skills or in the scientific content, and the participating student teachers practice them several times before they start work with the children. Nevertheless, it takes several repetitions until the learning of the children, their difficulties, and concepts can become the centre of attention.

Our observations of the student teachers match their own estimation about the need for up to seven repetitions until they can confidently focus on the children’s learning processes. Independently of the interviews, we noticed that the student teachers need more time (from about 50 to 60 minutes) for one learning sequence with a single student group after the first six or seven repetitions. This is understandable, if we consider that as student teachers gain confidence they keep more in the background, and give the primary students more space and time to work on their own problem solving, so they need more time for the learning cycle overall.

This focus is important because learning, and knowing and understanding of specific learning difficulties and students’ conceptions are a key element of pedagogical content knowledge (Van Driel et al., 1998). The use of theoretical knowledge in various contexts supports the development of pck (Ball, 2000**)**. At the same time (reflected) experiences seems to support an access to theoretical knowledge (Nölle, 2002), as the students stated in the interviews.

Some studies indicate that student teachers tend to change their behaviour during their teaching practice aiming for a stronger control over the class; at the same time they become less inclined to try things out (Hascher 2006; p. 132). This desire to control, Jones and Vesilind (1995) argue, emerges from the need for student teachers to reduce the complexity of classroom environments. School training is obviously necessary, but in addition, projects such as the one described here offers a setting of reduced complexity, which can be an opportunity for learning about (individual) teaching and learning processes.

One can also use the CHEMOL project for the training and development of innovative teaching ideas. In a usual internship situation, this is sometimes difficult, because there are so many factors to consider, so that the introduction of a new idea, possibly without the support of supervising in-service teachers, is difficult. Especially for primary trainee teachers, mostly without a science background, the project offers a rare opportunity: Here students have the chance to deal with science topics for a longer period and to put this into practice teaching and learning with children straight away. This could be a chance for primary teachers to develop greater confidence in their own scientific knowledge and ability to teach science, which then promotes the implementation of chemistry and physics in primary school classes. At the same time, beginning teachers could disseminate new ideas in their future schools. The analysis of these possible effects must involve long-term studies.

However, especially for beginning teachers, the setting up of more extensive experimental courses seems to be difficult, because in this period time pressure is extremely high or is assumed to be so. Beginning physics teachers, who definitely have more experimental experiences than primary-school teachers for example, name experimental courses as a special burden during the first years at school (Merzyn, 2004). For this reason, it seems that projects like CHEMOL are not only a chance for primary school teachers but also for secondary science teachers to achieve more practice in experimental work with children. Furthermore, working on basic science concepts or phenomena can be helpful for schoolwork alongside the often rather specialised courses or topics in university education. Some studies revealed that both trainee and experienced teachers criticise the emphasis on the teaching of specialised knowledge instead of a broader, more school-related knowledge in universities (Merzyn, 2004). Our finding, that not only the prospective primary teachers, but also some of the chemistry student teachers described an increase of their content knowledge might be due to fact that the topics they study during the CHEMOL course are very different from those of the usually (more specialised) chemistry courses.

Although not part of our research study, we noticed that the observation of selected video sequences during the coursework often initiates discussions on general educational issues, such as explaining, dealing with mistakes, types of questions, or common misconceptions. We also observed that sometimes student teachers raised questions that arose from pedagogic theories in a practical context.

Similar experiences are also described for multimedia learning environments in teacher education, for example the MILE project (Oonk et al., 2003). In MILE, records of teaching practice in an actual classroom setting are used for math teacher education. Despite these positive effects, it is crucial to define theory-grounded criteria for analysing and discussing the videos or the observations student teachers made in the CHEMOL lab. Otherwise, there is a risk of remaining on a superficial level or not moving beyond basic common sense. The small research questions students work on for their term papers proved to be helpful. Working on those during the course often gave a positive impetus to the discussions. With the formed (feed-back) pairs and/or the video feedback student teachers can practice observing, analysing and reflecting individually and in a team. All this is the basis for peer coaching and team coaching or social support in general, which is a key factor for life-long professional development.

The results from the first interview study are based on self-assessments of the prospective teachers. This approach requires that participants can see themselves retrospectively in a realistic manner and that they do not just provide socially desirable answers. In the future, we plan to assess formally the development of pck and content knowledge during the course. Besides that, another important research question is whether the knowledge and experience developed in the CHEMOL project have an impact on classroom activities in training courses or in the long term on teaching activities in schools. Knowing the barriers to the implementation of new teaching methods, topics, approaches and contexts into school practice, this will be the actual test of the effectiveness of the project. Time will tell.

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Practice

Developing practical chemistry skills by means of student-driven problem based learning mini-projects

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Abstract: Problem-based learning mini-projects (‘PBL mini-projects’) are used as an alternative to the traditional ‘recipe-style’ laboratory teaching method with the aim of enhancing students’ experience of chemistry laboratory practicals. Small groups of students (3–4) in the second year of their degree are assigned a project title and they must devise the experimental protocol to carry it out. This teaching method better reflects real-life problem solving situations. The students responded favourably in their feedback on these laboratory classes. Class attendance and general class morale were found to be noticeably higher than in previous years. This paper describes the implementation of the PBL mini-projects in our teaching laboratories and examines some feedback obtained from the students (42 in total) and teaching staff involved over a two year period (2004/5 and 2005/6). [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 130-139]

Keywords: Problem-based learning, group work, practical work, practical chemistry skills, mini-projects

Introduction

Traditional practical classes for undergraduate chemistry students where they follow a prescribed experimental procedure over a set time are the backbone of most chemistry degree courses. These practical classes are designed to complement material dealt with in lectures and give students practical experience, which will be invaluable in their future careers as chemists. However, there is much discussion on the merits of such a system (Meester and Maskill, 1995, Johnstone and Al Shuaili, 2001). Among the arguments against is the claim that the level of learning is limited, and that students are unclear of the aims of a practical and unsure of what the results mean or how they are applied to the theory provided in the lecture programme (McGarvey, 2004). In addition, the traditional style practicals often leave little room for creativity or contextualisation, and are often a verification of a known quantity or a testing of a theory that has been presented in lectures.

Several different types of laboratory-based teaching exist. Domin listed four descriptors that can be applied to the different laboratory teaching methods (Table 1) based on the expected outcome of the laboratory session, the student’s approach and whether the procedure was supplied (Domin, 1999). By far the most common among these is the *expository* or ‘recipe-style’ laboratory class. Students in our institution rarely perform any other type of laboratory work, except for that involved in their final year project.

Table 1: Descriptors of the laboratory instruction styles (from Domin, 1999).

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

In a major review on the role of laboratory teaching in science education, Hofstein and Lunetta (2004) detailed some of the factors that inhibit students' learning. Among these are the following:

- the recipe-style laboratory practicals used in most institutions do not allow the student to think about the larger purpose of their investigation and the sequence of tasks they need to pursue to achieve those tasks;
- assessment is seriously neglected, resulting in the impression that laboratory work does not need to be taken seriously;
- educators are not informed about what is best practice;
- resources for more appropriate laboratory teaching styles are limited.

PBL mini-projects allow for a lot of these issues to be addressed. The shifting of the responsibility for devising the experimental procedure onto the student means that students must now be aware of **whether** a particular experiment they devise is suitable, **why** it is so and **what** it will tell them. Hence, the students are now beginning to examine the usefulness of an experiment and think about it in the context of an overall problem solving scenario. This contrasts significantly with recipe-style laboratories, where students can complete an experiment and produce a report without ever really understanding or thinking about the experiment involved. The PBL mini-projects are assessed in part by examining the students' individual research diaries, where they report any work they did (background reading, laboratory work, follow up calculations). In addition, students give a presentation on their laboratory work and are asked questions about the project after the presentation as well as during the laboratory sessions. They also submit a short individual reflective piece summarising what they learned and how they found the mini-project, including any benefits and any difficulties. This provides a more holistic form of assessment as compared to traditional laboratory teaching, where only students' reports are assessed.

There are some reports of the use of PBL mini-projects as alternatives to expository practicals. Dunn and Philips (1997a, 1997b) describe PBL mini-projects for analytical chemistry. In the excellent book *Teaching in Laboratories*, Boud, Dun and Hegarty-Hazel (1986) discuss laboratory practicals where students develop their own procedure. According to Domin's descriptors (Table 1*)*, problem-based laboratories have a pre-determined outcome (but only the instructor knows of the outcome) and, significantly, the procedure is student generated. It is this alteration in laboratory teaching style that changes the entire emphasis of the laboratory class and which, we believe, has a significant impact on the students' learning.

In our own studies at the Dublin Institute of Technology we have examined the use of PBL mini-projects for the past two academic years. Students completed their laboratory work in groups and completed their projects over four to five sessions of three hours each. Students were assigned contextualised problems that show the applications of chemistry, similar in style to those suggested by Mc Garvey (2004). Some examples of mini-project titles are shown in Table 2.

This paper describes the implementation of PBL mini-projects in a second year chemistry degree course. An extensive student mini-project system was developed, which involves students completing their PBL mini-project over five 3-hour laboratory sessions. This runs concurrently with 'traditional' laboratory sessions, which students complete at other times during their week. In this paper, the operation of these PBL mini-projects alongside the traditional laboratory practicals is described and the additional benefits that result from combining this new approach with the existing system are examined. It has been recognised that the implementation of laboratory practicals where the student generates the procedure for the practical presents a number of significant challenges (Edelson 1999). This method requires more laboratory time than would normally be assigned to a pre-determined practical, but we believe the benefits observed make the time investment worthwhile.

Method

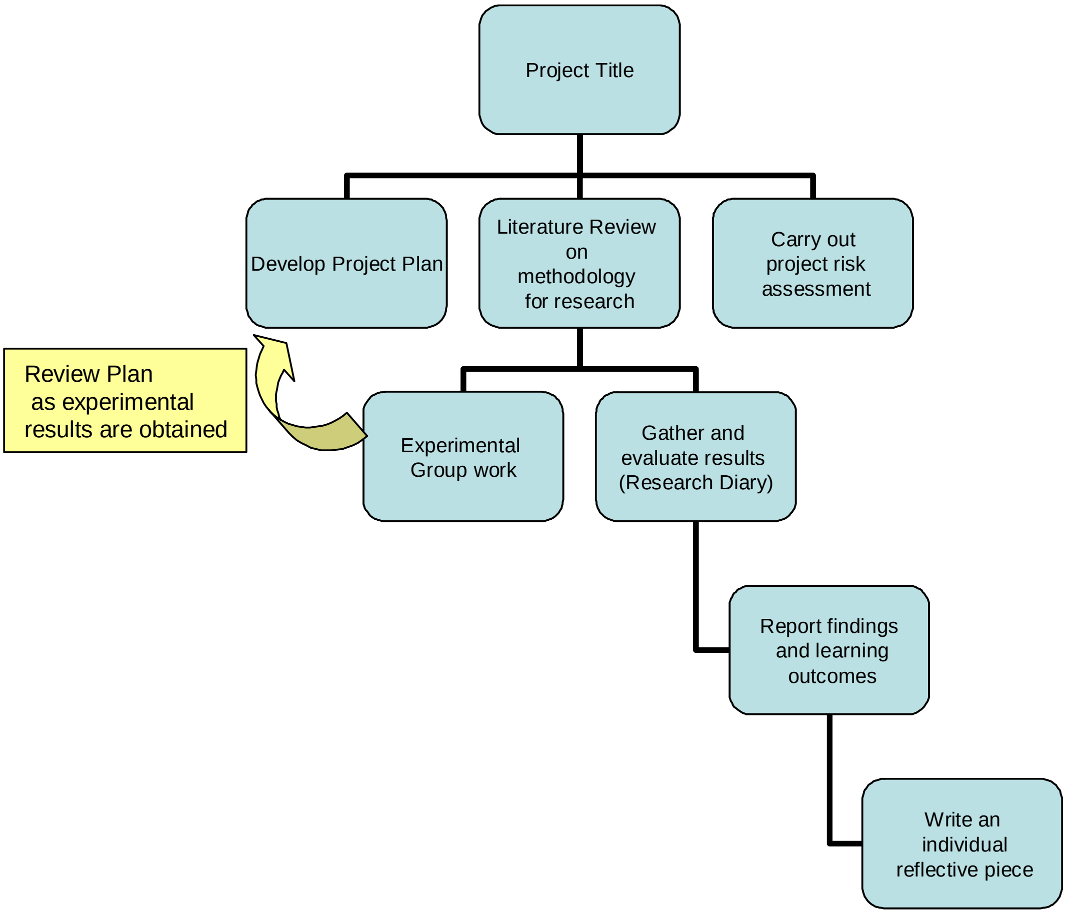
Student Group

The PBL mini-projects were implemented in place of traditional laboratory practicals for a module taken by a group of our Year 2 students studying for an ordinary degree in Physical and Life Sciences (Chemistry option). This degree is designated as a Level 7 degree (National Framework of Qualifications, 2006).

Implementation

Figure 1 shows the general project outline. Students were divided into small groups (3-4) and each group was assigned a member of academic staff as project supervisor.

Figure 1: Schematic flowchart outlining implementation of PBL mini-projects and requirements from students at each stage.



Groups were presented with a project title. The project supervisors could devise a project themselves or select from a list of provided titles (see Table 2). Details of some of these projects are provided in the Supplementary Material. Projects were devised so as to be at an appropriate level, with most of the required theory having being covered in lectures, or readily accessible to the students. The students were given a pre-project talk where the learning outcomes and project plan were explained to them. Each group then met with their supervisor for guidance on the project.

Table 2: Examples of PBL mini-project titles and their relationship to the syllabus.

Project Title	Topics Covered
“Do the forensic tools on CSI* really exist?”	TLC, microscopy, forensic methodology
“Investigation of sunscreen and sunglasses protection” (Abney and Scalletar, 1998)	UV-Analysis methods, Beer-Lambert Law
“Investigation of the calorific value of crisps”	Calorimetry, thermochemistry
“Who killed Mrs. Bernhard Schreider?” (Grove and Bretz, 2005)	Colligative properties, solubility, microscopy, flame photometry, chemical tests
“Can the active pharmaceutical ingredients in a range of analgesic products be extracted, separated and characterised?”	TLC, solvent polarity, recrystallisation, drug formulation
“Can the lipids in cheese be extracted and analysed?”	Saponification, TLC, extraction
“Fluorescent chemicals: analysis and applications”	Spectroscopy (UV-Vis and Fluorimetry), Beer-Lambert Law, Confocal Microscopy
“How are analyses of trace metals, dissolved oxygen and fluorine content in natural and potable water performed?”	Atomic Absorption, volumetric analysis, COD & BOD tests, Ion selective electrodes.
“What are the chemicals in cosmetics?”	Light microscopy, extraction methods, TLC, fluorescence

*CSI (Crime Scene Investigation) is a popular US television series dealing with forensic science.

One of the main aims of this initiative was to encourage student independence and ‘ownership’ of projects. Supervisors gave the groups an outline of the problem, in essence what the objective of the project was. Groups had to investigate what experiments they would need to do to complete the task. All groups were required to devise a project plan, do a short literature review on the topic and carry out a chemical risk assessment on materials they would be using. These were presented to the project supervisor before experimental work could begin.

Assessment

Students were required to keep individual project diaries for the duration of the project, which were used in the assessment of the projects. These were worth 40% of the individual’s mark. Supervisors looked for evidence that the student had kept records of background information gathered, together with references and had kept detailed records of their work in the laboratory. Importantly, we also looked for evidence that the students used both their background reading and experiences/results in the laboratory to modify or expand their experimental work as necessary to help with solving the problem. The project plan submitted at the beginning of the project counted for 15% of the mark. In this, we expected students to outline some of the initial experiments that they wished to carry out, and how they hoped those experiments would help to solve their problem. Risk assessments for any planned practical work were also submitted with the project plan. It is unfair at this stage of the project to expect a lot of detail, as these students were used to the 'recipe-style' labs, and one of the overall aims of the project was to encourage reflection on work completed at each stage, and subsequent modification of experimental procedures. On completion of the project each group was required to give a 15 minute PowerPoint presentation on their project, which was assigned an assessment weighting of 25%. The important criteria looked for were capability in presenting scientific data, along with of the ability to answer questions on their analysis, and to provide suggestions for further experiments/analysis. As this was a group presentation, coherence of the presentation was evaluated. The project statement, a summary and reflection by the student of their project work, was awarded 20%. These statements allowed students to comment on their experience of completing these type of laboratory classes, their experience on working in a group (together with a self-evaluation of their contribution to the group) as well as a reflection on the project and how they would approach it if given the same scenario again. These student reflections were refreshingly honest, and provided very useful feedback for evaluation of the PBL mini-projects. The outline of the assessment structure is shown in Table 3.

Table 3: Breakdown of assessment marks.

Element	Marks
Project Plan	15
Presentation	25
Reflective Project Statement (individual mark)	20
Project research diary (individual mark)	40

It should be kept in mind that the design of the assessment should drive the learning outcomes of the PBL mini-project (Biggs, 2002). On reflection, it would be a useful feedback exercise for the supervisor to identify the individual's strengths and weaknesses to each student in terms of their contribution to the project.

Evaluation

Evaluation of the effectiveness of the PBL mini-projects and extent to which they improved student learning was by means of post-lab questionnaire, examination of student reflections, staff interviews and informal feedback from students.

Results and Discussion

Pre-Experimental Work

All groups used the Internet extensively for several aspects of the project: to find information on the background to the projects; to find Material Safety Data Sheets (MSDS) data for risk assessments and, if possible, to find experimental procedures for their experiment! As reported by McGarvey (2004), students quickly realised that a certain level of critical evaluation of the material downloaded from the Internet was required, which in itself was a useful learning exercise. In several cases, they found that a textbook or reference book was a more useful source of information than the Internet.

Experimental Work

Experimental work began after about 3 hours (one session) of background research and project planning. During the initial practical sessions, most students found daunting such tasks as making up solutions, weighing out solids, or indeed any tasks that they attempted, as they weren't following direct instructions. Some students initially interpreted '*R*' and '*S*' phrases (risk and safety phrases) in the MSDS for the reagents being used without adjusting for quantity and the exposure involved. This made them appreciate the importance of considering these factors when interpreting and applying safety information in risk assessments. In the first few practical sessions, students were also very frustrated by the trial and error experiments or dry runs required for some projects. Also, some students were so used to the concept of recipe style laboratories that they would not have prepared any material prior to the laboratory practical. This was dealt with by telling students that the responsibility to produce an experimental procedure was theirs and hence they would have to spend their laboratory time devising the experimental work plan. Usually, these students had work prepared for the following week. However, mid-way through the study it became apparent that students were, in the main, taking control of their projects, and using their initial 'failures' to re-evaluate their project plan and devise better procedures. This emphasised the fact that students were beginning to think about whether experimental results obtained were useful to them and what role they had in solving the final 'problem'. This was undoubtedly one of the most positive aspects of these laboratories. The students kept a project diary, which they found very useful in this regard.

Student Evaluation

At the end of the projects, students were provided with feedback forms to allow them to give their views and reflections on the project. This questionnaire asked students to list five positives and five negatives, rank what they felt were difficult aspects of the project from a given list and respond to some 'Yes/No' questions on what they gained from the project. The details of these responses are listed below.

1. Positives and Negatives

Figure 2: 'Positives' and 'Negatives' perceived by students on completing PBL mini-projects.

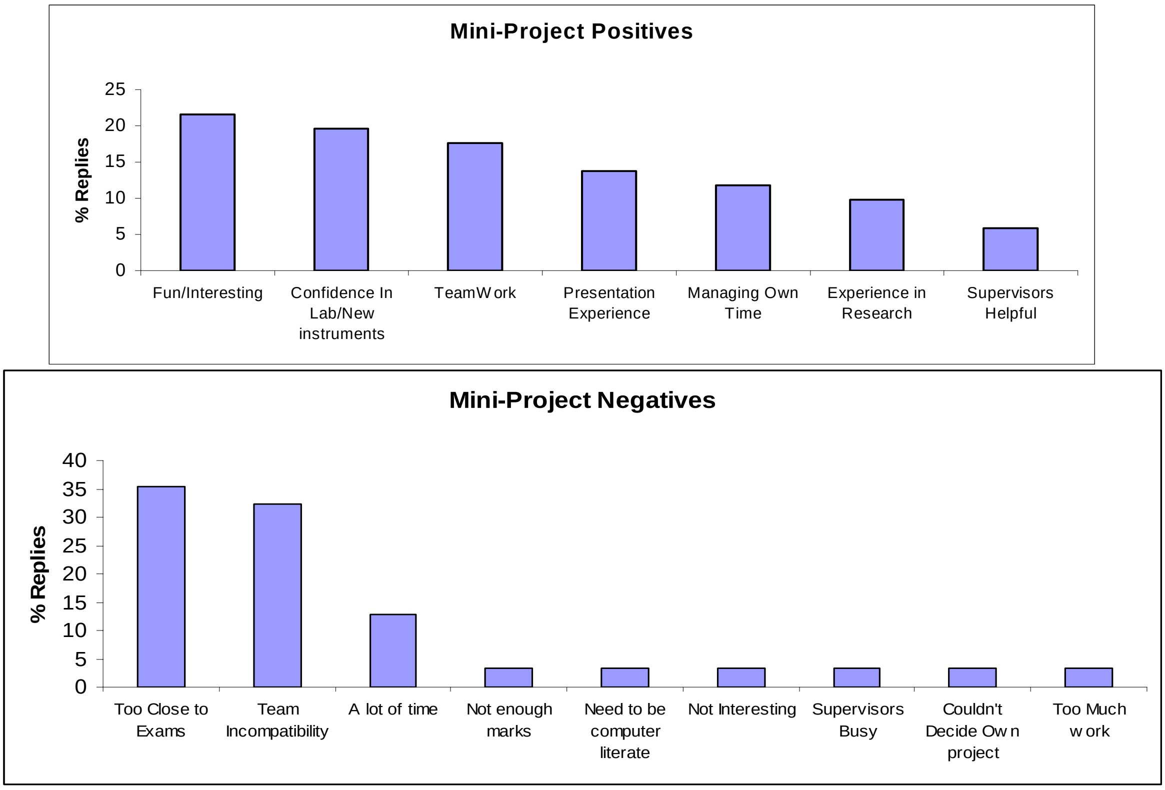


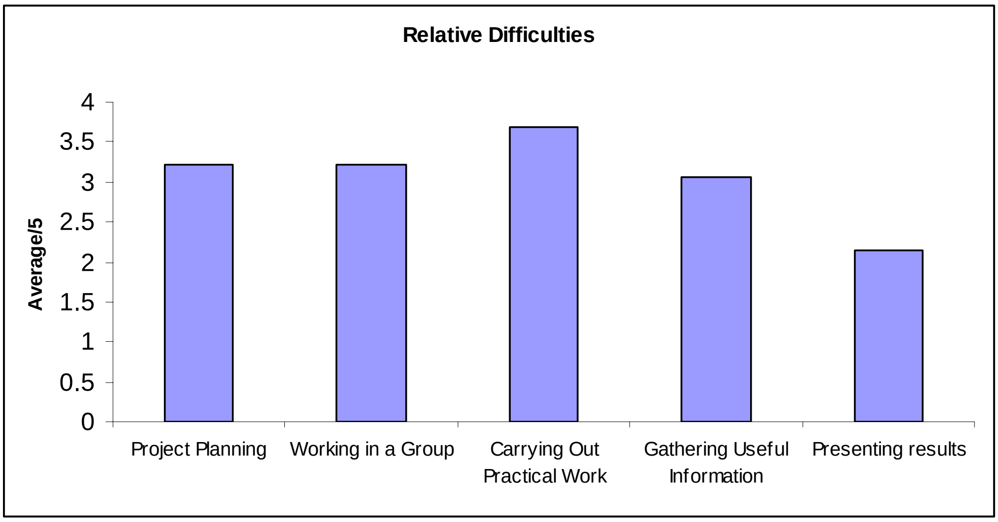
Figure 2 shows the positive and negative aspects of the PBL mini-projects in the opinion of the students. One of the most encouraging responses was that students found the projects 'Fun/interesting', seemingly having forgotten their initial frustrations with the projects. In addition, 'Confidence in the laboratory/use of new instruments' ranked highly, again a stark contrast to the situation observed at the beginning of the project. However, when asked in a separate question whether their confidence in the laboratory has increased, while almost all students (94%) answered 'Yes', there was still some reticence about how prepared they will be for their 3rd Year Individual Projects. This is attributed to a fear of the unknown, and we are confident that students do feel more at ease in the laboratory than they would having only completed traditional practicals. Indeed, as discussed below, we observed that classes who completed these projects settled in to their third year individual project much more readily than classes from previous years who had not.

Among the negatives, two featured predominantly. The first point, that the project was too close to the exams, is a fair criticism, and in future years we plan to run this module at the start of Semester 2 instead of in the second half of that semester. The second, '*Team incompatibility'* proved to be a major issue for some students, but it reflects a common situation that must be overcome in the real-life work environment. In future projects, we plan to use teams of mixed ability. In addition, this is the first time the students have undertaken a major project in a group. Future questionnaires will ask students to reflect in detail on their experience of working in a group.

2. Relative difficulties

For the relative difficulties question, (Figure 3) students were asked to grade on the scale 1–5 the extent to which they found a particular component of the project difficult. Carrying out practical work was perceived as the most difficult part of the project. However, we believe that this only emphasises the fact that students were really thinking about their practical work, and whether their experimental results were useful – which is the ultimate aim of laboratory work in science. Presenting results was, perhaps surprisingly, ranked as least difficult. Students were generally found to be very nervous and anxious about presenting. This had a positive side effect by generating general camaraderie among the class.

Figure 3. Relative difficulties encountered during a mini-project, on a scale of 1-5.



3. Student Comments

Student comments were generally positive. As already stated, team incompatibility and proximity to exams were the most contentious issues. Some of the student comments are listed below.

- *It was nice to have more time in the lab*
- *Got to use equipment we wouldn't normally use*
- *Learned to do more by myself without direct supervision*
- *Looks good on CV*
- *Better than writing up labs*
- *Change team members!*
- *It was nice working more closely with people from my class*

Students repeatedly stated that they used a wider range of equipment than they would normally use. In general, this wasn't really the case and the experiments students carried out were usually similar to the ones they would perform in traditional laboratory classes. What did become very clear is that students gained a much greater understanding of the principles and procedures for using particular instruments or carrying out specific experiments than they would normally do in traditional laboratory practicals (see staff comments, below). It is more interesting for students as they are working on a 'unique' project, as opposed to the traditional laboratory sessions where everyone does the same experiments. This new approach requires more time than traditional practicals. Nevertheless, we believe it reflects real-life problem-solving situations better.

Staff Evaluation of the PBL Mini-projects

We acknowledge that this project system placed an extra burden on our colleagues in relation to their supervision of groups. We were keen to examine if they felt the effort on their part had any extra benefits for the students. Some of the staff comments are listed below:

- *Students were planning their own experimental procedures instead of following a recipe*
- *Worked well, but would suggest a deadline for the project plan so that the experimental work is not unduly delayed*
- *Considerable support required initially, but as project progressed, students became more independent and took more ownership*
- *Found there was better engagement in the course in general*
- *Relies on goodwill of staff*
- *Would like to adopt this approach in other programmes*

The general feeling among academic staff involved was that the bulk of the work was involved in the initial stages – giving students the outline of the project, giving general guidance on how to proceed, assessing the project plan and help with general laboratory procedures. Some members of staff involved in teaching the students in lectures observed a greater enthusiasm among the class for chemistry and enhanced engagement generally after initiation of the PBL mini-projects. Tangible evidence of this is that the class attendance, which traditionally had declined slowly as the academic year progressed, increased after initiation of the mini-project programme.

To examine student understanding of their practical work and related theory after completing these labs, we discussed the impact of the PBL mini-projects with other members of staff assessing the students who have had many years experience in traditional style laboratories. Their comments indicated that, when compared to students who completed traditional 'recipe-style' practicals, students who completed these PBL mini-projects could describe why they were carrying out a particular experiment, what that experiment would tell them and why. In addition, understanding of the theory behind the laboratory work was assessed at the group presentation stage (in their ability to explain and answer questions), in the reflective piece by students, and in their project diary. Therefore staff had several opportunities to assess student understanding of the projects, and compare this understanding with students from previous years who would have completed "recipe-style" practicals. Another benefit worth considering was the class performance in their third year project. We observed that the students who had completed the PBL mini-projects in year 2 in 2004/5 adjusted themselves to the independent project in year 3 much more readily than was usually the case.

Sourcing Ideas

Given the success of this study, it is intended to continue with this PBL mini-project system in future years. The biggest preparatory task is sourcing suitable ideas for projects. Obvious sources are extensive laboratory descriptions in the primary literature (*Journal of Chemical Education*, *The Chemical Educator*), in laboratory textbooks (*Journal of Chemical Education Chemical Resources Shelf*) and on the Internet. We are currently developing several projects that are spectroscopy themed, which are being piloted at present. Details of these projects will be published following evaluation.

In order to implement these practicals on a wider basis, we have decided to eliminate the need for an advisory supervisor, and set up the laboratory sessions so that one laboratory supervisor can control all of the projects. To this end, we are currently developing and compiling some materials that outline the problems to be presented to the student together with support material (sample spectra, suggested pathways to solving problems) which will provide the laboratory supervisor with all of the material required to run the class.

Conclusions

Problem-based learning mini-projects have been used successfully as an alternative laboratory learning experience with second year Chemistry undergraduates over two years (2004/5 and 2005/6). The programme complements the existing traditional laboratory approach and provides students with stimulating 'real-life' problems (PBL mini-projects) to tackle in small groups. Increased class participation and engagement and improved class morale were observed as a result of this change in approach. This observation was confirmed by feedback obtained in an evaluation survey that the students completed. It was also the opinion of the authors that the students were better prepared for their individual research project in their third year as a result of participating in the PBL mini-projects the year before.

Note added in proof: after the submission of the paper the authors became aware of another example of a similar implementation of project-based work in physical chemistry (Tsaparlis and Gorezi, 2007).

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Educational research

Students’ perceptions of when conceptual development occurs during laboratory instruction

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Abstract: Seventeen first year students experienced the first semester of laboratory instruction of a year-long sequence of general chemistry in a problem-based format, followed by a semester in which the laboratory portion of the course was taught in a traditional manner. At the end of the second semester all the students were administered a questionnaire regarding their perceptions of the different laboratory instructional environments. Fifteen of the seventeen students participated in semi-structured interviews. Analysis of the surveys and interview transcripts showed that seven of the students interviewed believed that the problem-based environment helped them better understand course concepts relative to traditional laboratory instruction, whereas the same number found them to be equally effective. Further analysis of the interview transcripts revealed that different students perceived conceptual development to be occurring at different times during the various types of instruction. For problem-based learning, conceptual development was maximized during the activity while in the laboratory. In the expository environment, however, it was maximized outside of the laboratory, after the experiment had been completed. Both the instructional and research implications of this phenomenon are discussed. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 140-152]

Keywords: First-year undergraduate/general, laboratory instruction, problem-based learning, expository learning, phenomenography

Introduction

A clear and ever-present concern among science educators is what can be done with science laboratory instruction to improve student learning. Throughout its history, the science laboratory has been recognized as a unique instructional environment (Schwab, 1962; Hurd, 1969; Hofstein and Lunetta, 1982; DeBoer, 1991) and, while it shares many of the same goals and objectives for student learning as general science instruction, this unique structure allows students to engage in processes of investigation and inquiry in a manner not unlike actual scientists (Hofstein and Lunetta, 1982). As a result, this mode of instruction carries with it the expectation that student learning will be more meaningful than with other forms of science instruction (e.g., didactic lectures, demonstrations, museum exhibits, etc.). Unfortunately, as it is traditionally structured, science laboratory instruction has the enduring reputation of failing to live up to this expectation (National Research Council, 2006). As Roth (1994) succinctly put it, “*although laboratories have long been recognized for their potential to facilitate the learning of science concepts and skills, this potential has yet to be realized.*” (p. 197)

Consequently, throughout its history, alternative styles of instruction have been utilized in an effort to improve student learning. Domin (1999), for example, described, in addition to the traditional expository instructional method, three other commonly used styles of instruction: discovery (guided-inquiry), inquiry (open-inquiry), and problem-based. Although these other styles are often lumped together under the single rubric of non-traditional instruction, each is distinct and situates the student within a unique learning environment.

It is my contention that the perennial failure of science laboratory instruction to achieve its recognized potential stems from a lack of in-depth understanding regarding the constraints these different laboratory instruction styles impose upon the instructional environment and on the learning process. This study, therefore, attempts to partially alleviate this deficiency by addressing the perceptions students have as to how two different instructional styles, expository and problem-based, constrain conceptual development. In this paper, I discuss how such investigations can provide a deeper insight into how different laboratory instruction styles constrain the learning process. The implications from this affect not only the practical aspect of science laboratory education, but research in this area as well.

Background

Science laboratory instruction: traditional versus non-traditional

Science laboratory instruction is often presented as a dichotomy of styles, the exact label usage varying with the times. The most predominant manner of instruction is the traditional style (also commonly referred to as expository, deductive, or cook-book). This style relies almost exclusively on laboratory manuals to create a situation where students perform the activity by following a prescribed procedure to experience a pre-determined outcome. The other is the non-traditional style (also called student-centered, inductive, or inquiry). This, non-traditional, side of the dichotomy is actually a collection of different styles often grouped together because they share the same superficial characteristic of not being the traditional style.

Dichotomies are a fundamental attribute of human reasoning. They are a useful means of imposing order on something that is not well understood (Levi-Strauss, 1969). Dichotomous thought, however, suffers from two significant shortcomings. First, dichotomies are often based on superficialities; consequently, the understanding derived from the dichotomy is also superficial. Second, there is a propensity to exalt one element of the dichotomy over the other, resulting in one element being strongly advocated while the other is disparaged. In the context of science laboratory instruction this is expressed in the following mind-set: there exists a single best style of laboratory instruction (inquiry) and comparative studies are needed to simply confirm what is already known.

Comparative investigations between different styles of laboratory instruction are decades old and, despite claims to the contrary (Spencer, 1999), have yet to establish the supremacy of one style of instruction over another. For example, a meta-analysis conducted by Rubin (1996) found significantly improved student learning with non-traditional laboratory instruction relative to traditional laboratory instruction. Babikan (1971), on the other hand, found traditional laboratory instruction more effective than discovery learning with respect to overall achievement. Furthermore, a meta-analysis by Lott (1983) determined essentially no difference in overall student learning between the two approaches, although different styles did prove to be superior with respect to achieving specific learning outcomes.

Focusing on specific learning outcomes, however, also gives mixed results. Whereas Rubin (1996) found non-traditional forms of instruction superior in every respect: content knowledge, reasoning ability, attitudes, and manipulative skills, Lott's (1983) analysis showed non-traditional instruction to be superior with only content knowledge and understanding the process of science. The learning outcomes of 'problem-solving skills' and 'applying what has been learned' showed effect sizes favoring traditional instruction.

Blosser (1983, 1988), citing a number of methodological defects, cautions the reader against placing too much credence in comparative research studies. Such methodological defects include inadequate research design, inappropriate statistical treatment of data, small sample size, limited amount of time gathering data, inappropriate assessment instruments, and single studies with no follow-up of those who participated in the study. She stresses that comparative studies frequently are first-attempts at research conducted by graduate students pursuing a doctoral degree. And, she adds (Blosser, 1983), while many comparative studies describe the experimental treatment (usually non-traditional instruction) in great detail, the "*readers are often left to their own devices to determine what took place in the traditional approach* . . . ." (p. 167). This concern was also raised by Lott (1983).

An alternative taxonomy for science laboratory instruction

The inadequacies of the dichotomous paradigm are summed up very nicely by Reigeluth (1987) who, in his analysis of comparative research studies, stated the following:

> "*As with other disciplines, initial research on instruction tended to focus on very general, vague variables, such as discovery versus expository methods, and lecture versus discussion formats. However, in that research two different discovery methods often differed more than an expository and a discovery method differed, making it impossible to identify reliable causes of superior outcomes*." (p. 3)

A deeper understanding of the instructional dynamics associated with science laboratory instruction can be achieved by abandoning the current dichotomous way of thinking about science laboratory instruction in favor of a taxonomy where the non-traditional label is recognized as a collection of individual instructional styles. That is, non-traditional laboratory instruction is more usefully construed as consisting of three distinct instructional styles: discovery (guided inquiry), inquiry (open-inquiry), and problem-based (Domin, 1999). Each of these styles is unique, and distinguishing one from another, as well as from the traditional style, is achieved through a set of three descriptors: the approach taken, whether the outcome is known or unknown, and the origin of the procedure (Table 1).

Table 1. Descriptors for the laboratory instruction styles in Domin's taxonomy.*

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

* From Domin (1999).

The approach taken in a science laboratory activity is characterized as being either inductive or deductive. In an inductive approach, data is collected and general principles are derived from analysis of the specific phenomenon observed. The inductive approach is unique to discovery and inquiry style activities and is associated with initial concept formation. In contrast, the deductive approach proceeds from the opposite direction. Students are first exposed to the general principle, and then experience a specific episode in which the principle is evoked. In a deductive approach, the activity is intended to further conceptual development of something learned previously. Traditional expository instruction and problem-based activities extensively use a deductive approach.

Students can begin a laboratory activity either by knowing what constitutes the end of the experiment or they can come to that realization as they work through the activity. In the former, the outcome is regarded as predetermined, and in the latter it is undetermined. Expository, discovery, and problem-based activities are characterized as having pre-determined outcomes (in a discovery-type activity, the outcome may already be known to the instructor, but not necessarily to the students; for them, the outcome could be undetermined). In an inquiry activity, the specific outcome is initially undetermined. The students begin without knowing the specific concept or principle that will be invented or discovered. It remains undetermined until the students are well into the activity.

Finally, there is the procedure. In the cases of expository and discovery activities, students are given the procedure to follow. Usually, it is part of an activity within their laboratory manual, but it may also be supplied to them as a handout or be provided directly from the instructor. Regardless of how it is presented, the students are expected to perform the activity as it is prescribed in the procedure. In contrast, in inquiry and problem-based activities, the students are responsible for generating their own procedure.

Traditionally, comparative research studies have generally assumed that there is a single best method of instruction, and the purpose of the research is to empirically establish one style as being superior. These research findings would then be used as the basis for advocating a particular style of instruction as *the* manner of instruction (Spencer, 1999; Monteyne and Cracolice, 2004). Adopting a taxonomy of four styles instead of two immediately does away with the notion of a single best style of instruction, for it is hard to identify any single style as being the best at achieving every possible learning outcome. In fact, a more useful mind-set is to presume that there are at least four different styles of instruction, none of which is the best at achieving all of the desired outcomes. Instead, it is presumed that the different styles possess their own unique strengths and weaknesses and constrain the learning environment in different ways. Different styles, therefore, should be better at facilitating the fulfillment of different outcomes. Research, then, should be conducted not to determine which style is the best, but rather to ascertain the different constraints each style imposes upon the learning environment. Through a better understanding of the dynamics and constraints associated with each style a more effective laboratory curriculum can be developed.

As stated earlier, studies pertaining to laboratory instruction styles have focused predominantly on determining which of two different styles is a better form of instruction. Comparison studies for the sake of better understanding instructional constraints are uncommon. One example, a study conducted by Shepardson (1997), compared student thinking processes exhibited in an expository environment to those exhibited in an open-inquiry environment. Because the former utilized primarily a deductive approach and the latter an inductive approach, differences between the two should be expected. This is just what Shepardson found; the thought processes exhibited by students in the expository laboratory tended to relate more to procedural issues, whereas student thinking in the open-inquiry environment related more towards data analysis and making sense of the results.

Purpose

In their most recent analysis of the laboratory in science education, Hofstein and Lunetta (2004) advocated more intensive research on the effect of science laboratory instruction on, among other things, the development of students' conceptual understanding. They stated that "*to acquire a more valid understanding . . . science educators need to conduct more intensive, focused research to examine the effects of specific school laboratory experiences and associated contexts on students' learning. The research should examine the teachers' and students' perceptions of purpose, teacher and student behavior, and the resulting perceptions and understandings (conceptual and procedural) that the students construct*". (p. 33)

The purpose of this study is to understand student conceptual development better in the context of science laboratory instruction. It involves a post-hoc analysis of student perceptions of learning in both problem-based and expository laboratory environments. However, it is not a comparison study in the sense of trying to determine if one style is better than the other; rather, it is a means of elucidating the constraints the two styles of instruction impose upon the conceptual development of the students. The presumption is that a better understanding of how students perceive the two environments with respect to facilitating conceptual development will offer valuable insight towards the development of more effective laboratory instruction.

Theoretical framework

This study was conducted within the theoretical framework of phenomenography (Barnard et al., 1999). That is, it attempted to elucidate from the students their understanding of their experiences within a general chemistry laboratory curriculum. Phenomenography takes the theoretical stance that different people will not experience a given phenomenon the same way (Orgill, 2007). Rather, it assumes that there are a finite set of ways in which different people experience a given phenomenon (Marton, 1986). The role of the researcher in a phenomenographic study is to describe the variations in understanding of a set of participants experiencing a particular phenomenon to establish a collective meaning (Barnard et al., 1999). This is achieved exclusively through participant self reports, primarily through interviews (Orgill, 2007). These interviews may or may not be supplemented with other forms of self reports such as surveys. Besides being essential to phenomenographic studies, self reports are considered a common method of data generation for a number of different types of qualitative inquiries (Lawrenz et al., 2003) and possess the following identified strengths (Fraser and Walberg, 1981; Huffman et al., 1997):

- Students' perceptions are based on the complete experience, not just on a limited number of observations.
- The perceptions of all the students participating in the self reports can be pooled.
- What the student perceives may be of more significance than what an outsider would observe.
- Student perception data can be analyzed to provide information about the perceptions of different students within the same class.

Methodology

Design

Data collection took place at a small rural two-year college in the Midwestern part of the United States. Seventeen students participated in two semesters of a first-year undergraduate general chemistry course designed for science majors. Both semesters included a laboratory component as part of the curriculum; one semester comprised entirely of problem-based activities, and the other expository activities. The topics covered within the laboratory activities during both semesters are best described as typical for a general chemistry curriculum (titrations, gas laws, Hess's law, etc.). However, each semester had a different laboratory instructor. The author of this paper served as the instructor for the problem-based semester and had the students work in groups of three or four. The instructor for the expository semester had the students work in pairs.

The first semester employed the problem-based format. The pre-lab activity consisted of students being given a problem statement one week prior to working on the problem in the laboratory (see Figure 1 for an example). As part of the problem statement, the students were directed to read pertinent chapters of the course textbook and develop a procedure that would allow them to solve the problem. During the in-lab activity, students worked cooperatively on developing a viable procedure. All procedural information and data were recorded in laboratory notebooks. While the students were working in the laboratory, the instructor was available to interact directly with the small groups. These interactions consisted of answering questions, addressing safety issues, demonstrating how to use specific equipment, and utilizing a Socratic method to guide the students toward a viable solution path. The post-lab activity consisted of writing individual laboratory reports.

Figure 1. An example of a problem statement given to students during the fall semester.

Analysis of a Calcium Supplement

Calcium, in the form of calcium phosphate, makes up a large part of the mineral matter of bones and teeth. An inadequate supply of calcium in the diet of growing children results in poor skeletal development. Pregnant women who do not consume enough calcium may experience a softening of the teeth and bones. Older women need a large amount of calcium in the diet to offset calcium loss in bones, a condition known as osteoporosis.

A well balanced diet rich in dairy products and leafy vegetables usually provides an individual with all the calcium they will need. However, it is quite often the case that people are unable to supply enough calcium through their diet to satisfy their needs. Because of this, calcium supplements are available at many drug and health stores. The calcium in these tablets is usually in the form of a salt: typically calcium carbonate or calcium lactate.

Your group will be given a calcium supplement in the form of $CaCO_3$. Your project will be to determine the mass of Ca^{2+} in a single tablet of the calcium supplement. Your value must contain at least 3 significant figures. You will have two lab periods to complete the activity.

Make sure you have read Chapters 1 - 4 of your text before coming to lab next week.

The laboratory activities during the second semester utilized an expository approach. The experiments came from a commercially available general chemistry laboratory manual and each activity conformed to the following traditional instructional format: pre-lab questions pertaining to the methodology and theory behind the activity, a procedure to follow in order to complete the activity, and post laboratory questions which had to be answered and submitted as part of a written laboratory report. Before each activity, the instructor held a class discussion to go over safety concerns and to demonstrate the proper use of the equipment being used that day.

Procedure

Students were informed in the middle of the fall semester that the next semester there would be a change in the manner in which laboratory activities would be addressed. Instead of following a problem-based format, the style would be expository. They were asked to pay attention to the differences between the two styles and, if willing, communicate their perceptions during semi-structured interviews. At the end of the second semester all the students completed a survey regarding their laboratory experiences (see Figure 2). The surveys were anonymously completed without either instructor being present.

Fifteen of the seventeen students (seven women and eight men) volunteered to participate in interview sessions with the author during the last week of the spring semester. The interviews were conducted on a one-to-one basis between each participant and the researcher. The interviews were semi-structured. That is, the participants were asked to answer in more detail the questions that appeared in the survey, but the researcher frequently asked additional questions that arose during the participant's response to the survey questions. Each interview was audio-taped and transcribed.

Figure 2. Survey questions given at the end of the spring semester.

Laboratory Evaluation

The laboratory component of this course differed from what you experienced last semester. This semester's lab style is usually referred to as a more traditional form of instruction, whereas the fall semester style is referred to as problem-based. Because you had the unique opportunity to experience both styles of instruction within a single academic year, your opinion of these two methods is very valuable.

Please take some time to complete the following survey and return it to your course instructor. The survey is confidential and should be anonymous (please do not write your name on the survey). Your cooperation and input is very much appreciated.

For each set of statements, indicate which best represents your opinion of the traditional lab style (T) and which best represents your opinion of the problem-based style (P).

1. ___ a. I learned a lot of new chemistry principles in this lab.
___ b. I didn't learn anything new from this lab.
___ c. I didn't learn anything new from this lab, but it did help me develop a better understanding of the concepts presented in lecture.
2. The topics we addressed in lab were . . .
___ a. well beyond our understanding (too hard).
___ b. well below our level of understanding (too easy).
___ c. hard enough to be challenging, but not impossible (just right).
3. The topics and/or problems we addressed coincided well with the material we were learning in lecture.
___ a. agree
___ b. disagree
___ c. don't know
4. The number of people I worked with in lab was . . .
___ a. too large.
___ b. too small.
___ c. just right.
5. The lab format provided me with a better understanding of what it is like to do real science.
___ a. agree
___ b. disagree
___ c. don't know
6. Given the choice, in the future would you prefer the traditional style of instruction or the problem-based style of instruction you had during the fall semester. Why?
7. Please comment on what you liked, did not like, and what you would change about both styles of laboratory instruction.

Results and discussion

Students' preferences

Originally, it was expected that the analysis of the collected data would lead to the identification of preferences students had toward the instructional environment. Such data would help the instructor make more informed decisions as to how the laboratory curriculum should be structured to better facilitate learning. The results of the survey and interviews showed that seven of the fifteen students perceived the problem-based laboratory to be a better learning environment, and another seven felt they were equally good, but in different ways. Only one student preferred an expository laboratory curriculum.

Students felt more cognitively engaged while performing an activity in a problem-based environment than in an expository environment. Statements such as "*you have to think about* *how you are going to conduct experiments*" and "*it allows more creativity*" are representative reasons students communicated in the surveys and interviews for preferring problem-based over expository instruction. The most cited reason, however, for favoring problem-based instruction was the cooperative approach employed. Because this was not a controlled factor for both styles of instruction, it cannot be certain if it is the high level of cognitive engagement associated with problem-based learning that made it more appealing, or students simply preferred to work in groups. This, and the possibility of students feeling pressured to say things that they think would please the instructor, severely compromise any conclusion drawn regarding the preference of one style of instruction over another.

Conceptual development

A critical attribute of qualitative research is the richness of the data set, which allows for the emergence of themes not originally considered during the development of the study, what Patton (1990) describes as "*the fruit of qualitative inquiry*" (p. 14). The original working hypothesis for this study was that students would have a clear preference for one style over the other. This was true for 53% of the students interviewed (seven preferring problem-based and one preferring expository). The other 47%, however, held no preference for either style. Although this sub-set of participants held no preference, it was clear that they did not hold identical perceptions of both instructional styles. During the analysis of student survey responses and interview transcripts it became evident that the students perceived the two environments differently with respect to facilitating conceptual development. This is reflected in the following interview exchange:

> I (Interviewer): *"Did any style help you learn the concepts better?"*
> P (Participant): "*Learn the concepts better? I can't really, I think I would say each one helped me learn the concepts. In different ways, but I would say both of them."*
> I: *"How were they different?"*
> P: *"The first one [problem based] took a little bit more figuring out. Whereas the second one* [expository], *uh, just basically took reading, consuming knowledge. Basically what they told you."* (participant 12, interview)

Other students were able to articulate a temporal dimension as being a critical difference between the two styles in promoting conceptual development. For example, the following survey statement indicates that this student perceived the traditional laboratory as an environment with low cognitive engagement and suggests that with expository instruction understanding develops primarily outside of the laboratory:

> "*I think that the 'cook book' lab style [expository] is a little boring, but for a student that had no background whatsoever of chemistry it might be a better start . . . . I liked the fact that no time was wasted. You did what you had to do and you were done. I didn't like the fact that you were not really challenged at the experimenting time, but on certain days I was not in the mood to be challenged so I could think about the results at a later time when I was ready to.*" (anonymous, survey response)

Expository laboratory activities are well-known by both instructors and students as capable of being performed with little preparation or engagement on the part of the student. If the student is 'not in the mood' to learn at that time, he need only go through the motions and collect the data. Later, when (if) he feels up to it, he can try to understand what the lab activity was all about.

The idea of conceptual understanding occurring outside of the laboratory after the activity has taken place is further supported by comments from other students:

> I: "*Did any style help you learn the concepts better?*"

> P: *"In the second semester [expository] . . . I mean, I don't, I would really have no understanding until weeks afterwards of what we did."* (participant 15, interview)

Another student stated,

"The cook-book [expository], I really didn't get much understanding . . . If I did, you know and it tended to be well after the fact. Maybe, there may have been a problem that paralleled the lab in the book, perhaps." (participant 10, interview)

In this particular example, understanding for this student deepened when she was able to associate what was done in lab with another part of the course, in this case solving textbook problems. Additional exposure to the material at a later time facilitated conceptual development.

Students' perceptions were very definite as to when they began to understand material covered in the laboratory. In the expository environment, understanding developed outside of the laboratory after the activity had taken place. For some, it occurred by working out problems related to the material covered in lab; for others, it occurred while writing the laboratory report:

> I: *"I think I understand. Now, . . . which gave you a better understanding of the chemistry concepts?"*
> P: *"Yeah, but I could go without it you see. You know just going in and doing the stuff without it being a problem. Solving the problem, just gives you a fresh look."*
> I: *"Does that come from reading the lab experiment before or while you are doing the lab? The lab manual, did that help you understand?"*
> P: *"Uh, yeah doing lab you learn. A new lab . . . reading it before. I could understand. The traditional lab learned a lot more, especially the lab reports. I went way more in-depth the second semester."* (participant 2, interview)

Some students indicated that in an expository environment they felt the most significant part of their understanding occurred after the activity, when they had time to reflect:

> I: *"How about the spring semester"* [expository]?
> P: *"That was uh, obviously easier to know what you were doing as far as procedure again, because it was all cook-book. It was easier to figure out. Actually, you didn't even have to think about it, you did what it said and after you could reflect on what you just did and put it all together, after it was all done, after what has happened. And there was explanations as far as what chemical equations are pertinent to the experiment that would have been missed in the problem-based style."* (participant 12, interview)

Other student responses referred to being physically present in the laboratory, actually doing the activity, as a necessary condition for learning in a problem-based environment:

> I: *"Do you think you could complete a lab experiment from either semester without having to go through lab"* [inaudible].
> P: *"Yeah, the spring semester* [expository] *you could probably do it, just by reading the directions, but the fall semester* [problem-based] *you had to actually go to the lab."* (participant 13, interview)

Regardless of the style of instruction employed, students need an opportunity to think if understanding is to develop. Thinking engages the students. They reflect on what they have experienced, identify inconsistencies between their experiences and what they already know (cognitive dissonance), and attempt to alter their conceptual scheme in order to accommodate the new experience. Without students being provided the opportunity to think, their new knowledge stays rote knowledge with no further conceptual development. All instructional activities require a time for thought and reflection if the learning is to be meaningful. For problem-based and expository laboratory instruction a key difference is when the students are most likely to think.

Students partaking in a problem-based activity were most cognitively engaged while they were in the laboratory conducting the activity. This is indicated by the use of the terms ‘frustrating’ and ‘challenging’ to describe the problem-based activities. These terms indicate that students were, at some point in the lab, in a state of cognitive dissonance which they had to think through to reestablish cognitive equilibrium. These adjectives were never used to describe any expository laboratory session. Rather, terms such as ‘boring’, ‘repetitiveness’, and ‘robotic’ – terms more closely associated with low levels of cognitive engagement – were used by the participants to describe the expository activities. This does not mean that students did not learn from the expository lessons; many felt that they did. It simply means that the two styles of instruction differ as to when the students perceived themselves to be more cognitively engaged. Whereas students perceived themselves to be more cognitively engaged during a problem-based activity while they were in the laboratory, in an expository lesson higher levels of cognitive engagement were perceived to occur outside of the laboratory, after completing the activity, when the students had an opportunity to reflect on the material.

Conclusion

This study expands the scope of knowledge related to how two styles of laboratory instruction constrain the learning process. Specifically, it identifies a fundamental difference between expository and problem-based instruction with respect to fostering cognitive development. Both styles utilize a deductive approach, thus both should be capable of affecting conceptual development. This is supported by the finding that 47% of the participants found the two styles to be equal with respect to helping them understand pertinent concepts better. With respect to conceptual development, the distinction between them appears to be temporal in nature. In the problem-based format, the participants were more aware of conceptual development occurring while they were in the laboratory, engaged in the problem-solving activity. For expository instruction, the participants perceived conceptual development to occur outside of the laboratory, after completion of the activity. This finding has implications not only for chemistry teaching, but also for research pertaining to science laboratory instruction.

Teaching implications

Effective laboratory instruction requires engaging the minds of the learners so that they can think about the instructional episode in such a way as to evaluate their understanding in relation to what is experienced. This involves creating opportunities for reflection (Tien et al., 2007), as well as argumentation (Driver, 1995; Osborne et al., 2004). Both are necessary, and to be effective they must be explicitly linked to a specific laboratory experience (National Research Council, 2006). When to implement them for maximal effect depends on the instructional style used.

In the case of expository instruction, the participants in this study perceived understanding to develop outside of the laboratory, after the activity was completed, when they had the opportunity to reflect on what they had done. This included during the writing of the laboratory report or doing end-of-chapter problems that related to specific concepts addressed during a specific laboratory activity. For expository instruction, the post-lab activity is crucial for conceptual development; it may be the only opportunity the students get to reflect on what was done in the lab. During the actual in-lab activity, students’ minds are engaged not on the underlying principles, but on the procedural aspects of the activity. The cognitive demand placed on working memory in trying to understand and follow the given procedure allows for little, if any, cognitive resources to be devoted toward thinking about the concepts involved in the activity. This is supported by past research. Pickering (1987), for example, found that trying to increase the cognitive engagement of the students while they were in an expository laboratory environment collecting data interfered with their ability to complete the activity. Pickering rationalized this in terms of a hypothesis proposed by Johnstone (1984) of a working memory overload. That is, there is too much information within the traditional laboratory manual which hinders the students' ability to separate important information from extraneous material. These findings are further supported by the work of Mulder and Verdonk (1984), who found that students in an expository environment were rarely capable of learning both manipulative skills and the corresponding theory simultaneously.

Post-laboratory opportunities to reflect on the laboratory experience can be presented a number of ways, and should prove beneficial for conceptual development as long as the students can explicitly relate the post-lab activity to the laboratory experience. These can include, but are not limited to, the following: (1) post-lab questions from the laboratory manual, (2) end-of-chapter problems from the textbook, (3) structured reflection during the lecture component of the curriculum so that students can understand how the material relates to a previously completed laboratory activity, and (4) writing laboratory reports. Research by Keys (2000) has shown that the process of laboratory report writing can stimulate science learning provided that "*the students actively deliberated and reflected on science content as part of the writing process itself*." (p. 687)

Argumentation strategies are not typically associated with expository laboratory instruction. This is a deficiency that must be overcome, and as the results of this study suggest, they should be implemented as some sort of post-lab activity. This could be achieved through whole-class discussions immediately upon completion of the activity, in a similar fashion to what is advocated in discovery-type activities (Ricci and Ditzler, 1991). Alternatively, argumentation can be incorporated with reflection as part of an in-lecture activity where the instructor leads a discussion about a particular laboratory episode. Students would not only reflect on what was done, but would also develop and communicate a specific position pertaining to the underlying principles that overlap the laboratory episode and the current lecture topic.

Post-laboratory opportunities for reflection and argumentation are also beneficial in problem-based instruction. However, the findings from this study suggest that a maximum effect will be achieved when opportunities for these are presented during the in-laboratory activity as the students attempt to solve the problem. In a problem-based activity, students work cooperatively to develop a procedure that will allow them to solve a problem. This involves a high level of cognitive engagement where the students oscillate repeatedly between episodes of reflection and argumentation as they construct their own ideas on how to solve the problem; develop arguments to convince not only their peers, but also the instructor of the soundness of their idea; and evaluate the suggestions and arguments of others.

Research implications

In light of the results of this study, past studies comparing the expository approach to other laboratory instructional methods must be re-evaluated. For any comparative study to have any contemporary relevance, it must be established that the students in the expository group were provided with the full gamut of instruction: a pre-lab to prepare them for the laboratory activity, the actual laboratory experience, and a post-lab activity that provides an opportunity for both reflection and argumentation. Failure to include any of these components seriously compromises the validity of a comparison study. The format utilized by Suits (2004) that provides the instructional approach, pre-laboratory preparation, type of experiments utilized, experimental work, type of post-laboratory activity, and method of assessment for both the control and treatment groups should be standard in any comparative study.

This study strongly suggests that expository and problem-based instruction constrain the process of conceptual development differently. Further research is needed to expand our understanding of other differences between laboratory instruction styles with respect to the constraints they impose upon other learning outcomes. Additionally, research should be undertaken to investigate the mutability of these constraints. For example, is it possible to restructure expository instruction so that student cognitive engagement is maximized during the laboratory activity instead of during the post-lab activity? Some research has been done in this area with some rather interesting results. Cox and Junkin (2002), for example, found that embedding conceptual questions into the procedure of an expository laboratory activity and allowing students to discuss these questions in a cooperative environment during data collection significantly increased student gains on tests of conceptual understanding. Further research in this area is strongly needed.

Finally, science educators and researchers must be aware that each style of laboratory instruction is different and possesses different constraints that will invariably affect how and to what extent specific learning outcomes can be achieved. Each style, therefore, must be evaluated in light of these constraints. Before certain styles of instruction are written off as being ineffective, educators need to be certain that the activities are being implemented in a manner that conforms to the constraints imposed by the employed style. This can only be done by better understanding the subtleties associated with each instructional style.

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Educational research

Matching Higher-Order Cognitive Skills (HOCS) promotion goals with problem-based laboratory practice in a freshman organic chemistry course

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Abstract: The development of students' higher-order cognitive skills (HOCS) is central to the problem-based component of a freshman organic chemistry course. HOCS within science education is strongly connected to critical thinking (CT) and problem solving (PS), and often manifested by question asking and decision making. The laboratory, if utilized effectively, can be fertile ground for HOCS/PS development and CT advocacy. The ultimate goal is to develop a student culture having a broader, deeper, and more interconnected level of scientific literacy, conceptual understanding, and the contextual applications of knowledge. The concluding 6-hour laboratory session of the course 'Introduction to Modern Organic Chemistry' is presented here as an example of problem (not exercise) solving, and is proposed as a model for a 'HOCS-promoting'—CT/PS-requiring laboratory activity in organic chemistry teaching. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 153-171]

Keywords: Problem-based Laboratory learning, Problem solving, Critical thinking, Levels of knowledge, Situated cognition, Contextualized learning

Introduction: background, rationale and purpose

This paper deals with the systematic integration of three components involved in chemistry education in the context of the development of students' HOCS: problem solving, critical thinking and laboratory practice. The problem-based laboratory component of a one-semester freshman organic chemistry course, 'Introduction to Modern Organic Chemistry' provides a vehicle for research and an experience-based model for laboratory practice targeted to promote students' HOCS, particularly the bridge between problem solving and critical thinking.

A dominant component of the current reform in science education is a purposeful effort to develop students' higher-order cognitive skills (HOCS) of question-asking, critical thinking (CT), system thinking, decision making and problem solving (PS), as opposed to 'traditional' algorithmic-based lower-order cognitive skills (LOCS) (Zoller, 1993). This means a paradigm shift from the prevalent algorithmic teaching to 'HOCS learning' (acquiring the capabilities of *evaluative thinking* and transfer) and HOCS-promoting assessment methodologies leading to improved student PS capabilities (Zoller, 2000). This shift requires teaching and learning which take PS well above the level of algorithmic manipulation, into the realm of creativity, thus combating the common feature of traditional school science that all problems have a unique correct solution (Wood, 2006). Indeed, instruction in thinking skills was found both to improve academic performance and to enable students to become better problem solvers in other situations in and outside school

(Whimbey, 1985). Furthermore, instructional strategies incorporating cognitive activities that involve both knowledge and skills bases were found to be effective in assisting students to develop their CT and PS skills (Lyle and Robinson, 2001; Taconis et al., 2001).

Many educators perceive the development of learners' CT as one of the most important goals of education at all levels, particularly in the context of HOCS-promoting learning in science education (Zoller, 1993). CT is logical and reflective thinking that focuses on one's decisions about beliefs and doings (Ennis, 1989) and was later defined as the skill of taking responsibility and control over our mind (Paul, 1996). In the context of science education, CT has been conceptualized as a results-guided activity, reflective and evaluative in nature, requiring decisions about what to accept or reject and/or what to believe in. This is followed by a decision what to do (or not to do), an appropriate action, and the taking of responsibility for the consequences (Zoller, 1993).

Science education researchers have pointed out that students quite often fail in performing assignments that require CT skills (Bailin, 2002). Others have shown that students may be successful in performing such assignments, provided they were exposed to teaching that included both critical thinking and required student practice (Adey and Shayer, 1990; Zoller, 1993; Zoller et al., 2000; Ten Dam and Volman, 2004). There appears to be agreement that students' CT capability is developed by implementing instructional strategies that support and foster other HOCS such as *question asking* and *decision making* in problem solving situations (Potts, 1997; Halpern, 1999; Ben-Chaim et al., 2005).

Science and chemistry teaching is traditionally based on lectures and textbooks presenting unambiguous and authoritative theories, rules of nature and, ultimately, one correct solution to each problem (in most cases, an *exercise,* because it seeks to confirm previously taught and learned content) posed (Nakhleh, 1993). Similarly, much traditional university-level science (e.g., chemistry) teaching emphasizes rules, formal definitions, equations and algorithms, in terms of 'knowing', 'remembering', 'defining', identifying', understanding and 'applying' which, primarily, require just LOCS in order for the students to respond 'correctly' to examination questions; that is, *one correct* answer to one well-defined question.

A major issue of concern is whether such traditional teaching practices promote students' HOCS (such as CT and PS capabilities), which require more than just knowledge and application of known algorithms. The potential contribution of laboratory practice to the development of students' HOCS is clearly a related issue.

Laboratories have been described as contrived experiences where students interact with materials to observe phenomena (Hofstein, 1988), and thus involve students taking an active part in the learning procedure (Klainin, 1988). University chemistry departments rarely question the importance of laboratory work as an essential component of the experiences they provide for their undergraduates, despite the large number of resources committed to this work. However, institutions have begun to consider just how much *learning* is, in fact, taking place during laboratory sessions (Rollnik et al., 2001).

For three decades, laboratory work in school science courses was claimed to provide students with insight into, and experience and practice of, the methods of science. It was argued, however, that from 'discovery learning' in the 1960s – to process-led science – to contemporary constructive approaches, each of these styles of the laboratory work has seriously misrepresented and distorted the nature of scientific inquiry (Hodson, 1996). Recent studies suggest that appropriate models of laboratory practice can contribute conceptual benefits to participating students (Johnstone, 1997; Rollnik et al., 2001; Roth and Welzel, 2001).

The importance of students' HOCS development in science and chemistry education is apparent and supported by many science educators. Our recent studies have demonstrated that the development of students' PS and CT capabilities is feasible via persistent purposeful HOCS-promoting teaching and assessment strategies (Ben-Chaim et al., 2005, 2006). In this special themed issue of *CERP*, this three-component-based paper, dealing with PS and CT on the theoretical level and the related laboratory practice on the practical level, constitutes a modest contribution to the intended LOCS teaching-to-HOCS learning paradigm shift in science education.

While problem solving, critical thinking and progressive pedagogical and curricular practices are advocated in science education literature (e.g., Zoller, 1990, 1993; Zohar, 2004; Flick and Lederman, 2005; Pushkin, 2007), there is no consensus on the specific definition of 'critical thinking'. Pushkin (2007) notes a wide spectrum of contexts for critical thinking (e.g., decision-making, cognitive self-consciousness, paradoxical situations). However, a primary connection to critical thinking is with scientific problem solving, most notably chemistry and physics (e.g., Zoller, 1987, 1994; Carnine, 1993; Lewis and Smith, 1993; White, 1993; Maloney, 1994; Zoller et al., 1995; Pushkin, 1995, 1999, 2000, 2007; Zoller and Tsaparlis, 1997 Ben-Chaim et al., 2006;).

The union between critical thinking and problem solving forms an 'umbrella' that encompasses levels of thinking, levels of knowledge, levels of cognitive skills, the implications of these different levels, and how these different levels interact. The HOCS-promoting components of this umbrella, specifically CT and PS, clearly require consistent and persistent employment of explicit pedagogical and curricular practices. This requires flexible and contextual learning activities, as well as HOCS developing teaching strategies and assessment modes – all to be consistent with related course goals, as well as contribute to these goals, and encouraging student attainment of them. The first part of this paper is a review of HOCS-relevant pedagogical research and theoretical literature. The second part focuses on the concluding six-hour laboratory session of a one-semester introductory organic chemistry course involving HOCS-promoting, CT/PS-requiring laboratory practice. This practice, which has been successfully applied for more than two decades, will be described and its relation to assessments and evaluations critically discussed.

Review of HOCS-related literature

Levels of thinking

A hierarchy of thinking levels is established in the literature (e.g., Fogarty and McTighe, 1993; Lewis and Smith, 1993; Pushkin, 1999, 2000, 2007). These levels are known as lower-order thinking, higher-order thinking, creative thinking, and critical thinking. Two additional levels of thinking are known as systemic/lateral thinking and evaluative thinking (Zoller, 2000).

The lowest level of thinking is referred to as *lower-order thinking*. Lower-order thinking typically reflects rote memorization, regurgitation, or recitation of basic facts, or perhaps performing a simple one-step computation with assistance of a calculator (e.g., addition, subtraction, multiplication, division, squaring numbers or determining a logarithm). For example, stating the name of a chemical formula, or identifying an element on the periodic table, or stating that the pH of an acid is typically below 7.0, all illustrate lower-order thinking. On the other hand, *higher-order thinking* (one step up on the hierarchy) typically reflects taking new information and combining it with *a priori* information, or rearranging such information to find possible answers to perplexing situations (Lewis and Smith, 1993). For example, a student combining principles of stoichiometry with the ideal gas law or the concept of molarity, or determining the mass of a liquid based on its density and measured volume, illustrate higher-order thinking.

In many respects, algorithmic exercises are the classic illustration of lower-order thinking. This does not, however, imply that conceptual exercises illustrate higher-order thinking. In fact, lower-order thinking is hardly conceptual, even though it is primarily concept-focused (e.g., Pushkin, 2007). Conceptual thinking is actually more evolved than higher-order or algorithmic thinking, for it requires learners to understand on a broader level what computational exercises address (Tobias, 1990, 1992; Tobias and Tomizuka, 1992; Pushkin, 1998). For example, to determine the limiting reagent for a chemical reaction and calculate an expected yield correctly, does not necessarily mean one genuinely understands the role of a limiting reagent and its implications on product formation.

Problem solving has been defined as what people do when they do not know what to do (Wheatley, 1984) and as a get-oriented sequence of cognitive operations (Anderson, 1980). The process of PS is difficult to outline, but psychologists and educational researchers agree that it involves cognitive, operative and affective variables. In the thus far dominant algorithmic-LOCS science teaching, PS has been perceived as a process by which the learner discovers a combination of previously learned rules that can be applied to achieve a solution (Holroyed, 1985). In other words: problem solving is a process of applying previously taught and learned algorithms to achieve a solution to an **exercise**. However, in the context of our concern, students' ability to resolve HOCS-requiring **problems**, we perceive a problem to exist when there is a gap between where a person is and where he wants to be, without knowing how to cross the gap (Hayes, 1981).

Several 'composite-type' models of, and/or associated with, the PS process in relation to its cognitive functions have been put forward (Newell and Simon, 1972; Tsaparlis, 1998; Shin et al., 2003; Stamovlasis and Tsaparlis, 2003, 2005). Researchers agree that: (a) the context of the problem is a critical determining factor in the process (Raine and Symons, 2005; Tsaparlis, 2005), and (b) by the application of appropriate relevant teaching and assessment strategies, the improvement of students' problem solving capability is attainable (Sawrey, 1990; Zoller, 2000; Danili and Reid, 2004; Perels et al., 2005).

Researchers distinguish between well-structured and ill-structured problems (Zoller and Tsaparlis, 1997; Shin et al., 2003), or between conceptual and algorithmic problems (Nakhleh, 1993; Stamovlasis et al., 2004, 2005). As a result, questions and/or exam items have been categorized into those that require LOCS and those that require HOCS for their solution and resolution (exercises and problems) respectively (Zoller et al., 2002). Accordingly, exercises are categorized as questions, exam items, assignments, or tasks which require mainly or exclusively LOCS on the part of the solver, namely simple recall of information or a routine application of known method, theory or knowledge to familiar situations and contexts. Such items can be solved by means of algorithmic processes (mechanistic application of what procedures are taught/recalled/known, but not necessarily understood), already familiar to the learners through previous specific directives or practice, or both (Johnstone, 1993; Zoller, 1993; Zoller and Tsaparlis, 1997). Exercises are, usually, familiar to the students and solving them is simply a matter of writing out the solution and checking for mistakes (Lyle and Robinson, 2001). Problems, on the other hand, require for their solution the application of HOCS.

Problems (as opposed to exercises), whether qualitative or quantitative, are intellectually and cognitively challenging 'conceptual' questions that may require several cycles of interpretation, representation, planning, deciding, execution, evaluation and re-evaluation. These problems are operationally defined as quantitative or qualitative conceptual questions, unfamiliar to the student, that require for their solution more than knowledge and application of known algorithms; namely, the HOCS of reasoning, analysis, synthesis and problem solving, making of connections and critical evaluative thinking, including the application of known theory or knowledge or procedure, to unfamiliar situations or situations with an unusual element or dimension (Zoller et al., 2002). When solving a problem, the student not only arrives at a resolution, but also acquires a new or revised knowledge (Lyle and Robinson, 2001), as well as a higher level of cognition. Meta-analysis of forty case studies indicated that providing learners with guidelines and criteria that can be used in judging their own problem-solving process and product, and with immediate feedback, are prerequisites for the acquisition of PS skills (Taconis et al., 2001).

While there are similarities between creative thinking and critical thinking, distinctions are evident (Fogarty and McTighe, 1993). *Creative thinking* is often associated with visualizing, personifying, associating relationships, making analogies, and dealing with ambiguity and paradox. *Critical thinking* is often associated with attributing, comparing/contrasting, classifying, analyzing for bias, solving for analogies, and evaluating. It would seem that creative thinking involves recognition of novel situations, while critical thinking involves consideration of the implications of such situations. For example, consider the following problem previously given during an organic chemistry lesson to pharmacy students:

> Liver alcohol dehydrogenase (LADH) is an enzyme in the liver responsible for the 'breakdown' of ethanol into ethanal (i.e. acetaldehyde), according to the following reaction,
>
> $$CH_3CH_2OH + NAD^+ \rightleftharpoons CH_3CHO + NADH + H^+$$
>
> (Note: NAD^+ = Nicotinamide adenine dinucleotide, a coenzymatic form of Niacin, one of the Vitamin B complex)
>
> A) The kinetics for this reaction is zeroth order. What does this tell you about commonly known methods to 'sober up' after getting drunk?
> B) Is dehydrogenation an example of oxidation or reduction? Why? How?
> C) Could this reaction possibly explain to you why drinking 'wood alcohol' (i.e., methanol) has far more serious consequences than drinking 'grain alcohol' (ethanol)? Might it explain why rubbing alcohol is now made of isopropyl alcohol (i.e., 2-propanol, $CH_3CH(OH)CH_3$)?

In the context of Fogarty and McTighe's (1993) definition, a student identifying the issue that exists within part A of the problem reflects creative thinking. Students must understand of what "zeroth order kinetics" means. It appears that the liver, which produces the enzyme needed to "break down" (a common term used in biology textbooks to describe catabolism to first-year biology students (e.g., Starr and Taggart, 1987)) alcohol, does this independently of the amount of alcohol in one's body, and appears to do its job at its own rate, regardless of any efforts on our part to speed things along. This realization on the part of students reflects critical thinking, for students must attribute prolonged inebriation to the behavior of LADH.

Part B is a question to assess students' understanding of what oxidation and reduction mean, and combines aspects of creative and critical thinking, for it forces a comparison and evaluation of various operational definitions encountered by biology majors. Many students learn contrasting definitions of oxidation and reduction in their introductory biology and chemistry courses. A common conception among students from an introductory biology course is that oxidation involves a reaction with oxygen while reduction is associated with electrons and/or oxygen removal, or reactions involving water and/or carbon dioxide (Garnett and Treagust, 1992; Schmidt, 1997). In an introductory chemistry course, students encounter that Red-Ox reactions involve an exchange of valence electrons.

However, in an organic chemistry course, students encounter a new context for electron exchange. In the given LADH reaction, ethanol is converted to acetaldehyde; thus two covalent bonds (i.e. sigma bonds) are converted into one unsaturated covalent bond. Thus, oxidation not only involves removal of an electron pair; it results in the formation of a multiple bond as an alkyl carbon is converted to a carbonyl carbon.

In part C, students not only need to consider the size of the alcohol molecule ingested relative to this enzyme's effectiveness, they must also consider the historical context of methanol as a substitute for the ethanol found in wine, beer, and liquor. Methanol (once the main ingredient in rubbing alcohol) is too small a molecule for LADH to act upon, thus methanol remains unmetabolized by the liver, and this toxic chemical builds up in the body with catastrophic consequences (e.g., blindness or death). Thus, the importance of *a priori* knowledge should not be overlooked relative to learners' thinking skills and evolving conceptions (e.g., Ausubel, 1968; Posner et al., 1982; Millar and Driver, 1987; Vosniadou and Brewer, 1992; de Jong et al., 1998; Duit and Treagust, 1998; Gitomer and Duschl, 1998; Tamir, 1998).

System/lateral thinking essentially addresses the question of whether a learner solves problems with a defined conceptual framework (i.e., is there a "game plan"?). For example, consider the following critical thinking problem involving solution stoichiometry, limiting reagents, and percent yields, closely-related to a laboratory setting typically experienced by students in their first chemistry courses:

> *50 milliliters of 0.5M ammonium sulfate are added to an excess solution of barium chloride. A precipitate results.*
>
> 1. If you recover 3.25 grams of precipitate, what is your percent yield?
> 2. How might your result differ if you used 50 milliliters of 0.1M silver nitrate instead? Please justify your answer quantitatively. (Pushkin, 2000, p. 211)

Solving this problem requires several steps and considerations along the way. First, for part 1, learners need to be able to write a balanced chemical reaction with the correct chemical formulas for all reactants and predicted products. Second, they need to determine which reactant-product pair provides the relevant stoichiometric relationship for calculations. Third, they must determine the number of moles of ammonium sulfate in a given molarity and volume, then the number of moles of barium sulfate (i.e., the precipitate) by means of a mole ratio. This will lead them to determine a theoretical yield based on stoichiometry, and a percentage yield based on the actual yield of 3.25 grams.

On the other hand, learners need to consider a new reactant (and limiting reagent) in part 2, thus leading to a different precipitate and theoretical yield. As noted by Pushkin (2007), the theoretical yield calculated in part 2 forces a learner to realize that 3.25 grams of recovered precipitate is an impossible outcome in a laboratory setting, thus creating an opportunity to consider the implications of using different reagents and amounts in similar-type reactions (i.e., precipitation). Again, to solve part 2 of the problem, a learner must return to the initial foundation established in part 1 (i.e., a balanced chemical equation and mole determinations).

This finally leads to *evaluative thinking*, which involves a learner making attributions for the results obtained during problem solving. For example, returning to the stoichiometry problem, does a learner see a connection between the given problem, its solution, and the relevant principles one must understand in order to solve the problem? In other words, does a learner recognize any cause-effect relationships within a problem to reinforce concepts encountered during several class lessons and/or laboratory sessions?

In many respects, both system/lateral thinking and evaluative thinking are similar to critical thinking, as a dimension of *cognitive regulation*, or consciousness of knowledge exists (Shin et al., 2003). In both, a learner must be able to take information, analyze it, and discuss the implications of that information, including any paradoxical situations. However, in order truly to appreciate the amorphous definition of critical thinking, one should consciously consider the connection thinking has with knowledge. More importantly, one needs to consider the parallels between levels of thinking with levels of knowledge.

Levels of knowledge

As with thinking, knowledge has a hierarchy (e.g., Ryle, 1949, cited in Gagné et al., 1993; Gagné, 1977, 1985; Schoenfeld, 1978; Anderson, 1990;, Maloney, 1994; Pushkin, 2007;) – declarative knowledge, procedural knowledge, and conditional knowledge. Conditional knowledge has two subcategories, situational knowledge and strategic knowledge.

In the relationship between thinking and knowledge there are parallel hierarchies. Declarative knowledge is the lowest level of knowledge and is parallel to lower-order thinking. Procedural knowledge is parallel to higher-order thinking. The combination of situational and strategic knowledge, *conditional knowledge* (Schoenfeld, 1978), is parallel to critical thinking.

"***Declarative knowledge*** *is knowing that something is the case…* ***procedural knowledge*** *is knowing how to do something,*" suggesting that declarative knowledge is a collection of "*facts, theories, events, and objects*" (Gagné et al., 1993, pp. 59-60), while procedural knowledge involves steps of doing things.

Does this mean that declarative knowledge is conceptual, and procedural knowledge is algorithmic? Or, does this mean the opposite, declarative knowledge is algorithmic and procedural knowledge is conceptual?

It is somewhat awkward to apply the term 'conceptual' to either declarative or procedural knowledge (Pushkin, 2007). The term 'conceptual' is defined as "coming from, or belonging to, the concepts, ideas, or principles something is based on" (Microsoft Office 2001 Dictionary); this makes for a poor description of declarative or procedural knowledge. It might be best to consider 'conceptual knowledge' or 'conceptual understanding' as the **sum** of declarative and procedural knowledge, although 'conceptual understanding' was previously related to declarative knowledge, and 'skills/strategies' to procedural knowledge (Gagné et al., 1993).

When we consider conditional knowledge, and its two components, *situational knowledge* (deJong and Ferguson-Hessler, 1986) and *strategic knowledge* (Schoenfeld, 1978), we need to appreciate that this level of knowledge relates to *situated cognition*, an alternative term for critical thinking (Kincheloe et al., 1992, 1999; Kincheloe, 1999, 2000; Pushkin, 1999, 2000, 2007). What does this mean? It is the level of thinking that takes the *context* of a learning situation into account. More specifically, conditional knowledge brings together a learner's declarative and procedural knowledge, especially with regards to *problem solving*.

Looking back at either chemistry problem presented earlier in this paper, it appears that both situational and strategic knowledge go hand-in-hand when solving problems. Learners cannot truly identify a problem solving strategy without contextualizing the problem, nor can they contextualize a problem without considering available problem solving strategies within working memory. While conditional knowledge may be more prevalent in physics, chemistry problems involving stoichiometry or reaction mechanisms could also create opportunities to develop this level of knowledge (e.g., states of matter of reactants and/or products, orders of kinetics, structures of reactants and/or products).

This essentially comes down to the extent of schema development for a learner; the broader and more in-depth a learner's schema, the stronger and more flexible their problem solving strategies potentially become (Fischler et al., 2001). As with critical thinking, conditional knowledge depends on a level of cognitive consciousness by learners. In order to solve problems, learners first need to be able to recognize relevant aspects of problems and connect them to specific principles, which in turn are connected to specific methods of qualitative and/or quantitative analysis.

Levels of cognitive skills

According to Zoller (1993), cognitive skills fall under two categories: LOCS (lower-order cognitive skills) and HOCS (higher-order cognitive skills). Zoller defines LOCS in terms of simply knowing (i.e., basic recall of memorized information) or simply applying basic or memorized information to familiar situations, and/or applying algorithms to repetitious *exercises* (e.g., end-of-chapter textbook problems or exam questions). On the other hand, HOCS involve question asking, critical thinking, system/lateral thinking, decision making, problem solving (as opposed to mere exercises), evaluative thinking, and knowledge transfer (Zoller, 1987, 1990, 1993, 1994, 1997, 2000; Zoller and Tsaparlis, 1997; Zoller et al., 1995, 2002). Most importantly, what distinguishes HOCS from LOCS is the confronting of learners/problem solvers with unfamiliar situations, non-algorithmic and/or open-ended questions, as opposed to familiar and routine situations (Zoller and Tsaparlis, 1997).

How does this work? Consider Pushkin's (2000) precipitation problem. The first part of the problem can be considered quite routine, and calculating a percent yield from stoichiometric data can very well represent a typical end-of-chapter textbook problem. However, the presentation of a problem requiring students to 'fill in missing information' is often criticized as not being pedagogically direct enough (Pushkin, 2000). To some chemistry educators, the process of gathering and identifying information as well as the need of applying critical and/or evaluative thinking (not to mention transfer) towards problem solving, seems 'unfair' to learners. To them, proper assessment of learning should either involve *automatized* (i.e., robotic) regurgitation of lecture material or reproduction of algorithmic steps with concrete information. The sad reality is that writing balanced chemical equations from the names of reactants followed by stoichiometric analysis is too fundamental to qualify as representative of HOCS, but to chemical educators convinced that LOCS pedagogy is 'rigorous enough', expecting more of students seems beyond the scope of a university-level introductory chemistry course (Pushkin, 1999, 2000, 2001).

Such chemical educators fail to recognize that it is the second part of the problem that more substantially presents HOCS pedagogy, asking students to make predictions and consider the implications of using a different limiting reagent (silver nitrate as opposed to ammonium chloride). Consequently, students need to consider new products, different solubility rules (for silver chloride and barium nitrate, as opposed to barium sulfate and ammonium chloride) and, finally, observe the quantitative evidence of how the second reaction will produce something different from the first (Pushkin, 2007). The mere presentation of open-ended questions (even if a definitive answer is expected by an educator) encourages learners to consider a wide array of information and *make connections* between such information with existing schematic or related, relevant knowledge, a process identified by Bransford (1979) as *spread of activation*. HOCS-oriented problems encourage learners to have a broad and deep consciousness of a problem, its context, implications, connections to and relationships with relevant issues, and their *activated* (as opposed to existing) knowledge base. Thus, it appears that HOCS, like CT and PS, are contextually-bound but not, necessarily content or discipline bound.

When discussing cognitive skills development, it becomes evident that such discussion overlaps with discussion of levels of thinking and levels of knowledge. Chemistry educators who advocate the pedagogic advantages of introducing HOCS into the curriculum also need to advocate creative, critical, systemic/lateral, and evaluative thinking, as well as situational/strategic knowledge. Advocates (perhaps unintentional) of LOCS erroneously believe that rigorous content equates with critical thinking. They fail to recognize that 'lots of information' does not translate to knowledge if a learner's working memory is inactivated. Simply reiterating or confirming the known, the familiar, and 'standard facts' does not stimulate or challenge the mind; rather, this approach stunts the mind and limits its potential, creating what Kincheloe et al. (1992, 1999) refer to as a "cognitive illness."

HOCS advocacy is more than pedagogical and curricular; it is also *socio-cultural*. From Vygotsky's (1978) concept of the zone of proximal development, to Perry's (1970) levels of adult intellectual schema, to Freire's (1985) and Giroux's (1988) concept of teaching and learning as "transformative intellectualism," two pre-requisites for changing thinking are to change the learning culture and to change the classroom dynamics. If a specific cognitive outcome is desired, explicit pedagogical and curricular practices need to be consistently employed; short-term actions will not necessarily result in long-term effects (e.g., Jonassen, 1993; Pushkin, 1995). Furthermore, if flexible and contextual thinking are expected of learners, educators should provide flexible and contextual learning activities as well as use flexible and contextual modes of assessment, so the even the practice of critical thinking does not become an automatized routine (e.g., White and Gunstone, 1992).

The same is applied to PS, transfer, and other components of HOCS, since CT and PS are both quite global, as are what constitutes knowledge, and what constitutes and represents HOCS. Together, knowledge, thinking and cognitive skills serve as a metaphorical lens of maximum aperture. To see all, to be aware of all, to interconnect all, systematically, and to recognize potential implications of all, learners (and educators) need to focus on scientific literacy not as a vast collection of information, but as means of understanding a continuum of ideas, principles, and methodologies towards the capability of evaluative thinking.

Attaining this overriding goal requires the 'matching' of teaching practice and students' experiences with intended learning outcomes. In the following section, a HOCS-promoting, CT/PS requiring problem-based laboratory session at the end of an introductory organic chemistry course for freshman biology majors and the practice employed therein will be described and discussed. This will be followed by a summary of active research-based conclusions and implications for HOCS-oriented science (e.g., chemistry) teaching.

The concluding laboratory session

The content of the course "Introduction to Modern Organic Chemistry" is quite similar to 'classical' freshman organic chemistry courses, provided in the following syllabus excerpt:

- Introduction: Fundamental concepts, the tetrahedral carbon atom, the chemical bond.
- The structure and chemistry of – Alkanes, alkenes, alkynes and aromatic compounds.
- Stereochemistry: stereoisomerism, chirality and optical activity.
- The chemistry of alcohols and sulfur analogs, aldehydes and ketones, spectrophometric methods for structure determination: UV, IR, NMR and MS.
- Amines and related nitrogen compounds, carboxylic acids.
- Esters, amides, and related derivatives.
- Organic synthesis.
- Amino acids and the peptide bond.
- Selected topics in modern organic chemistry in the modern biological/sociological context.

This introductory first-year course is mandatory for biology majors, offered annually in the second semester of the academic calendar. Forty to sixty students are typically enrolled each year, dividing into smaller laboratory sections of approximately 20 students. The laboratory component of this course constitutes an *integral* part of this course and was consistently taught by a course instructor (one co-author of this paper), together with a laboratory guide and assistance of a lab technician. The semester-long course usually consists of three 'lecture' hours per week and five, bi-weekly, 4-5-hour lab sessions. Students work in pairs during laboratory sessions. This laboratory component provided a significant vehicle for HOCS and CT development for more than two decades.

The specific HOCS-oriented objectives for this course, all made explicitly known to course participants, intended to develop and foster students' (1) self-learning as a major component in the learning process within the course framework; (2) system thinking and PS capabilities which will enable them to understand the chemical-molecular basis of the functionality and operational mechanisms of biological systems; (3) critical lateral/evaluative thinking which will enable them to solve *problems* in the context of basic organic chemistry; (4) capabilities of analysis, synthesis, decision making and transfer in the context of organic chemistry; and (5) getting closer to modern organic chemistry and subjects within this discipline relevant to, or pertaining particularly to the science-technology-environment-society (STES) context.

The very ambitious goals of this course cannot, nor should expect to be achieved during a one-term course; similarly, the extent of attainment of these goals will differ among students. What is important, however, is the conscious effort and collaborative persistence of both teachers and students in going ahead on this rocky trail (Zoller, 2000). Several teaching, assessment and learning strategies made gains in this direction (see e.g. Zoller, 1987, 1990, 1994, 1997, 2000; Heppert et al., 2002; Wang, 2005), all of which have been extensively applied to this course, including in its fourth and final fifth laboratory sessions (4 and 6 hrs each, respectively).

With respect to our five HOCS-oriented objectives, the following teaching and assessment strategies were applied throughout the course:

- There was no one textbook assigned for this course. Students were encouraged to use any textbook they find individually appropriate and/or useful. A list of 20-25 recommended textbooks was provided to the students at the course outset.
- Course participants were requested to come self-prepared, bringing their *questions* to the lecture sessions *before* hearing the instructor lecture on each of the course topics.
- Students, encouraged to work in groups, were required to respond to bi-weekly homework problem sets; a substantial portion of the sets required system CT/PS capabilities for their resolution.
- Students submitted their problem set responses for review by the instructor and former course students; *feedback* and grading were done individually for each student (see example questions in Appendix A).
- Self-assessment and grading of both homework assignments and examinations were an integral part of the course (Zoller et al., 1999), as was occasionally the examination where the students ask the questions (Zoller, 1994).
- There was occasional inclusion of short STES-oriented, interdisciplinary modules, relevant to the course syllabus (e.g., "Freones-the hole in the ozone layer-UV radiation-cancer induction and society response").

Relevant illustrative examples of a laboratory-related mixed HOCS/LOCS-type take-home exam question in this course are given in Appendix B (Zoller, 1993, and more recent unpublished sources).

During the semester, students were requested to respond to 5-6 homework problem sets, to be worked out collectively, in small groups, or individually (students must submit solutions individually) approximately every other week. These problem sets were usually assigned in parallel with, but occasionally before, class coverage of relevant chemistry content. The students' responses were reviewed and graded by the course instructor and two graduates of this course (sophomores by then), who were extensively briefed by the instructor beforehand. All three reviewed each student's works thoroughly and provided detailed written feedback on each individual student's submitted set. Three illustrative questions related to the laboratory course and taken from the last home problem set (just before the concluding laboratory session) are provided in Appendix B.

The assessment methods were in full compliance with the course HOCS objectives; all pertained to the assessment of students' performance and also included learning in the laboratory. Examinations were administered in either in-class individual, oral or take-home format. For either examination format, students were permitted to use their textbooks and/or notes, as well as any other material they wanted to bring with them. Regardless of examination format, the students have sufficient time to read the questions (20-30 minutes in the oral exams), to think about them, and ultimately select 3-4 questions (out of 5-6 available) to be examined on and respond to.

Given the integration of the lecture and laboratory components of this course, examinations selectively integrated all that was taught and was supposed to be learned. The final course grade was determined by the following weighted criteria: final exam 50%, homework problem sets 20%, mid-term take home exam 10%, and laboratory work 20%.

The concluding problem-based laboratory session

The entire laboratory practice, in this concluding session, is devoted to the identification of unknown (to the students) organic compounds and whatever this process involves in the organic chemistry research context. It is based on what has been learned throughout the course and requires the application of skills, both cognitive and practical, that the students have already acquired, LOCS and HOCS as far as the former are concerned. The students are requested to come "ready" to this lab session, meaning going *beyond* just a routine review and study of all that has been learned in the course in the class, the laboratory, at home, the library or any other relevant resources. The laboratory booklet, pre-adjusted and edited by the chemistry laboratory team, provides the students with the essence of the relevant practical information, guidance, and methodologies to be used, a couple of worked examples, and tables of relevant data; e.g., boiling points and solubility and basic spectrophotometric data (UV, IR, NMR). The identification process scheme – preliminary qualitative analysis of organic unknowns (e.g., identification of nitrogen, sulfur, or halogen-containing compounds via the sodium fusion test), solubility in acidic and/or basic aqueous solution, identification of functional groups, spectroscopic data (UV, IR and NMR) and, finally, the procedures for preparation of derivatives (e.g., dinitrophenylhydrazones from ketones; esters from carboxylic acids), necessary for the 'ultimate' proof of the identified unknown. It should be emphasized, however, that the essence of the identification of the unknown process does not reflect LOCS-oriented protocols. Rather, students initially receive *all* the *necessary* information and data relative to the 'unknown' and what is required of them in order to solve the problem (i.e., thorough systemic CT and application of their HOCS). The role retention and LOCS play in this process is very minor.

The lab session is divided into two parts: in the first, the students, in teams of two, are provided with two *known* 'unknowns' samples; that is, the provided samples A and B are fully identified and were made known to the students to begin with. All the relevant data, including physical data, derivatives, UV, IR and NMR spectra and the data provided has already been analyzed for the students (in the laboratory booklet) and is used by each team while they simulate the relevant identification process, making sure that they have understood each step in the process and the conclusions derived. The students are then required to demonstrate their comprehension via an in-depth oral summary of the simulation and to respond to the instructor's questions, comments, or suggestions, in 2:1 (students: instructor) mini-sessions. These are intended to prepare the students for dealing with real "unknowns," which for their full identification require the students to undergo a process similar to the one they have just experienced, but now demanding much more application of HOCS compared to LOCS.

Finally, in the last part of this summative laboratory session, each student team is confronted with real *problems* to solve; namely, to identify the two unknowns. Each team received samples of unknowns accompanied by the corresponding relevant physical, chemical and spectroscopic data: m.p./b.p., M.W., the presence of nitrogen sulfur and halogens, if applicable, uv, ir and nmr. This problem solving process has to be performed and is followed by each team explaining to the course instructor and assistants, their mental (thinking, logic, analysis and synthesis) operations they have applied in each step throughout the process and what has been learned from it specifically. This includes the conclusions reached and consequently applied, and what was shown later to be correct in accord with UV, IR, and NMR data as well as the related properties of the derivatives prepared by each team, following the identification of the two "unknowns". The particular process, conducted by each of the teams and the conclusions derived from the findings were summarized and discussed by each team, and after the session were submitted to the instructor for review and feedback.

The two unknown compounds used in this stage of the course included simple alkenes, aromatic compounds, aldehydes/ketones, amines, esters, and amides. More significantly, however, the identification process emphasized PS-based thinking, rather than laboratory practiced-oriented.

Concluding comments

Throughout the years, the students' achievement (in terms of scores) on HOCS-requiring exam questions related to laboratory practice and learning were, in most cases, similar to those related to other course topics dealt with mainly or exclusively in lecture sessions. Students' overall final laboratory grades were, in most cases, higher than their final course grade. Course letter grades correlated, in most cases, with each student's homework problem set grades. Taking these results into account, as well as previously reported related results (e.g. Zoller, 1987, 1993, 1994; Zoller et al., 1999; Tsaparlis and Zoller, 2003), there appears to be a positive academic affect from a problem-based laboratory that promotes HOCS.

This laboratory activity contributed to the participating students' advancement on the lengthy, rocky trail of HOCS development. Students' responses of appreciation and satisfaction, at the end of the course, were gratifying and encouraging for future design of similar laboratory practices in organic chemistry and other science courses.

Relating HOCS promotion goals to problem-based laboratory practice is one way to achieve HOCS-promotion advocacy. The proposed model, here described, of a CT/PS-requiring laboratory activity, is plausible and feasible. Not only can it be done; it should be done. It is crucial to match goals and practice.

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Appendix A

1. a. Which product would you expect to receive on heating of compound **1** in high dilution conditions? Draw the structure of the expected product **2** and explain the reason for its formation.

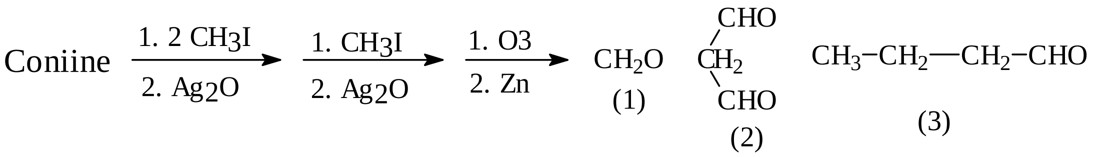
$$O{=}CH-CH_2-CH_2-CH_2-CH_2-NH_2$$

1

b. Draw, qualitatively, the IR and NMR which you would expect to get from **1**.

c. Can you, based on the IR spectrum of **2** (when taken), determine that, indeed, the expected reaction did take place? Explain!

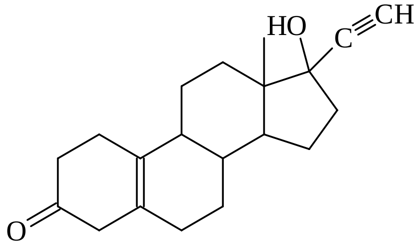
2. a. Based on the following reactions, try to suggest the structure of coniine. [Guidance: try to work out the problem backwards, i.e., reconstructing, first, the partial structures from which (1), (2) and (3) were obtained.]



$$\text{Coniine} \xrightarrow[2.\ Ag_2O]{1.\ 2\ CH_3I} \xrightarrow[2.\ Ag_2O]{1.\ CH_3I} \xrightarrow[2.\ Zn]{1.\ O_3} \underset{(1)}{CH_2O} \quad \underset{(2)}{CHO-CH_2-CHO} \quad \underset{(3)}{CH_3-CH_2-CH_2-CHO}$$

b. Assuming that you have succeeded in separating (2) and (3) from the reaction mixture in (a), will you use UV, IR or NMR in order to determine which is which?

3. The steroid **4** suppresses the egg fertilization process and is therefore used as a component in the birth control pill, enovid.



4

a. Draw (crude approximation only) the expected IR spectrum of **4**. Is the IR spectrum sufficient, in this case, to determine the structure of **4**? Explain.

b. Suggest two chemical reactions (one for each functional group) on the results of which you will be able to determine that **4** contains both hydroxylic and carbonyl groups. Provide the relevant chemical equations in full.

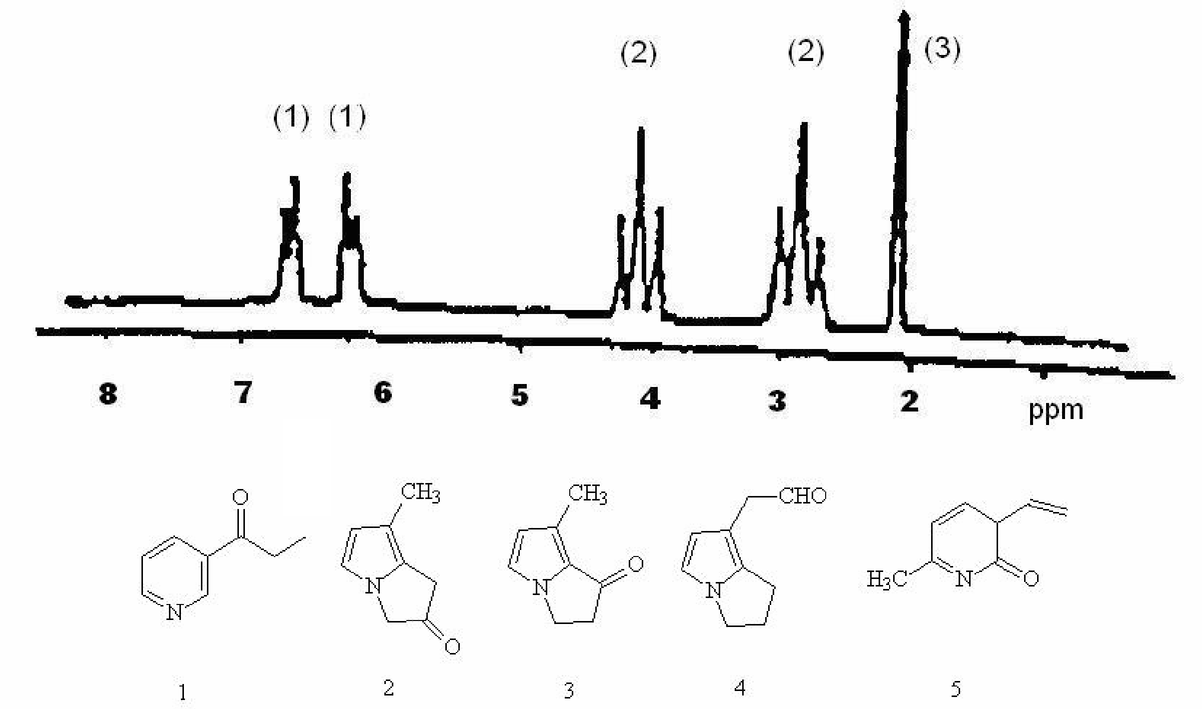
c. Would you expect **4** to be soluble in water? Explain your answer! Will an addition of 2-propanol to an aqueous solution of **4** increase or decrease the solubility of **4** in the new solution?

d. What is, in your opinion, the final product that would be obtained in the reaction of **4** with $NaBH_4$ followed by acidification of the reaction mixture?

Appendix B

Question I.

The Florida Butterfly produces a compound A having the formula C_8H_9NO, which is essential for attracting the males for mating and reproduction. The NMR spectrum of compound A and five possible structural isomers of A are given in the figure below.



NMR spectra and some possible structural isomers of compound A

1. Which of these structural isomers best fits the given spectral data? Explain.
2. * Suggest two simple chemical reactions, the results of which will enable you to confirm your conclusion in (1). Provide the chemical reactions involved.
3. * Which of the given isomers may, in principle, be optically active?
4. Draw *qualitatively* (crude approx. only), the IR spectrum you expect for one of the given isomers of your choice.
5. Is the use of UV for the identification/characterization of this isomer effective? Explain.
6. * [optional] What direction of research (if any) would you recommend concerning compound A? Be specific and rationalize your answer.

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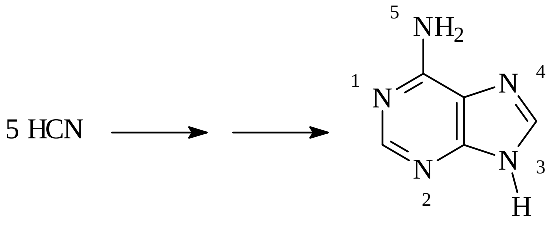
* These are HOCS questions.

Question II.

One of the theories concerning life formation on earth attributes a special importance to the HCN molecule, which was apparently abundant in the primary global atmosphere. Thus, for example, it is possible to envision Adenine (**1**) as an HCN pentamer:



1

1. Is **1** an aromatic substance? Rationalize.
2. * Which of the Adenine's nitrogen atoms (1-5) is the most basic? Explain and rationalize.
3. Which spectroscopic method (UV, IR, NMR) would you suggest to use for determining the Adenine structure? Explain!
4. * Suggest at least one chemical reaction to apply to Adenine, from the result(s) of which you would be able to obtain some idea about the chemical properties of **1**.
5. In your opinion, are hydrogen bonds possible in **1**? Explain and rationalize.

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* These are HOCS questions.

Perspective

The role of laboratory work in university chemistry

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Abstract The place of experimental work in laboratories has always assumed a high profile at all levels of chemical education. This paper seeks to review the main strands of evidence available today and argues that the place of experimental work needs to be reconsidered at higher education levels. There is a need for a clarification of aims and objectives, and these need to be communicated to learners. It argues that higher education needs to be acutely aware of what goes on at school and to build on these skills. Pre-laboratory exercises are strongly supported by the evidence, while there needs to be a radical re-thinking of the use of laboratory manuals, with assessment being explored afresh. In addition, seeing the laboratory experience in the context of what goes on before and after, as well as other learning, will enhance the learning potential of this time. Examples of some ways forward are presented. Overall, it is argued that much more could be gained by the students if the laboratory experience, using similar experiments, was radically re-thought. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 172-185]

Keywords: Higher education laboratory work, aims and objectives in laboratory instruction, pre-laboratory exercises, post-laboratory tasks

Introduction

Laboratory work is an established part of courses in chemistry in higher education. The original reasons for its development lay in the need to produce skilled technicians for industry and highly competent workers for research laboratories (Morrell, 1969, 1972). Today, the aims may be different, in that many chemistry first degree graduates are not employed as bench chemists in industry (Duckett et al., 1999; Statistics of Chemistry Education, 2006), and the needs of research have inevitably become much more specialized as chemical knowledge has expanded.

This paper seeks to offer an overview of the current situation in higher education, and explores what might be the aims for today. It also argues that laboratory work in higher education cannot be seen in isolation. For most students it follows school laboratory experiences which are rapidly changing, and has to relate to material taught in lectures and tutorials. However, of greater importance is the need to see the 'hands-on' laboratory time as part of a wider process of learning. In this, there is a need to prepare students for their time in the laboratory as well as develop follow-up activities. Together, these may enrich and enhance the whole laboratory experience, and enable it to contribute more effectively to the overall learning of students in chemistry.

Historical perspective of laboratory work

The first teaching laboratory in chemistry in Britain was established by Thomas Thomson in the University of Edinburgh in 1807. In 1819, he introduced this to the University of Glasgow, when he joined this University. In 1824, Liebig established a Chemistry Laboratory at the University of Giessen. This was a most exciting period of the nineteenth century. Liebig's was the first institutional laboratory in which students were deliberately trained for membership of a highly effective research school by means of systematic research experiments (Morrell, 1969, 1972).

Laboratory classes then gradually developed over the next fifty years until eventually, in 1899, it came to be considered necessary that school pupils be allowed to carry out experiments for themselves. By this time, however, most schools in England had already adopted this way and regarded practical work as an essential requirement for science teaching in England (Gee and Clackson, 1992). Thus, practical training in chemistry sprang up in universities all over the Europe and North America. These were devoted to the teaching of skills directly used in industries and research (Letton, 1987; Johnstone and Letton, 1989; Khan, 1996). Practical work at this time played a vital role in *confirming* the theory which was already taught in the classroom. However, some doubts also arose about the efficiency of teaching through practical work in chemistry.

This work in higher education had its impact on school teaching in the sciences. Here, a century ago Armstrong advocated the direct experimentation by the pupils rather than demonstration experiments performed by the teacher. However, too much time was wasted on repetitive individual practical work (Hodson, 1990). Therefore, attention switched back once again to teacher demonstration. In 1932, the Education Board in England supported the same idea (pamphlet no. 89). This declared that there was "*too much practical work of the wrong kind ...., too much remote from the natural interests and everyday experience of the children*" (cited in Hodson, 1993). In 1935, Schlensenger studied the contribution of laboratory work to general education. He noticed that students who had previously exhibited "*real interest in chemistry developed the habit of doing their experiments mechanically to get the result expected rather than to observe what is actually going on in their test tubes*" (Letton, 1987). Little seems to have changed since then.

Towards the end of the twentieth century, more sophisticated alternatives had been introduced to facilitate effective learning in university laboratories. These included pre-laboratory experiences, films, video experiments, computer based pre-laboratories, post laboratory exercises and computer simulations [see Carnduff and Reid (2003) for a review].

Bennett and O'Neale (1998) proposed guidelines for the design of laboratory courses in chemistry in higher education in terms of the "*logical sequence*" of ideas, "*opportunity for real investigations very early in the course*" and "*pre- and post-laboratory sessions which actively engage the students*". These principles reflect the ideas of Denis Diderot, the French philosopher, who outlined three principal means of acquiring knowledge available to us: observation of nature; reflection; experimentation. Observation collects facts; reflection combines them; experimentation verifies the results of that combination (cited in Lester, 1966). All of these illustrate the need to decide what the aims are for using laboratory work in the teaching of chemistry in higher education.

Why have laboratories?

Laboratories are one of the characteristic features of education in the sciences at all levels. It would be rare to find any science course in any institution of education without a substantial component of laboratory activity. However, very little justification is normally given for their presence today. It is assumed to be necessary and important. It is taken for granted that experimental work is a fundamental part of any science course and this is especially true for chemistry courses. Very frequently it is asserted that chemistry is a practical subject and this is assumed, somewhat naively, to offer adequate justification for the presence of laboratory work. Thus, the development of experimental skills among the students is often a suggested justification. Nonetheless, this argument needs to be questioned to justify the position or role of the laboratory in the field of chemistry education.

One of the main reasons to question the place of laboratory teaching is that laboratory programmes are very expensive in terms of facilities and materials, but also, more importantly, in terms of staff time (Carnduff and Reid, 2003). University students' reactions to practical work are often negative and this may reflect a student perception that there is a lack of any clear purpose for the experiments: they go through the experiment without adequate stimulation (see for example, Johnstone and Letton, 1988 and 1990).

It is important to think about goals, aims and objectives in the context of laboratory work. Laboratory work here is used to describe the practical activities which students undertake using chemicals and equipment in a chemistry laboratory. Of course, the word 'practical' can include other activities as well, and it is interesting to note the use of the word in so many titles in papers. However, this paper is discussing *experimental activities* conducted in the laboratory by students although other practical activities may have their place and be important.

Many years ago in a schools context, Rose and Seyse (1974) raised a fascinating question: could many important aims still be attained even if practical work were abolished? They suggested that this depends partly on our view of science. Science can be seen as established human knowledge, a problem solving activity, or concerned with the relation between theory and experiments. A similar question may be posed for higher education chemistry: what would be lost if laboratory work vanished from higher education courses? It is likely that students would still pass the examinations based on lecture courses with little or no change. However, would the students have any 'feel' for chemistry, for chemicals, for instrumentation, or for the way experimentation is conducted or reported? In some ways, this starts to define what could be the important aims which can be uniquely achieved through laboratory courses.

Hawkes (2004) has challenged the place of the laboratory in many higher education chemistry courses. He argued that the evidence does not support the idea that the laboratory assists in achieving many of the aims for chemistry courses. He noted that, "*The enormous expenditure of time and treasure and student dislike of laboratory teaching demands substantial evidence that it has value commensurate with its cost and with the loss of subject matters that must be omitted to make time for it.*" Given that today many students taking chemistry courses do not intend to become bench practitioners in any sense, his argument has some substance. However, the absence of the laboratory experience may leave students with perceptions of chemistry that are very abstract and theoretical. Since it is not possible to know which students will become bench practitioners, it is important not to reject the important place of the laboratory. However, Hawkes's basic argument does challenge the over-emphasis on practical skills and suggests that it is important to think through the aims of laboratory work so that some of the wider scientific skills may find an appropriate place. Specific laboratory skills may be rarely used even by bench practitioner chemists in their careers but the place and nature of experimentation will be a very important understanding to be gained.

Wills (1974) quoted results of a survey of students' opinions on the teaching of practical biochemistry as part of a medical course. He observed that half of the students showed little enthusiasm for laboratory work. Its perceived relevance was low, while students noted that theoretical understanding is gained relatively slowly through practical work, providing a poor reward in knowledge gained for their future medical career. Although these comments were written long ago and in a different context, many still apply in chemistry where students do not always see the point of what they are doing (Shah, 2004). Of course it is not always easy for students to see the importance of certain activities until later on in their studies but a perceived lack of relevance at any stage will not help learning, and this has to be addressed.

In thinking of laboratory work, there are some inevitable tensions. Students are not always best placed to see the relevance and importance of all the elements of their course. On the other hand, there is a tendency for specialists to think in terms of presenting their subject rather than of meeting the students' needs. Here again, the need for clearly formulated objectives, communicated effectively to students, is seen to be important.

Aims and objectives

Several writers and researchers have discussed the rationale for laboratory work in Higher Education and have presented their aims and objectives for specific science courses as well as for laboratory instruction. Some of these are discussed below.

It does seem important that, for practical work to be effective, the goals, aims and objectives should be well defined. Thus, Boud et al. (1986) stressed that, when planning a course it is important to state clearly the course aims, goals and objectives: what to be taught, who is it to be taught to, by what means, and most importantly, what are the intended outputs? The issue is to find some agreement about what these aims and objectives might be. Such a question has been under investigation for decades, especially in the UK where much money and time has been spent on laboratory work in schools as well as in universities (Woolnough, 1994). Quite apart from the setting up costs for building laboratories and the costs for running them in terms of heating, resources and technicians, the labour costs for 3 hours of laboratory teaching may well be around 15 times the costs for a one hour lecture for 100 students. Is the learning gain 15 times greater?

Much of the research effort has looked at the place and nature of laboratory instruction at school level. It is important to note the outcomes from such work in that the university classes are drawn from those who have experienced laboratories at school before they arrive at university. At the school level, there have been many lists of aims and objectives offered in the literature (eg. Shymansky and Penick, 1975; Johnstone and Wood, 1977; Black and Ogborn, 1979; Johnstone and Al-Shuaili, 2001). They all tend to refer to skills and techniques as well as skills related to the conduct of experiments in a scientific way. Some have emphasized affective aims strongly (e.g. Kerber, 1988; Johnstone and Al-Shuaili, 2001) while others have emphasized other aims (e.g. Pickering, 1987, argued that laboratories might illustrate scientific method, might build confidence and might improve understanding).

Thinking of university chemistry laboratories, Kirschner and Meester (1988) suggested the following student-centred objectives for practical work:

1. To formulate hypotheses
2. To solve problems
3. To use knowledge and skills in unfamiliar situations
4. To design simple experiments to test hypotheses
5. To use laboratory skills in performing experiments
6. To interpret experimental data
7. To describe clearly the experiment
8. To remember the critical idea of an experiment over a significantly long period of time.

Their list is interesting in that traditional university laboratories often do not give opportunities for the development of some of these skills. Thus, for example, formulating hypotheses and designing experiments to test them is largely out of the range of most undergraduate laboratory experiences, although such an approach might well be possible (Johnstone et al, 1994). Very often, solving problems is seen as an algorithmic process in which students put experimental data into a formula, or solve some problem by applying a routine procedure (see Reid and Yang, 2002, for a discussion of problem solving in chemistry). Experimental problem solving is very different from the algorithmic exercises that may be part of the calculations in some chemistry laboratory work in university classes, especially in physical chemistry.

The eighth aim on their list is fascinating in that it suggests that there are critical ideas in experiments or, indeed, that there are critical experiments in the sense that the outcomes offer precise insights relating to a specified hypothesis. This is the fundamental nature of the place of experimentation in all science-based research. There is little research on how this might be achieved, other than suggesting that giving students many experiences may assist in developing the right ways of thinking and developing experimental ideas. Reid and Serumola (2006a, 2006b) considered this with younger school pupils, and found little evidence that much could be achieved. Later work showed the same with school pupils at the final stages of their education, but the latest observations showed that recently graduated science students (50 students drawn approximately equally from the biology, chemistry and physics) could handle this way of thinking very clearly (Alsamawat, 2007). Clearly, there has been a change. Was it the actual degree in the science discipline? Was it the laboratory work experiences? Was it simply that the graduates were, on average, about 4-5 years older than senior school pupils? (is it simply developmental or experience of life?)

Carnduff and Reid (2003) outlined the need of the laboratory work in chemistry in higher education in terms of three broad areas:

1. *Practical skills* (including safety, hazards, risk assessment, procedures, instruments, observation of methods);
2. *Transferable skills* (including team working, organisation, time management, communication, presentation, information retrieval, data processing, numeracy, designing strategies, problem solving); and
3. *Intellectual stimulation*: connections with the ‘real world’, raising enthusiasm for chemistry.

This still highlights the practical skills element but sees it in terms of more generic skills rather than the specific ones such as handling a burette appropriately or purifying a reaction product. They (Carnduff and Reid, 2003) offer a long list of transferable skills that go well beyond the confines of chemistry (assuming that when developed in one context, they do indeed transfer). The making chemistry real is also stressed, and the absence of a laboratory course would make this very difficult to attain. In their summary, some aspects of scientific thinking emerge as well. Thus, most of these aims will be, and perhaps can only be, achieved in laboratories or in laboratory related activities.

Carnduff and Reid (2003) went on to provide a set of possible reasons for the inclusion of practical work in undergraduate courses in chemistry:

- Illustrating key concepts
- Seeing things for ‘real’
- Introducing equipment
- Training in specific practical skills and safety
- Teaching experimental design
- Developing observational skills
- Developing deduction and interpretation skills

- Developing team working skills
- Showing how theory arises from experimentation
- Reporting, presenting, data analysis and discussion
- Developing time management skills
- Enhancing motivation and building confidence
- Developing problem solving skills.

There are some very important aspects here. For example, ‘teaching experimental design’ may be incredibly important, but it will not easily be achieved in the kind of set experiments which are often seen in university laboratory manuals. Similarly, ‘showing how theory arises from experimentation’ stands in strong contradiction to the idea of confirming theory which was seen so strongly in the 19th century and which still persists today. The development of powers of observation, measurement, prediction, interpretation, designing of experiments are dependent on laboratory work. However, laboratories at undergraduate level (perhaps also at other levels) do not seem play their role very well to gain these goals and objectives (Carnduff and Reid, 2003).

Overall, these are some of the tasks or objectives which more or less demand the presence of laboratory work in chemistry courses. Of course, laboratory experiences do not guarantee that such tasks and objectives can be achieved in the present situation. There may be a major need to change or improve the present situation to create more opportunity for the students to fulfill these objectives.

The lack of a clear sense of purpose in the design of laboratory courses is another factor which emphasises the need for review and change. From a study of first-year chemistry manuals in UK universities, Meester and Maskill (1993, 1995a) reported that the aims of the course were stated in only half of the manuals while in only one manual of the 49 surveyed were the learning objectives for each experiment clearly stated.. It might be more reasonable to conclude, however, that the main problem is the plurality of purposes.

Meester and Maskill (1995b) reviewed briefly, but usefully, the range of developments in these areas, before noting that little had been achieved in practice among the range of courses sampled. They suggested that:

> “*The reason little has changed in practical classes is probably that university teachers concentrate on the experiments to be performed by students and on the time available, rather than on the educationally best way to achieve their teaching aims .., although all the evidence that they need to improve practical teaching is easily available.*”

This is quite an amazing statement. It pinpoints the root of the problem: too much emphasis on the *experiments to be performed* and not enough emphasis on what the *students should be gaining*. It asserts that ‘all the evidence to improve practical teaching is easily available’. Perhaps the word ‘all’ is somewhat optimistic but, certainly, there is a wealth of evidence available that would enable university laboratory experiences to become much more effective in benefiting students.

This leads on to the question about the students’ perceptions about the purposes of the practical work and how they match the perceptions of the experts. Little work has been carried out on this comparison. However, Kirschner et al. (1993) compared the students’ perceptions with those of experts’ using a list of possible objectives. An interesting result was that the objectives set by ‘experts’ were not those that the students expected to happen and did not match what they actually found. The reasons were that students were not well prepared to perceive the purposes of the practical work and also the students have limited or no experience of this type of exercise. The authors pointed out that the value of laboratory work must be severely limited by the students’ unpreparedness, a conclusion, which would apply to many practical exercises. In a recent study, Shah (2004) found, with a total sample of 708 drawn from two countries in various stages of a first degree and after completing the degree, that enjoyment and illustrating theory were the most frequently selected aims chosen by students. The former is encouraging, while the latter, if it means that the experimental merely illustrated what was being taught in the lecture course, is a matter of concern.

The conventional way of preparing students would be to encourage them to read their laboratory course manual, but these typically overload them with information to be held at the same time. Equally, if there is an incessant barrage of information, the students get completely lost in the argument and sequence of ideas. The manuals need to be re-written with simplicity in mind if it is desired that students do not use them as ‘cookbooks’ (Johnstone and Letton, 1990). Experienced university lecturers know that only a minority of students do read the manuals before entering the laboratory unless specific tasks are allocated to them! Indeed, the question of information overload turns out to be rather important, and will be discussed later when considering the place of pre-laboratory experiences.

Some conclusions

In this quick overview of laboratory work in university chemistry courses, a number of issues have become clear. Firstly, there seems much agreement that laboratory work has a rightful place in undergraduate courses. Secondly, there is much evidence which indicates that all is not well: an expensive learning experience is not bringing the benefits which justify the outlay. Thirdly, there is lack of clarity about the aims for laboratory work, and students’ perceptions and experiences do not match aims.

Drawing things together, it is possible to present the aims for laboratory work under four headings, although there is some overlap:

Skills relating to learning chemistry. There is opportunity to make chemistry real, to illustrate ideas and concepts, to expose theoretical ideas to empirical testing, to teach new chemistry.

Practical skills. There is opportunity to handle equipment and chemicals, to learn safety procedures, to master specific techniques, to measure accurately, to observe carefully.

Scientific skills. There is opportunity to learn the skills of observation and the skills of deduction and interpretation. There is the opportunity to appreciate the place of the empirical as a source of evidence in enquiry and to learn how to devise experiments which offer genuine insights into chemical phenomena.

General skills. There are numerous useful skills to be gained: team working, reporting, presenting and discussing, time management, developing ways to solve problems.

Two things are important. The students do not come, in general, with no experience of laboratory work. Although school laboratory teaching is heavily circumscribed by examination requirements, in some courses there are open-ended projects (e.g. the Scottish Certificate of Sixth Year Studies, 1969, which then later changed to Advanced Higher Grade Chemistry in 1999). The planners of first year university courses need to know what is being done in schools and how it is being done so that the first year laboratories can build on this. Secondly, there needs to be progression so that, over a degree, there is a build up in all the four areas of skills listed above.

The important issue is that the university teacher needs to decide which skills are to be developed in a particular laboratory course, to set these out in clear, unambiguous terms for the students, and to ensure that the whole design of the laboratory experience is consistent with the specified skills. With this in mind, the next stage is to explore what evidence there is to enable such aims to be achieved.

Issues for today

It is possible to compare what happened over 40 years in typical Scottish universities (Table 1). The figures are approximate in that there are minor variations from year to year. However, the general pattern is likely to have been similar in most university chemistry departments, and it illustrates that there has been a considerable reduction in time allocated to laboratory learning.

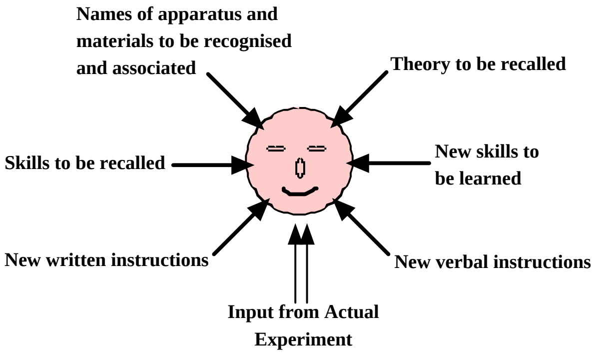
Table 1. Time spent in chemistry laboratories.

	1960s	2000s	Proportion Left
Level 1	5 hours for 22 weeks	3 hours for 16 weeks	44%
Level 2	12 hours for 22 weeks	6 hours for 16 weeks	36%
Level 3	12 hours for 22 weeks	12 hours for 16 weeks	73%
Level 4	Every waking moment!	Large amount	Unquantifiable

The time reduction may have arisen for many reasons: costs associated with staffing; reduction in student time available because of jobs; general student resistance to the vast time spent on laboratories when compared to other (mainly non-science) courses. However, given the reduction in time, it is *imperative that what time is left is spent extremely effectively and efficiently*. There have been several useful contributions in seeking to achieve this (e.g. Johnstone et al, 1994; Hunter et al, 2000).

There are several problem areas that need to be addressed. In order to make laboratories manageable, laboratory manual development is quite sophisticated, giving, typically, ‘recipes books’ (Carnduff and Reid, 2003). This has led to too much emphasis on ‘product’ and not enough on the processes of thought. Frequently, there is excessive repetition of relatively unimportant skills (Meester and Maskill, 1995a 1995b). However, of even greater importance, typical laboratories involve vast information overload for students and, therefore, actual learning (in terms of understanding) is minimal (see, for example, Johnstone and Wham, 1982). In this early work, they observed some quite bizarre student behaviour (such as endless repetition of familiar tasks to avoid the new ones) as students struggled to cope with the bombardment of information coming at them in a typical laboratory (see Figure 1).

Figure 1. Sources of information for students in undergraduate laboratories (derived from Johnstone and Wham, 1982).



Pre-laboratory instruction

Pre-laboratory exercises were introduced as a means to reduce the information overload on students. It was found that these can have a major effect (Johnstone et al., 1994; Johnstone et al., 1998). They can allow laboratory manuals to be reduced in length. They can encourage the laboratory planning process to focus on what is really important and to ensure that the students share these perceptions. Of greatest importance, they can allow understanding to increase simply by reducing information overload. Many examples exist and most are paper-based (see Carnduff and Reid, 2003) but the use of computer based pre-laboratory exercises is not uncommon (e.g. Nicholls, 1999; McKelvy, 2000; Tomlinson et al., 2000).

Humans all learn in fundamentally the same way. New knowledge and experiences have to be processed in a part of the brain known as the working memory. As this is limited and cannot be expanded, it has to be used efficiently. The working memory is where a person holds information temporarily. However, it is also the place where many important processes take place: thinking and reflecting; understanding and applying; analysing and synthesising; problem solving; being critical and even sceptical!

A pre-laboratory exercise is a short task or experience to be completed before the laboratory starts. It can take around 15-30 minutes to complete, depending on the experiment and on the background knowledge of the individual student. It may need to be submitted and checked before work begins. Its fundamental aim is to *prepare the mind for learning.* It can reduce the information load for the student, releasing mental capacity for thought. Sources of overload might include the laboratory manual, verbal instructions, equipment and materials, theoretical background, terms, symbols, representations, skills: what to do, how and when.

The pre-laboratory exercise can be used to do many things, although it is more or less impossible that it can do them all for any specific experiment. A pre-laboratory exercise may be able to:

1. Stimulate the student to think through the laboratory work, with a mind prepared for what will happen.
2. Encourage students to recall or find facts such as structures, equations, formulae, definitions, terminology, symbolisms, physical properties, safety hazards or disposal procedures.
3. Check that the experimental procedure has been read and understood and it can offer practice in data handling, drawings or calculations of the kind to be used in the write-up.
4. Lead the student into thinking about the procedure or the concepts and may encourage the student to connect and revise prior knowledge, thus providing some reassurance about the grasp of the topic.
5. Offer experiences in planning (the apparatus, the procedure, the quantities and the data presentation).
6. Bridge the (common) gap between laboratory and lecture, experiment and application.
   (Drawn from: Carnduff and Reid, 2003.)

Carnduff surveyed the university chemistry scene in the UK and beyond, and found many examples of pre-laboratory work (Carnduff and Reid, 2003). However, the most comprehensive system found was that developed and described by McKelvy (2000) in the US. This did depend on high levels of facilities and organisation, which are not so common in many parts of the world. Nonetheless, it reveals a well thought out and consistent pre-laboratory experience which shows what is possible.

Do prelabs work?

In a series of experiments, the effectiveness of pre-laboratory activities has been shown to be effective. In a study in undergraduate physics laboratories, pre-laboratories increased performance on traditional demonstrator marking by around 5%. However, in a test of understanding, the pre-laboratory exercises were found to increase performance by around 11%, while it was found that students were dramatically more positive about laboratories (Johnstone et al, 1998).

In an earlier study, in an undergraduate inorganic chemistry laboratory course, the power of pre-laboratories to improve understanding was demonstrated, but the authors also observed that pre-laboratories enabled mini-projects to be particularly effective; the power of the pre-laboratory to make more open-ended work accessible being shown very clearly (Johnstone et al., 1994). This is an important finding. More open-ended work is not so easy in university classes and this finding shows a possible way forward.

However, there are some warnings, as a later experiment in a physical chemistry laboratory course revealed (Shah, 2004). Attitude surveys suggested that students found the pre-labs too long, while the demonstrators were not pleased with the extra marking. However, interviews with some 60 students revealed that the students saw the purpose of the pre-laboratories very clearly and considered them valuable. This experiment revealed very clearly that all aspects of the laboratory experience must be seen as a whole. Simply adding on extra work was not acceptable. The interviews also showed that there was a ‘black market’ in pre-lab answers! A later implementation reduced the pre-lab exercise length, and this seemed more acceptable.

Developing the actual laboratory

The pre-lab exercise development serves a number of purposes. It reduces working memory overload, and prepares the students for what they are to experience in the laboratory. This enables the laboratory manual to be reduced in size. However, the actual laboratory experience may also need to be developed and changed. This is where the specification of clear aims can be helpful. For example, some laboratories can be developed that illustrate the chemistry being covered in lecture classes and make it real for the students. Thus, some synthetic organic chemistry may be covered, while in the inorganic area, the synthesis and study of the spectra of various metal complexes may be highly relevant. However, much can be enhanced with a little thought. The literature is full of papers describing all kinds of ingenious ways to make experimental work more interesting, relevant, safe, and yet exciting (e.g. feature articles, ‘In the Laboratory’, in issues of the Journal of Chemical Education).

Thus, instead of every student synthesising and purifying the same organic compound, students might work in groups of four to discuss how to synthesise a type of compound (eg. an azo dye) and then each goes on to make a different dye. They can then compare uv spectra and try to develop an understanding of why their spectra are similar but not identical. This might involve another group of four students with another set of azo dyes. A parallel approach can be used with complexes where groups can synthesise and purify similar complexes of the same ligands with different transition metals, comparing the spectra obtained and making deductions about structures and d-electron energy levels.

Analysis experiments can also easily be adapted. Thus, for example, phosphomolybdate analysis for the phosphate ions in water can be made much more real by allowing a group of, say, four students to develop the calibration curve *together* by undertaking two analyses of standard phosphate solutions each and then working together to analyse river water sampled from an industrial river at various points on its flow. The results can be related to the environment, using a simple map and involving the students in discussion. In such ways the traditional experiments involving analysis or synthesis can be adapted to achieve different aims. However, the assessment may have to be re-thought so that it does not distort the whole experience. Marking for right answers is not appropriate. Perhaps a group report might be an interesting way forward, with recommendations based on the accumulated evidence.

Post-lab tasks

This leads to an important aspect: what happens after the experimental work is completed in a laboratory? Very often the writing up of a report is seen by the students as pointless, particular when it is marked for the production of a ‘correct’ result. It is here that post-lab tasks can be invaluable, provided that they are designed to match the aims for the laboratory.

Some of the ideas above implicitly involve post-lab tasks. Much can be built around discussion, looking for patterns in results and seeking to relate data obtained to underlying understandings in chemistry. This may involve a report or it may involve reaching a group conclusion. It may involve an application of a finding in a new situation, ideally, related to life outside the laboratory. For example, in the phosphomolybdate experiment described above, the phosphate levels were found to be related to bus washing depots, with their extensive use of low temperature soaps and the wash-out into the local river. Assessment may simply require the completion of the task adequately rather than producing a graded mark.

Overall conclusions

With time at such a premium, it is vital that university chemistry laboratory experiences are used efficiently and effectively. The key is to have clear aims. While specific practical skills are relatively unimportant, there needs to be an opportunity to handle equipment and chemicals, to learn safety procedures, to master specific techniques, to measure accurately, to observe carefully. However, of greater importance is the importance of making chemistry real and exposing ideas to empirical testing. Skills of observation, deduction and interpretation are important as the place of the empirical as a source of evidence in enquiry is offered. In addition, there are many other important practical skills to be developed (e.g. team working, reporting, presenting and discussing, time management, developing ways to solve problems).

Many school courses seek to develop some of these outcomes and often offer considerably *more* freedom for students to think scientifically. University students are capable of building on these successful outcomes. Indeed, it is important that those directing university chemistry laboratories are aware of what is currently happening at school by means of curriculum documents and, even better, visiting typical schools to observe. In this way, it is possible to plan university chemistry laboratories so that they can avoid repeating school laboratory experiences but also *build on the kinds of thinking skills* which school courses seek to inculcate. This alone might improve student attitudes.

Translating such goals into a stimulating laboratory experience is the next stage. The laboratory course must be seen as a whole and the experimental experiences introduced to develop such outcomes. The pre-lab draws out prior experiences and ideas and sets the scene for the actual laboratory. The student now knows and understands more of the purpose and nature of the laboratory experience ahead. Laboratory manuals need to be shortened considerably and students encouraged to plan the actual experiment, and see why it is they are doing what they are doing. Greater open-endedness will be helpful and students are found to respond to this most positively. There needs to be more emphasis on the process of thought and enquiry and much less on getting a ‘right’ answer.

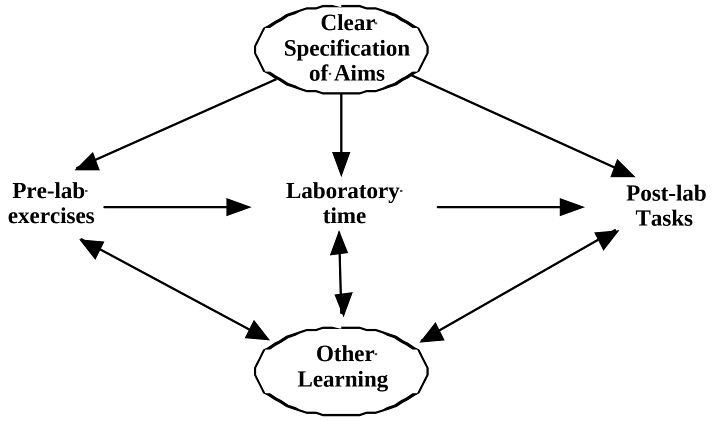
The post-laboratory experience also needs careful thought. In the work described by Johnstone et al (1998), imaginative post-laboratory exercises were used. These allowed students opportunities to apply the ideas they had learned, as well as offering some insights into their understanding. A range of ingenious post-laboratory exercises in physics were also developed by Skryabina (2000) and were considered very valuable when she conducted student interviews. A formal ‘write-up’, with answers marked for accuracy fails to offer the student a stimulating intellectual experience, especially when there is frequently a ‘black market’ in right answers.

Table 2 summarises what needs to be done in order use time more efficiently and effectively, the aim all the time being to encourage the maximum student learning. The laboratory experience must, therefore, be seen holistically (Figure 2).

Table 2. Summary of recommendations.

Stage	Activity	Tasks
Planning	Clear Aims	Make chemistry real Expose ideas to empirical testing Develop skills of observation, deduction and interpretation Develop general practical skills (eg team working)
	Background	Know what happens at school and why Don't underestimate school experiences
Before the Laboratory	Pre-labs	Share aims for experiments Establish background information Plan experiments
During the Laboratory	For the experimental	Keep manual brief Allow experimental freedom
After the Laboratories	Post-labs	Apply ideas learned in a 'real-world' setting For assessment, look at process not 'right' answers

Figure 2. The laboratory experience.



The aim in this paper has been to develop an acceptable set of aims under the general headings of:

Skills relating to learning. Making chemistry real, illustrating ideas, empirical testing ideas, teaching new ideas.
Practical skills. Handling equipment and chemicals safely, measuring and observing carefully.
Scientific skills. Learning skills of deduction and interpretation, seeing a science at work, devising experiments.
General skills. Team working, reporting, presenting and discussing, developing ways to solve problems.

These aims cannot be met easily (if at all) by lectures and tutorials. They are part of giving the student an appreciation of the way chemistry, as a science, works. Meeting many of the aims will offer skills and insights which will be useful in numerous employment opportunities. Above all, the aims offer possibilities where the student learner can be challenged to think, to argue, to weigh evidence, to explore chemical ideas.

The traditional laboratory experience in higher education can be enhanced by applying these aims and setting the laboratory learning in a context of pre-learning and post-learning.

The former enables the student to make more of the time in the laboratory while the latter allows the student to think through and apply ideas.

Examples have been offered of ways by which the traditional experiments can be re-thought so that different aims can be achieved. The aim is to move away from following a recipe, not matter how well written. The aim is to move towards laboratory experiences which stimulate and challenge, allowing students to see chemistry, as a science, at work.

The conclusion can be summed up thus: “*To change the experience, you don’t need to change the experiment, just what you do with it*.” (Cited in Carnduff and Reid, 2003.)

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Educational research

Using lecture demonstrations to promote the refinement of concepts: the case of teaching solvent miscibility

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Abstract: Novices often lack the descriptive knowledge of phenomena that is the basis for an expert's interpretation of scientific concepts. Such lack of knowledge may lead to poor conceptual understanding, and misinterpretation of these concepts. Lecture demonstrations can provide essential experiences that serve as a context for discussion of over-generalized or over-simplified concepts. The design of such demonstrations starts from surveying the limited knowledge base of the student, followed by exploration of the richness of relevant contexts of the expert, and identifying key instances that can serve as meaningful discussion topics. An example of the design of a demonstration set for teaching solvent miscibility and its relation to intermolecular interactions is given, followed by results of its application in two different presentation modes: confrontation (aims at generating a conflict with existing conceptions) and refinement (aims at promoting differentiation and contextualization of scientific concepts). The students' involvement in peer discussion, associated with these demonstrations, is evaluated by considering the distribution of students' predictions. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 186-196]

Keywords: lecture demonstrations, classroom discussion, confrontation demonstrations, refinement demonstrations, solvent miscibility, intermolecular interactions

> *"To approach demonstrations simply as chances to show off dramatic chemical changes or only to impress students with the 'magic' of chemistry is to fail to appreciate the opportunity they provide to teach scientific concepts and descriptive properties of chemical systems… In planning a lecture demonstration, I always begin by analyzing the reasons for presenting it."*
>
> Shakhashiri (1984)

Introduction

The above citation, from demonstration master Bassam Z. Shakhashiri, highlights the importance of lecture demonstrations as pedagogical, rather than just motivational, opportunities. What kind of pedagogical reasoning can help transform a demonstration from being simply a form of entertainment into a learning tool? In this paper, we will discuss two factors that affect the pedagogical effectiveness of lecture demonstrations – their design focus and mode of presentation.

By tradition, the aim of lecture demonstrations was to show students a concrete example of an abstract description they encountered in class, and to help them make connections between the theory they were taught and reality (Tanis, 1984). These *verification* demonstrations focused on the scientific concepts that were taught in class. They were designed to illustrate these concepts visually, and to assure the students that the theory actually works in practice.

A more contemporary, research-based strategy is to focus the design of the demonstration on students' misconceptions – what they actually believe rather than what they have been taught. When targeting misconceptions, there are two different theoretical approaches that can be followed. The first one considers misconceptions as inappropriate pieces of knowledge, which contradict the current scientific concepts, and therefore should ultimately be replaced with proper concepts (Posner et al., 1982). According to this approach, these misconceptions should be actively confronted – the students should be exposed to discrepant events and anomalous data, which contradict their expectations. Only after the students are dissatisfied with their existing conception can the instructor present the proper scientific concept that explains the data. One way to introduce discrepant events in the classroom is by demonstrating an unexpected behavior of a chemical system (Bodner, 2001; Zimrot and Ashkenazi, 2007). Such *confrontation demonstrations* focus on the differences between students' misconceptions and the scientifically accepted concepts. They are designed to emphasize the shortcomings of these misconceptions, while providing a fruitful context for the application of the accepted concepts.

The second approach considers misconceptions as "*faulty extensions of productive prior knowledge*" (Smith et al., 1993). These so-called 'misconceptions' are regarded as fruitful elements of knowledge that serve both novices and experts. The difference is that novices apply these knowledge elements indiscriminately, even where they are inappropriate, while experts know in which contexts, and under which conditions, the application of a knowledge element will still prove fruitful. For example, the idea that motion implies a force is scientifically 'incorrect' and considered a 'misconception', but is fruitful in everyday situations which involve high friction, and is also a good model for the linear dependence of electrical current on voltage. Instruction should help students reflect on their present commitments, find new productive contexts for existing knowledge, and refine parts of their knowledge for specific scientific purposes.

Refinement involves the differentiation of contexts in which knowledge elements are applicable, and helping students use the appropriate scientific terminology to distinguish these contexts. For example, students often think that in a car-truck collision, the truck exerts more force on the car. Instead of confronting this misconception by stating that it contradicts Newton's 3rd law, the students' conception that the car 'reacts' more than the truck can be refined by making a distinction between 'reaction' as force (inappropriate context) and 'reaction' as acceleration (appropriate context). Since the mass of the car is smaller, it may 'react' (accelerate) more even if it experiences the same force. This results in a refined understanding of the situation, which is consistent both with the students' prior conception and Newton's 2nd and 3rd laws (Hammer, 2000).

In physics, many misconceptions may be traced back to students' previous experience with nature (Driver, 1983), and the refinement process utilizes these experiences as the building blocks for a more robust interpretation of physical situations. In high-school or tertiary level chemistry, however, students' direct experience with relevant chemical phenomena and concepts is quite limited (Taber, 2001). In many cases, this lack of personal experience, coupled with the small number of illustrative examples they encounter, leads to two possible outcomes:

1. Over-generalization: The coincidental association of two properties in a limited context is taken to be the general rule for all other cases. For example, when students are taught about titration curves, the primary illustration is the neutralization of HCl with NaOH, which has a neutral pH at the equivalence point. This may lead to the misconception that the equivalence point is always neutral (Schmidt, 1997). This is a good generalization for

all strong acid-strong base titrations, but is an over-generalization when weak acids or bases are considered. The result is under-differentiation of concepts; students do not differentiate between seemingly similar but fundamentally different concepts like equivalence ($n_{acid} = n_{base}$) and neutrality ($[H^+] = [OH^-]$).

2. Over-simplification: A continuum of properties or interactions is replaced by two mutually exclusive categories, which correspond to the two extremes of the continuum. For example, when students are taught about precipitation reactions, the illustrations are of either freely soluble salts, or practically insoluble salts. This may lead to the misconception that solubility equilibrium only occurs with ‘insoluble salts’, and when ‘soluble salts’ reach their solubility limit it is because “*all the H_2O molecules are holding onto the salt, and no more are freed up in order to dissolve the extra salt on the bottom*” (Brown, 2005). The result here is over-differentiation – students distinguish between two seemingly different but fundamentally similar concepts like soluble and insoluble salts.

We suggest that it is the students’ lack of experience with chemical phenomena that hinders them from making meaningful distinctions between related concepts. Lecture demonstrations can be used to expand the relevant experience base of students, providing a context in which such distinctions may become meaningful.

Refinement demonstrations should focus on similarities between students’ knowledge elements and the ways experts use the scientifically accepted concepts. They should be designed to test the validity of these knowledge elements in different contexts. This would support a process of refining limited ‘misconceptions’ into robust scientific concepts, by letting students experience the need for making relevant distinctions.

Regarding the mode of presentation, we argue that in order to be effective, lecture demonstrations need to provide an opportunity for classroom discussion. By tradition, lecture demonstrations (as their name implies) were demonstrated to an audience of passive observers. Even if the teacher supplemented the demonstration with relevant questions (Shakashiri, 1984), this would only engage a small number of participants, while most of the students would remain passive in the process. Research in physics education has shown that students learn difficult scientific concepts most effectively when actively engaged with the material they are studying, and that cooperative activities, such as classroom discussion, are an excellent way to engage students effectively (Hake 1998, 2002). Crouch and Mazur (2001) describe one such interactive teaching method – Peer Instruction – in which students are required to apply core concepts in the context of a conceptual question, and then to discuss those concepts with their fellow students. Students are given one or two minutes to formulate individual answers and report their answers to the instructor, using an electronic class response system. Students then discuss their answers with others sitting around them; the instructor urges students to try to convince each other of the correctness of their own answer by explaining the underlying reasoning. Following the discussion, students’ answers are collected again. The researchers report that after discussion, the number of students who give the correct answer increases substantially, as long as the initial percentage of correct answers is between 35% and 70%, and that the improvement is largest when the initial percentage of correct answers is around 50%. When most of the students start out choosing the same answer (whether correct or incorrect), the discussion doesn’t seem to be fruitful, and there is little benefit from it.

Peer Instruction can be easily coupled with lecture demonstrations, by using the demonstration as the context for discussion. The students are asked to predict the outcome of the demonstration before it is carried out, discuss their reasoning with their neighbors, and report their predictions. Crouch et al. (2004) tested students’ ability to recollect the outcomes of lecture demonstrations and explain them a few weeks after witnessing them. They have shown that students that predicted and discussed the demonstrations in class scored significantly better than students that just observed the demonstrations; the students that were passive observers scored only marginally better than students that didn't witness the demonstration at all. Similar results were found for lecture demonstrations in chemistry (Zimrot and Ashkenazi, 2007).

The combination of research-based design focus with research-based presentation mode results in increased effectiveness of lecture demonstrations. Sokoloff and Thornton (1997) have developed a set of Interactive Lecture Demonstrations (ILD) for physics, where the term 'Interactive' refers to the prediction-discussion presentation mode. These demonstrations are designed to target specific concepts that students have difficulty understanding and applying, based on research of students' misconceptions. Fagen (2003) found that in a prediction-discussion presentation mode, misconception-focused ILDs were more effective in enhancing students' learning than traditional demonstrations adapted to the same mode of presentation.

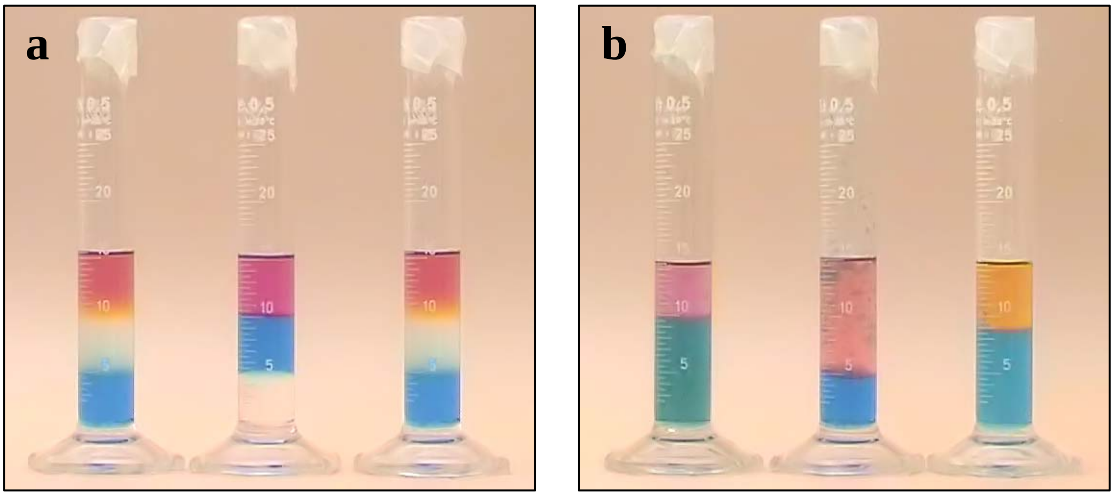
This paper demonstrates a combination of research-based design focus with research-based presentation mode, applied to lecture demonstrations in chemistry. We first present the elaborate process of designing a refinement demonstration, which focuses on the similarities between the multifaceted nature of expert knowledge and the limited experience base of students, rather than on the differences between correct scientific concepts and 'misconceptions'. We then show how the same demonstration set can be interactively presented with different emphases, to produce different effects that match the aforementioned design approaches – verification, confrontation, or refinement. We conclude by examining the relative effectiveness of these presentation modes in promoting classroom discussion.

Design

To illustrate the design process of a refinement demonstration, we chose a topic in which students' experience is limited – solvent miscibility and its relation to intermolecular interactions. This topic is typically associated with the rule of "*like dissolves like*", which is used by novices and experts alike, but not in a similar way. Novices use the rule literally, and apply it excessively, even when its use leads them to incorrect conclusions. Experts, on the other hand, have a wider set of experiences, which compels them to change the meaning they confer on the rule in different contexts. The simple textbook definition – "*substances with similar intermolecular attractive forces tend to be soluble in one another*" (Brown et al., 2005, p. 538) – cannot be used as a literal problem solving algorithm, because it contains much room for interpretation (what forces are considered 'similar'? How general is this 'tendency'?). We will show that this rule serves to guide the expert's meaning making process, but can not be used to replace it.

We start by examining students' prior experience in the field. Most general chemistry textbooks give two examples for liquid-liquid solubility: water and oil don't mix, and water and alcohol are miscible. These are also two common everyday phenomena – the separation of phases in Italian salad dressing, and the homogeneity of alcoholic beverages. The first demonstration repeats this common experience, by introducing a hydrocarbon layer (pentane) and an alcoholic layer (methanol) over water (Figure 1a, left cylinder); after a short vigorous shake, the methanol mixes completely with the water, and the pentane stays as a separate phase (Figure 1b).

Figure 1. Relative miscibility demonstration



a) Setup of the demonstration: the violet phase is pentane (d = 0.63, μ = 0.00) colored with iodine; the blue phase is water (d = 1.00, μ = 1.85) with food coloring; and the colorless phase is (from left to right) methanol (d = 0.79, μ = 1.70); 1,1-dichloroethane (d = 1.17, μ = 2.06); and acetone (d = 0.78, μ = 2.88). Density values (d) are in g/mL, dipole moment values (μ) are in Debye (CRC, 2001a). b) The results after a short vigorous shake: the methanol transfers completely into the water phase; the 1,1-dichloroethane transfers completely into the organic phase; and the acetone partitions between the two phases, with a water:organic ratio of about 4:1. A video of the demonstration is available at http://www.fh.huji.ac.il/~guy/links/CERP2007b.html .

Next, we examine the experts' explanation for the phenomena, noting what knowledge elements influence their interpretation of concepts such as “similar” and “tend to”. Being familiar with solvent miscibility charts (for example, http://www.phenomenex.com/phen/Doc/z366.pdf), an expert knows that all the organic solvents that are miscible with water are made of molecules that can form hydrogen bonds with water (contain an O or N atom) and have less than 4 carbon atoms. An expert also knows that hydrogen bonds have a partly covalent character (Gilli et al., 1994), which accounts for the fact they are specific and directional, for example in ice (Isaacs et al., 1999). ΔH and ΔS values for the solvation of hydrocarbons in water show that the hydrophobic effect is entropy driven (Silverstein, 1998). Taking all this data into account, the expert easily accepts the explanation that the immiscibility of a hydrophobic solvent with water is due to the inability of its molecules to form hydrogen bonds with water; the water is forced to form ice-like structures around the solvated molecules, and the formation of these rigid structures lowers the water's entropy. The expert summarizes all this knowledge in the rule “*like dissolves like*”, with the implicit distinction that hydrogen bonds are “unlike” any other intermolecular interaction.

Novices, oblivious to all of the above data, are left to consider the only two examples they know, in which, coincidentally, the hydrogen-bonding methanol is also a polar molecule. This knowledge is coincidental, because even though all molecules that can form hydrogen bonds are polar, not all polar molecules can form hydrogen bonds. Based on this limited information, and their knowledge of bond polarities and molecular structure, it is reasonable to over-generalize the ‘like dissolves like’ rule and say that polar molecules dissolve in polar solvents, while non-polar molecules don't. The novice fails to differentiate between the concepts *hydrogen bond* and *dipole-dipole interaction*, because the distinction between them serves no useful purpose – they coincide in all known cases. This under-differentiation can also be found in many general chemistry textbooks, which consider the former concept merely as an extreme case of the latter.

To help students differentiate between the two concepts, we chose a demonstration in which this coincidence is broken, i.e. in which a distinction between hydrogen bonds and dipole-dipole interactions becomes fruitful. We replaced the methanol with a highly polar molecule that cannot form hydrogen bonds: 1,1-dicholoroethane (Figure 1a, middle cylinder). Even though the molecular dipole moment of this molecule is larger than the dipole moments of water and methanol, experience shows that it does not dissolve in water, and is miscible with pentane (Figure 1b).

Another piece of data that is not disclosed in textbooks is the fact that alcohols and hydrocarbons are generally miscible[1]. A look at the solvent miscibility chart reveals that most organic solvents are inter-miscible, whether polar or non-polar. Therefore, there is no prohibition that excludes polar liquids from dissolving in non-polar solvents. The fact that the methanol transfers completely into the water phase, and does not transfer into the organic phase, is due to its higher affinity towards water (lower ΔG of solvation), than towards pentane. This relative affinity between liquids can be quantified as a polarity index (Snyder, 1978), which is an average measure of the interaction of a solvent with three test solutes (ethanol – medium dipole, proton donor; dioxane – weak dipole, proton acceptor; nitromethane – strong dipole, proton acceptor). Solvents with high affinities towards these polar, hydrogen bonding, test solutes have higher polarity values. The polarity index is strongly influenced by the hydrogen bonding capability of the solvent, and therefore does not always correlate with the molecular dipole moment. For example, methanol has a higher polarity index (6.6) than acetone (5.4), even though acetone has a larger molecular dipole moment (Figure 1, legend). The polarity index correlates well with other experimental measures that depend on the relative affinity of a solute to a solvent, e.g. the elution strength on silica or alumina in chromatography (http://home.planet.nl/~skok/techniques/hplc/eluotropic_series_extended.html), or the partition coefficient in water-octanol extraction (CRC, 2001b). Experts regard the polarity of a substance as a continuous measure of interaction, and evaluate it based on a set of considerations that they know to be relevant to the case at hand. In this context, 'like dissolves like' means that the closer the polarity of two substances, the stronger the interaction is between them.

Novices are unaware of all these considerations. Based on their limited experience with the water-oil and water-alcohol systems, they may over-differentiate and think of polarity in terms of a dichotomy; for them, substances are either polar or non-polar, and substances from different groups simply do not interact (because they are not 'like' one another). Since textbooks do not mention the polarity index, novices are also likely to interpret *substance polarity* only in terms of *molecular dipole moments*. Again, this over-differentiation into two distinct groups is common in many general chemistry textbooks.

The second demonstration has already introduced students to the idea that polar molecules can interact favorably with non-polar molecules. The London dispersion forces which hold non-polar molecules together originate in induced dipole-induced dipole interactions; therefore, polar molecules can interact with non-polar molecules by dipole-induced dipole interactions. But they may still think of solubility as a dichotomous property, seeing that all of the dichloroethane had transferred into the pentane. To allow students to see intermolecular interactions as a continuous measure, we replaced the dichloroethane with acetone (Figure 1a, right cylinder). Being only a proton acceptor, the acetone is less attracted to the water than the methanol was (both a proton donor and acceptor), and partitions between the two phases (Figure 1b). If the substances are ordered twice, once according to their

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[1] Except for methanol, which becomes miscible with most hydrocarbons (C < 7) at slightly elevated temperatures (Kiser et al., 1961). In our case, methanol and pentane are miscible at temperatures above 15°C.

relative affinity to water, and a second time according to their dipole moments, the need for a more refined definition of substance polarity becomes evident.

Presentation and results

The two authors have used this set of demonstrations on six different occasions (Table 1). In all cases, the topic of intermolecular interactions was taught during two lecture sessions to first year general chemistry students at two large research universities. The first session was a background lecture, in which all the relevant theoretical concepts were taught (such as hydrogen bonds, dipole-dipole interactions and London dispersion forces). The second session was devoted to the interactive presentation of the demonstrations. For each demonstration, the system before shaking was shown, together with structural formulas for all substances and their dipole moment values. The students were asked to predict the state of the system after a short vigorous shake, and discuss their predictions among themselves. Following a short discussion (2-3 minutes), the students used an electronic classroom response system to vote for one of the following options: (1) The colorless layer will stay separated; (2) It will mix with the water layer; (3) It will mix with the pentane layer; (4) It will mix with both. After the votes were collected and displayed to the students, the result of the shaking was shown. The instructor followed up each demonstration with a discussion of the result, soliciting explanations from the class, and addressing the students' predictions. The discussion following the first demonstration (methanol, water and pentane) concerned the polarity of the methanol and its ability to form hydrogen bonds, whereas the pentane is non-polar and does not form hydrogen bonds. The second discussion (following the dichloroethane, water and pentane demonstration) focused on the differences between hydrogen bonding and dipole-dipole interactions, including a summary of the necessary conditions for hydrogen bonding to occur. The third demonstration (acetone, water and pentane) was followed by a discussion of relative polarity, in terms of relative strengths of interactions between solvent and solute.

Table 1. Distribution of students' predictions of the three demonstrations.*

Tested solvent	*Prediction*	*Confrontation mode*	*Refinement mode*	
		University A Spring 2005 n = 277+241	University A Fall 2006 n = 387+322	University B Fall 2004/5 n = 140+127
methanol	Stay	1%	N/A	N/A
	Mix with water	**90%**		
	Mix with pentane	8%		
	Mix with both	1%		
1,1-dichloroethane	Stay	9%	21%	21%
	Mix with water	77%	39%	47%
	Mix with pentane	**7%**	**25%**	**16%**
	Mix with both	7%	15%	16%
acetone	Stay	10%	13%	4%
	Mix with water	36%	23%	16%
	Mix with pentane	26%	5%	9%
	Mix with both	**28%**	**59%**	**71%**

* Correct prediction is in bold. Each column combines data from two different sections of the same course. In university B, the two sections were taught in two different academic years.

The procedure for staging each demonstration was always the same. However, we found out that the way the students interacted with them was dependent on the emphasis given to certain concepts in the background lesson. This resulted in two different presentation modes, the *confrontation* mode and the *refinement* mode, which correspond to the two theoretical approaches described in the introduction.

Confrontation mode

In the spring of 2005, one of us had taught the topic of intermolecular interactions in a traditional manner without emphasizing the differentiation between dipole-dipole interactions and hydrogen bonds, and without emphasizing interactions between different types of molecules. The instructor did emphasize the rule of ‘like dissolves like’, and showed a demonstration of how iodine transfers from a polar water phase into a non-polar dichloromethane phase. The fact that dichloromethane is considered non-polar, even though its molecules have a dipole moment comparable to water ($\mu = 1.60D$), was never mentioned. Following this lesson, the instructor was introduced to the demonstrations, and decided to implement them on the next lesson. The results of the students’ votes on each demo, in the following lecture, are given in Table 1.

The first demonstration can be classified as a *verification demonstration*. The students have been taught a rule, and were asked to apply it in a specific case. 90% of the students were able to apply the rule correctly.

The second demonstration can be classified as a *confrontation demonstration*. Almost none of the students expected the result of the demonstration – they applied the rule, according to the best of their understanding, and obtained an incorrect result. It is evident that there is one prime misconception that guides their thinking – 77% of the students chose the same incorrect answer

In the first and second demonstrations, the students’ vote was almost unanimous. There was little room for discussion, as the students just technically followed a rigid rule. Only after the second demonstration caused them to be dissatisfied with the algorithmic application of the rule, could they start to explore the meaning of the concepts behind the rule.

The third demonstration can be classified as a *refinement demonstration*, because the students need to refine their use of concepts such as ‘like’ and ‘polar’, to fit what they saw in the second demonstration and predict the outcome of the third. The results show that students are indeed exploring different avenues, as no one prediction gets a majority of the votes.

Refinement mode

On four other occasions, the topic was taught by both authors at their respective universities, with a different emphasis. In light of the demonstrations, the emphasis in the background session was on the differentiation between dipole-dipole interactions and hydrogen bonds, and on possible interactions between different kinds of molecules. The rule of ‘like dissolves like’ was presented as a guideline, rather than a strict rule. Also, the notion that different intermolecular interactions can be at work simultaneously for a single substance was emphasized and described for various examples, such as detergent molecules and phospholipids membrane molecules.

In this presentation mode, the first demonstration was just explained and demonstrated, without student interaction. The rationale was that if the students don’t know what to expect, they have to resort to use memorized rules, as they did in the previous mode. By showing an *expository* demonstration, the students know what to expect, and can start applying their reasoning to identify relevant distinctions that will help them transfer the results of the first demonstration to the other systems. In this case, we expected them to note that methanol is like water in two ways – it is both polar and can form hydrogen bonds. This point was raised in the discussion.

The effect of the demonstration mode can be seen in the shift of distribution of student responses for the second demonstration. The results show that students are exploring these different options rather than following a rule, as no prediction gets a majority of the votes. Therefore, in this mode of presentation the second demonstration serves as a *refinement* demonstration, where students try to see which aspects of 'like' are more relevant in the current context.

In the third demonstration, there is a majority of students that chooses the correct prediction, a considerable increase from the prior case in which the third demonstration followed a *confrontation mode* presentation. Nevertheless, it is unlike the almost unanimous vote of 90%, encountered in the verification demonstrations. The students don't have a rule they can go by; they need to weigh the different possibilities and be open to the novel concept of partitioning of a solute between two solvents, which emerges from the outcome of this demonstration. Therefore, we regard this as a second *refinement* demonstration.

Conclusions

Design

We have shown an effective method for designing refinement demonstrations, which focus on the similarities between the multifaceted nature of expert knowledge and the limited experience base of students. It starts with an exploration of the way experts apply the target concepts in specific contexts, trying to identify implicit distinctions and interactions between concepts that they use to guide their meaning making process. Then the knowledge base of the students is compared against these distinctions and interactions, and the following questions are asked: Are the students likely to under-differentiate and treat two different concepts as synonyms, because they are unaware of any cases in which the two concepts don't coincide? Are they likely to over-differentiate and treat a single continuum as mutually exclusive categories, because they haven't encountered any intermediate states? If the answer is positive, a demonstration is constructed to provide an experience that will help the students refine their understanding by differentiating seemingly similar but fundamentally different concepts, or integrating seemingly different but fundamentally similar concepts.

This design method is not unique for the topic of intermolecular interactions, and can be applied to any topic in which students tend to over-generalize or over-simplify because of their limited experience with chemical phenomena.

Presentation

This study was not designed to compare the effect of different modes of presentation on students' understanding and retention of the relevant concepts. However, we trust the research literature documenting the benefits of peer interaction, and believe that fruitful classroom discussion will ultimately lead to these desired goals. The data we presented suggests that if the objective of lecture demonstrations is to encourage discussion among students, then verification and confrontation demonstrations provide little opportunity for that. A good discussion will only occur if students are divided in their opinions, with a substantial fraction supporting at least two different opinions (Crouch and Mazur, 2001). Table 1 shows that in both the verification and the confrontation demonstrations, most students agreed on the prediction (whether right or wrong). Refinement demonstrations are more likely to produce a fruitful discussion, because each one of the relevant concepts has merit in a specific context (rather than being just 'right' or 'wrong'), and therefore each one can be argued for or against. This is supported by the data, which shows a larger spread in predictions for the refinement demonstrations. While the confrontation mode of presentation can serve to stimulate surprise and interest on the part of students because of the unexpected result, it does not appear to be an effective way for them to learn about the scientific basis of the apparent anomaly. The refinement mode of presenting a demonstration is more effective at helping students extend their reasoning to new and ambiguous situations. Based on our personal experience in conducting these lessons, we feel that the class discussion which followed each demonstration was more productive in the refinement mode. The outcome of such discussions is a better understanding of the relation between different concepts, and the ability to apply the relevant concept in the appropriate context.

We also found the demonstrations had great impact on our approach to teaching the subject in the introductory lesson. Being ourselves explicitly aware of the different meanings the rule ‘like dissolves like’ acquires in different contexts, we changed the emphasis of the lesson. More attention was given to differentiate hydrogen bonds from dipole-dipole interactions, and to show similarities between permanent dipoles and induced dipoles. This emphasis during the introductory lesson wasn’t enough to bring the desired learning outcome, as can be seen from the results of the students’ predictions to the second demonstration in the refinement mode. However, it sets the theoretical background to which the results of the demonstrations can be tied back, and gives the students the required vocabulary to conduct meaningful and fruitful discussions.

Our presentation concentrated on a specific topic. Still, this approach is applicable in most other topics in chemistry in which students have limited experience. Following a similar design process, refinement demonstrations can be constructed for many other hard-to-teach concepts. We believe that it is only through discussions of actual phenomena that the students can construct a mature scientific understanding of such concepts. The validity or utility of scientific concepts cannot be decided by theoretical arguments alone. Their validity and utility are always associated with specific contexts, and their meaning is derived from their application in these contexts. It is imperative for a novice to be introduced to these contexts, and be provided with an opportunity to discuss the relevant concepts in context. The effective design of lecture demonstrations provides such a context. Their effective presentation provides the opportunity.

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Educational research

Interactive lecture demonstrations: a tool for exploring and enhancing conceptual change

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Abstract: Interactive Lecture Demonstrations (ILD) are a student centered teaching method, in which students are asked to predict the outcome of an experiment, observe the outcome, and discuss it with respect to their former expectations. The demonstrations are designed to contradict students' known misconceptions, generate cognitive conflict and dissatisfaction with the existing conception, and promote a process of conceptual change. An ILD based course was used to explore the effect of cognitive conflict on the conceptual change process, and the role of student interactivity in this process. Three major levels of conceptual change were identified: high – students who remember the outcome of the demonstration, and explain it using the consensus model; medium – students who can recall the outcome, are dissatisfied with their alternative model, but do not switch to the consensus model; and low – no meaningful recollection of the outcome, and no change in the alternative model. A multiple-choice test based on the lecture demonstration was given to two groups, one of which only observed the demonstrations, without predicting and discussing. We found a significant difference between the groups, with an obvious drop in students' ability to recall the outcome of the demonstrations in the non-interactive group. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 197-211]

Keywords: Interactive Lecture Demonstrations (ILD), conceptual change, cognitive conflict, mental models, levels of conceptual change

Introduction

Science is a human endeavor to interpret natural phenomena in an efficient and consistent way, which allows accurate predictions and coherent explanations. Students often interpret natural phenomena in naïve ways, which may differ radically from what modern science considers as efficient or consistent (Driver et al., 1985). Such personally constructed interpretations have proved difficult to change by traditional instruction. One important goal of research in science teaching is to construct methods guiding learners to think in terms of efficient and consistent scientific concepts. This means helping individuals to transform their *mental models* (internal representations of objects, events and processes individuals construct in order to predict and explain phenomena) into the *consensus models* (the expressed representations used by the scientific community for the same purpose) (Gobert and Buckley, 2000). This is a process of *conceptual change*. The change from naïve mental models to consensus models is seldom straightforward, and many times it goes through intermediate stages which combine parts of both models – a *hybrid model* (Galili et al., 1993). In this work, we refer to both naïve and hybrid models as *alternative models*, to distinguish them from the scientifically accepted consensus models.

A major difference between alternative models and consensus models is in the range of their validity. While alternative models are usually only consistent with the limited experience base of the individual, the consensus models are based on the collectively accumulated experience of generations of scientists. The efficiency of consensus models arises from their consistent capability to predict and explain a vast range of phenomena using a small set of assumptions and rules. Therefore, to facilitate the process of conceptual change, students should become familiar with a larger set of natural phenomena than they normally encounter in everyday life. For this purpose, we devised an extensive set of lecture demonstrations, which introduce students to phenomena that cannot be easily predicted or explained by their naïve personal models.

Our approach was partly inspired by the work of Posner and his colleagues (Posner et al., 1982; Strike and Posner, 1992). Their theory of conceptual change is based on the historical development of science. They argued that students will be willing to change their alternative models only if they are dissatisfied with them, and the proposed model proves to be more fruitful. Therefore, students should be confronted with discrepant events and anomalous data their existing models cannot account for, in much the same way that new discoveries in science challenged existing theories. Concurrently, the students should be exposed to a consensus model which is able to account for the new data. In light of this theory, methods for promoting conceptual change have focused on establishing conditions where the student's existing conception can be made explicit, and then is directly challenged to create a state of conflict. However, Posner et al. (1982) admitted that while such a *cognitive conflict* is a necessary condition for conceptual change, they do not expect its mere introduction to be sufficient to induce the change, nor to make the process straightforward.

More recent studies of the effect of cognitive conflict on promoting conceptual change have corroborated this expectation (Limon, 2001; Mason, 2001). Instead of directly addressing the anomalous data and modifying their existing conceptions, students exhibit a diverse range of behaviors in response to being confronted with discrepant events (Chinn and Brewer, 1993, 1998; Tirosh et al., 1998; Shepardson and Moje, 1999; Mason, 2001; Kang et al., 2004). For example, Chinn and Brewer (1998) describe a progression in the ways in which undergraduate students respond to reported anomalous data: (1) Ignoring – the outcome simply goes unnoticed; (2) Rejection – denying the validity of the discrepant event and explaining the reasons for rejection; (3) Uncertainty – not sure if data is believable; (4) Exclusion – considering the discrepant event as irrelevant; (5) Abeyance – expecting that their existing model might be able to explain the anomalous data in the future; (6) Reinterpretation – making peripheral changes to the data so the existing model can fit it; (7) Peripheral theory change – Accepting the data and making peripheral changes to the existing model; and (8) Theory change – Accepting the data and fundamentally changing their model to accommodate the new data. In all the above scenarios save the last, the students' confrontation with anomalous data did not result in conceptual change. In many of the scenarios, the students found a way to avoid the conflict, and reconcile the anomalous data without having to consider their existing model.

In order to encourage students to actively employ their existing models in the context of lecture demonstrations, and thus make conceptual change more likely, we followed the Interactive Lecture Demonstration (ILD) teaching strategy (Sokoloff and Thornton, 1997). In this method, the students are asked to predict the outcome of a demonstration and write down their prediction and an explanation, and therefore commit to an explicit model. Peer discussion follows, with the students discussing their predictions in small groups – again, they have to address their existing models explicitly. The instructor engages the class, soliciting predictions and highlighting common predictions. The demonstration is then performed, and the instructor discusses the results of the demonstration in view of the students' previous predictions, emphasizing the conflict and providing the consensus way to resolve it.

In addition to enhancing students' commitment and explicit involvement in the conceptual change process, the highly interactive nature of the teaching method allowed us to investigate the different ways in which the students were involved in this process. To this end, we conducted a combined qualitative and quantitative study regarding the effect of interactive lecture demonstrations on students' conceptual change process. Our research questions were:

1. What are the possible effects of the cognitive conflict, triggered by the lecture demonstrations, on students' conceptual change process?
2. What is the contribution of the interactive part of the ILD method, as compared with passive lecture demonstrations?

Pedagogical Context

The study was conducted over a period of three years, starting in the fall semester of 2001, while the second author was teaching the course 'General Chemistry for Biology Majors'. This is a one-semester freshman course, given each fall, with an average enrollment of 200 students.

Content

The fall semester is 14 weeks long. One week was devoted to each of the following topics:

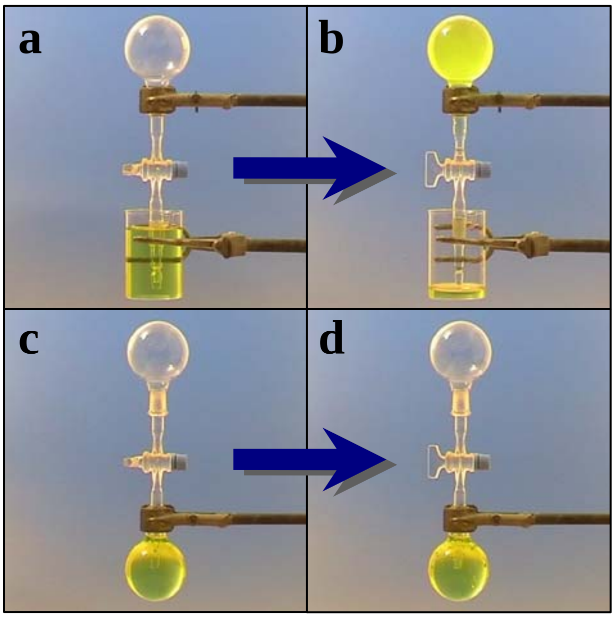
1. Chemical change and conservation of mass.
2. Particulate nature of matter.
3. Electronic structure of metallic, ionic and molecular substances.
4. Quantities in chemistry: mass, volume and number.
5. Electrolytic decomposition and reactions in aqueous solution.
6. Thermal energy, motion and temperature.
7. Interconversion of chemical and thermal energy.
8. Theories of bonding and molecular structure.
9. Intermolecular interactions and physical properties.
10. The ideal gas law and the kinetic molecular theory.
11. Collision theory and the rate of chemical reactions.
12. The dynamic nature of microscopic equilibrium.
13. Acid-base equilibrium (2 weeks).

Each week, the class met for two 90 minute lecture periods, plus one 90 minute small group recitation session.

Teaching Method

One lecture period each week was devoted to the discussion of lecture demonstrations. For each topic (except for topic 8), we developed a sequence of 3-5 demonstrations, all of which can be explained using the same consensus model. Some of the demonstrations were designed with the expectation that most students will predict the outcome correctly, even if they just use common sense gained from everyday experiences. However, at least one demonstration in each sequence was designed to contradict predictions based on common alternative models, as known from existing misconception literature (Pfundt and Duit, 2000) and our own pilot study (to be described under the Methodology section). Figure 1 shows an example of a common sense experience vs. the *conflict demonstration* in topic 2, designed to counter models which consider vacuum as exerting a pulling force (Nussbaum, 1985). The demonstrations were projected on a large screen, using a video camera connected to the classroom's projection system, so that all students could see them clearly.

Figure 1. Common sense experience vs. conflict demonstration.



(a) The demonstration system is composed of an evacuated glass bulb (top), connected through a closed valve to an open glass containing water with green food coloring. (b) When the valve is open, the water is pushed by the pressure of the atmosphere into the evacuated bulb, creating the common sense feeling of suction, as if the vacuum was 'pulling' the water up. (c) The experiment is repeated, this time with an air-tight closed glass bulb at the bottom. (d) When the valve is opened, the water stays at the bottom – the vacuum by itself has no 'pulling' force, and the rigid wall of the container keeps the atmospheric pressure from pushing the liquid up. For a video of the demonstrations, visit http://www.fh.huji.ac.il/~guy/links/CERP2007a.html .

The structure of the lesson for each demonstration was:

1. The instructor shows the class the experimental setup, and explains what he is about to do.
2. The students select one of the pre-determined possible outcomes, and write down an explanation for their prediction on a Prediction Sheet (Figure 2), which is collected at the end of class.
3. The students discuss their predictions with their neighbors for 3-5 minutes, and then vote for one of the possible outcomes.
4. The instructor displays the distribution of predictions, and solicits explanations from the class for the different opinions.
5. The instructor performs the demonstration, noting which of the predictions proved correct. Students record the results on a Results Sheet, which they keep.
6. The instructor projects a PowerPoint slide that offers different explanations for the observed experimental result, only one of which uses the consensus model (Figure 3). The other explanations are based on known students' alternative models. The students discuss the alternatives among themselves and vote for the best explanation.
7. The instructor discusses the outcome of the experiment using the consensus model, while explicitly referencing students' alternative models and noting their deficiencies and limitations.

The prediction and discussion prior to the demonstration help students to construct an explanation based on their personal models. The outcome tests the validity of these models and demonstrates their limitations (generates a cognitive conflict). The discussion of alternative explanations, after seeing the outcome, illustrates the wider domain of validity of the consensus model over the alternative models, and therefore establishing its fruitfulness.

Figure 2. Part of the prediction sheet for topic 2.*

Demo 3

The nozzle of an evacuated bulb is inserted into a flask filled with water.

Predict the state of the system after the valve is opened.

Provide a short explanation:

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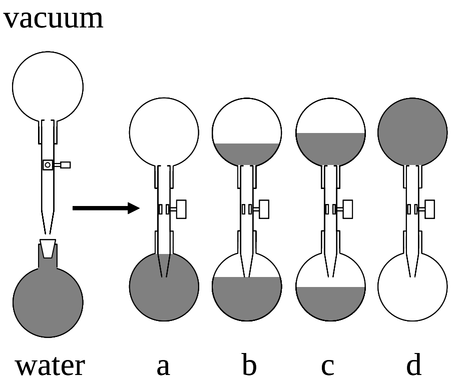


* The pre-determined distracters for the predictions (a-d above) were taken from the pilot study. The complete sequence included four demonstrations. The first is depicted in Figure 1a and 1b; the second used the same system as above with NO_2 (a brown gas) instead of water; the third is depicted above; and the fourth used NO_2 + air (instead of vacuum). For videos of all the demonstrations, visit http://www.fh.huji.ac.il/~guy/links/CERP2007a.html .

Figure 3. A follow-up discussion question for the conflict demonstration.

Which of the following statements best explains the observed phenomena (the liquid stays down)?*

1. If the liquid went up to fill the vacuum on top, vacuum would be formed at the bottom.
2. The particles in the liquid are attracted to each other, and to the earth.
3. The negative pressure by itself is not strong enough to overcome the weight of the water.
4. The liquid has the property of keeping its volume, and filling the bottom of the flask.

* Explanation 1 is based on the model that vacuum causes water to move because matter has an aspiration to fill empty space. Explanation 3 is based on the model that vacuum is a negative pressure that pulls on the water. Explanation 4 is correct, but is limited to liquids. Explanation 2 uses the consensus model which analyzes the system in terms of particles and forces between them.

Methodology

In educational research, one must take into account the complexity of human thinking and its influence on the process of learning. Different individuals often act differently under the same circumstances, and the same individual may act differently under different circumstances. Before trying to assess the impact of a new teaching method at the population level, one must first get acquainted with the possible different ways in which each individual can be affected. We therefore employed a combined qualitative-quantitative methodology in this study.

Pilot Study

In fall 2001 we ran the course for the first time, in order to fine tune the teaching method, and construct a research based questionnaire for the quantitative study. The teaching method was similar to the one described above, with two changes: there were no pre-determined possible outcomes in step 2, and no pre-determined alternative explanations in step 6. Instead of selecting a prediction from a list of options, the students were asked to draw their own prediction on the prediction sheet, before writing their explanations. The prediction sheets were collected at the end of the lesson, and students were given credit for handing them in, regardless of the correctness of their responses.

We used the prediction sheets to learn about students' alternative models in the context of the demonstrations. The collected data was analyzed according to the facets-schemes method (Galili and Hazan, 2000). Initially, responses which seemingly presented the same meaning were grouped together, even if they were expressed in somewhat different wording. Then, we identified representative categories of explanatory patterns or strategies employed by the students in addressing particular situations. These are the observable facets of knowledge. At the last step, we grouped facets of alternative knowledge elicited in different experimental contexts around a smaller number of less specific explanatory models. These models represent the tacit underlying schemes of knowledge.

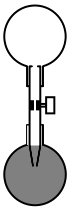
Following the analysis, we completed the lesson plans for the subsequent years. We chose pre-determined predictions for step 2, and alternative explanations for step 6.

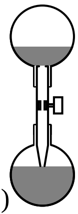
Next, we constructed a conceptual test based on the facets-schemes analysis. In every topic, we chose a single demonstration which proved to be the hardest to predict correctly, and constructed two multiple-choice questions addressing the specific demonstration. The first question in each pair is a prediction question, for which we chose the most common students' predictions as distracters. The second question asks the student to select the scientific explanation out of five options, four of which correspond to the most common alternative models. Figure 4 shows sample questions from two topics.

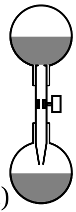
The questionnaire was aimed to measure whether students accept the anomalous data provided by the conflict demonstration, and whether they can recognize explanations based on the consensus models taught in the course. The completed questionnaire was examined for correctness and intelligibility by one other chemistry professor and two high-school chemistry teachers. Since the questions were taken directly from the teaching materials, content validity is inherent.

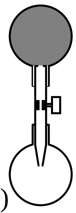
Figure 4. Part of the conceptual test, for topics 2 and 11.

3. The nozzle of an evacuated bulb is inserted into a closed flask filled with water, and the valve is opened. How will the system look after one minute?

a)


b)


c)


d)


4. What is the accepted scientific explanation for this phenomenon?

a) The liquid flows from high pressure to low pressure in order to equalize pressures.

b) The liquid flows up in order to fill the empty space.

c) There is no force pulling upward.

d) Gravitation pulls the liquid down and the vacuum pulls it up.

e) The liquid conserves its volume, therefore the system cannot act to fill the vacuum.

19. 40 mL of 3.0 M $HCl(aq)$ react with excess limestone in an open flask, releasing carbon dioxide gas according to the equation:

$$CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + H_2O(aq) + CO_2(g)$$

The graph of the change in weight of the reaction flask in the first minute is linear, with a slope of -0.3 g/min. The experiment is repeated with 20 mL of 6.0 M $HCl(aq)$. In both cases the acid covers all of the stone. What will the slope of the graph of the change in the system's weight be, in the first minute?

a) Steeper than -0.3 g/min.

b) -0.3 g/min.

c) Less steep than -0.3 g/min.

20. What is accepted scientific explanation for this phenomenon?

a) The rate of collisions between the reactants' particles is greater.

b) The number of moles of acid is equal.

c) Larger volume means a larger surface area.

d) There is less acid in the second experiment.

e) The stronger acid can overcome the activation barrier more easily.

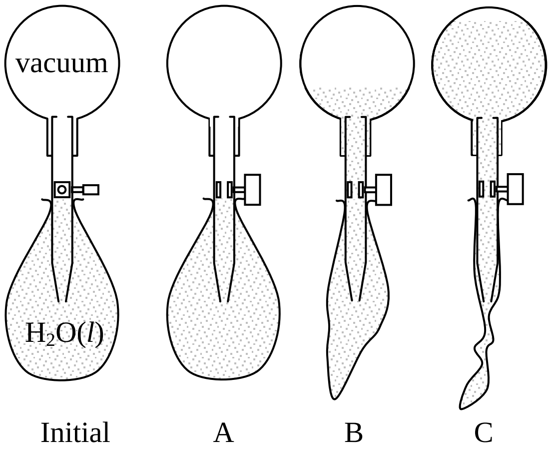
Qualitative Study

In this part of the study, we characterized the levels of conceptual change attained by the students. In other words – do they think about phenomena in terms of consensus models, or do they still use their naïve mental models?

This study was conducted during the fall 2002 semester. From all the students who fully participated in the class in the first 4 weeks (filling all prediction sheets completely, and solving all homework problems), twelve were picked for personal semi-structured interviews. Each student was interviewed 3 times throughout the semester, at week 4-5, week 8-9 and week 14 (end of the semester). Each interview was approximately an hour long, and included questions about learning in general, and specific content questions. There were two types of content questions: recall and near transfer. Recall questions addressed the demonstrations that were presented in class: what happened, how they explained the outcome in the prediction sheet, how would they explain it now (during the interview), and (in the relevant cases) why did they change their explanations. Near transfer questions concerned a similar system, but in a slightly different context. Figure 5 shows an example of a near transfer question (compare to Figure 2).

When analyzing the interviews, we compared the students' models that emerged from the interviews to the models that emerged from their prediction sheets. The comparison focused on three key questions, adapted from the work of Chinn and Brewer (1998): (1) Can the student recall or reconstruct in his mind the conflicting outcome of the demonstration? (2) Does the student offer an explanation to the outcome of the demonstration? (3) Does the student accept the consensus model?

Figure 5. A near-transfer interview question.*



* This system is similar to the one depicted in figure 1c, except that the water is held in a flexible plastic bag, instead of a rigid glass bulb. The student is asked to predict what will happen to the system when the valve is opened (1) on the Earth, and (2) on the moon.

Quantitative Study

This part of the study examined the contribution of the interactive part of ILD to the overall effect of lecture demonstrations on students' conceptual levels. We used an experimental comparative design. Because we consider ILD to be the norm in our course, the experimental 'treatment' was the discontinuation of the interactive part half way through the semester. This was done in fall 2002. After week 8 (that didn't have any demonstrations associated with it), the instructor stopped using the interactive components (steps 2, 3, 4 and 6 of the teaching method) in his lectures. The instructor still carried out all the demonstrations (steps 1 and 5), and discussed students' alternative models after showing the result of the demonstration (step 7). However, these models were not solicited from the students in class, but merely presented to them as experience gained from the pilot study ("*When I taught this topic last year, many students thought that…*"). Skipping the prediction and discussion part of the demonstration freed up a lot of lecture time. Since the same time was still allotted for each topic, the lectures in the second part of the course included more detailed explanations by the instructor regarding the consensus model.

The control group, in fall 2003, continued to learn using ILDs throughout the entire semester. The two groups were comparable in terms of academic achievement. At the end of the study, we obtained the group grade average of participating students in six other courses (in biology, physics and math), which showed no significant difference ($t = 1.44$, $p > 0.1$) between the treatment group (85.2 ± 11.5, $n = 115$) and the control (83.0 ± 13.0, $n = 141$).

In both groups, we administered the multiple-choice conceptual test on the last day of the course. The students weren't informed about the test in advance, and therefore the test reflects the knowledge and understanding they constructed during the course, before they started preparing for the final exam.

Results

Qualitative Study

From the interviews, we have identified three major levels of conceptual change. Each level is associated with a different degree of impact that the cognitive conflict had on the student's prior model. To promote clarity, we limit the presented evidence to students' citations that pertain to topic 2, which was described in detail in the previous sections. This topic had the largest percent of wrong in-class predictions – only 1/3 of the students, each year, predicted the conflict demonstration correctly (option a in Figure 2), while the other 2/3 expected at least part of the water to go up into the vacuum (nearly equally split between options b and c in Figure 2). Similar levels of conceptual change were identified across all topics.

High Level

At this level, the students recalled what they saw in class, they recalled their previous explanation, and they changed their explanation in the interview to one which conforms with the consensus model. In most cases, the students declared that the conflict demonstration helped them to sort out their conceptions and to change them. For example:

> Q: In demo 3 [Figures 1c, 1d], you now say that you remembered that the water stayed down, but you predicted something else, as you can see in your sheet. What did you feel when you saw a different outcome?
>
> A: It changed my conception. It changed my conception [repeating, for emphasis]. Like, my previous conception was from that I had no knowledge of chemistry, and I didn't deal with such things. And my conception was that the vacuum is really a sort of suction force, and because of this I thought the water will go up. […] There will be here the same vacuum as here [points at the top and the bottom bulbs in option 'c' in Figure 2], because it is a kind of a suction force, and will result in an equalization of pressures. But after we, like, saw – I understood why it is not like that […]
>
> Q: When you saw it, did you change your conception at the same moment?
>
> A: No. I was very surprised when I saw it. I'm speaking about during the course, after the instructor explained it to us, and after I read about these topics […] And especially after I saw it, that it really doesn't happen. Because of this I think these demonstrations are very important. Because if you just came and told me, like tell me in class that someone did this experiment, show me these drawings and tell me 'this is what happened', I probably would not remember it now. But I remember it because I remember it surprised me, and I remember I pondered over it. Like I didn't understand why it is so. It is a process.

There was some variability within this broad level. Some of the students that successfully used the consensus model to explain the lecture demonstration, did not succeed in predicting or explaining the answer to the near-transfer question by themselves. However, these students were able to answer correctly after being prompted by the interviewer to go back to the prediction sheet and look for a similar situation they have already seen in class.

Medium Level

At this level the students recalled what they saw in class, they recalled their previous explanation, and they were aware that it was inadequate to account for the outcome of the conflict demonstration. However, the model they used to explain this outcome in the interview was not the consensus model, but a different alternative model. They were often unsure about their new model, and used it hesitatingly. For example:

> [While answering the near-transfer question in topic 2 – Figure 5] Maybe the [atmospheric] pressure can influence outside of the bag, and it will be half-and-half […] because then there will be equal pressures. There is gravity that pulls downward, and on the other hand it is pulled [up]

> because of the vacuum, then it probably equalizes there […] I learned in class that vacuum is not a force, but somewhere… [hesitates] it is still like… but the vacuum pulls! I don't remember what caused the vacuum to pull – this is the principle I'm trying to recall. I know it is not a force, but there is something in it that causes a force.
> Q: Let's get back to the lesson. In demo 3 [Figures 1c, 1d], the instructor opened the valve. Do you remember what happened?
> A: It seems to me now that the water didn't go up. I don't remember. [Asks for verification] Yes? There is no atmospheric pressure to push them up. There is just the vacuum that I don't remember what it does. […]
> Q: You wrote that the vacuum will cause it to go up. Why?
> A: Back then I was sure that vacuum is a force, and when you have vacuum it pulls. I didn't know then about the force of atmospheric pressure, about all these things. […]
> Q: When you see things that don't behave as you expected…
> A: It amazed me. I didn't have the smallest bit of idea why it didn't go up. I tried to think why it happened, but no idea came to my mind.
> Q: When you think of something and it comes out the opposite, does it frustrate you or do you want to know why?
> A: I want to know why, because it annoys me that I'm not right!

Again, there is some variation in this category. Some students just switched from one naïve model to another. Others, like the one in the example, made an effort to incorporate the consensus model into their existing scheme. While this student struggled to make sense of the new model, she did not abandon her previous model. This resulted in a hybrid model, in which the pulling force of vacuum complements the pushing force of the atmospheres.

Low Level

Students that belong to this group did not remember the outcome of the demonstration. Without a vivid memory of the demonstration, they could only rely on their alternative models when they tried to recollect what happened in lecture. This resulted in students giving incorrect predictions to experiments they had actually observed in the past. For example:

> Q: Can you explain what you saw in demo 1 [the common sense experience in Figures 1a, 1b]?
> A: I remember that what I was thinking wasn't correct [laughs in embarrassment], but I still remember what I thought then.
> Q: What did you think then?
> A: That there is some kind of aspiration of matter to spread out into the vacuum. That is, it will flow in the direction of the vacuum, and fill the bulb. But I think this is not the correct explanation. […] It is like drinking with a straw, where the vacuum is equivalent to a pressure acting on the liquid, pulling it up – it [the liquid] seeks to fill it [the vacuum]. […] It is not really a force – the vacuum has no force, but because matter seeks to fill it, so to speak, then the pressures' differences are those that push it up.
> Q: Do you remember what happened in demo 3 [Figures 1c, 1d]?
> A: [Asks herself hesitantly] Could it be 'd' [in Figure 2]? [Laughs in embarrassment] I don't remember. [Suddenly sounds more sure] OK – there is a vacuum on top, so it would equilibrate, and it could be c as well. It is actually a balance between the two bulbs, something like that, because it is a closed system, and the pressures between the bulbs want to be balanced and will reach some state of equilibrium.
> Q: This is what you wrote in the prediction sheet. Let me tell you what actually happened – the water didn't go up.
> A: OK… [sounds doubtful, gives a puzzled look]
> Q: When I remind you now, can you recollect why it didn't go up?
> A: I really don't remember. [Asking herself] Why didn't it go up? Maybe because it is a liquid, contrary to a gas, where the gas spread out in the second demo and filled the container, and the water didn't.

This is an example of a student who cannot let go of her prior scheme that matter flows purposefully in order to fill the vacuum. Even though she's aware that her explanation is incorrect, she still used the same argument when answering the near-transfer question. Her inability to explain the conflict demo in class has led her to ultimately ignore this data, and she couldn't remember the fact that it contradicted her expectation. When re-confronted with the anomalous data, she chose to exclude it, by suggesting that while her model works well for gases, liquids might behave differently.

Other variations of low level responses included students who just declared they did not understand the subject matter, and a few cases of students who actually believed that they saw what they expected to see.

To summarize, the three levels differ in their ability to recall and explain the phenomena they saw, and this ability is connected to the degree to which they changed their prior models. Students at the low level of conceptual change cannot recall the outcome of the conflict demonstrations. They have not been affected by the conflict, and did not undergo any conceptual change. Students at the medium level of conceptual change can recall the outcome of the conflict demonstration, but cannot give a scientifically accepted explanation. They have been affected by the conflict, but their conceptual change is limited, because they could not give up their alternative models. At the high conceptual change level, students can both recall and give a scientifically accepted explanation. They have completed the process, as they started out with an alternative model, and can now use the consensus model.

Quantitative Study

In light of our findings in the qualitative research, we classified students' responses to each pair of questions on the conceptual test (Figure 4) into similar categories. A student's understanding of a specific topic was classified as *high conceptual level* only if both the prediction (first question) and explanation (second question) were correct; as *medium conceptual level* if the prediction was correct but the explanation was incorrect; and as *low conceptual level* if the prediction was incorrect, regardless of the correctness of the explanation.

Since the goal of science teaching is for students to achieve a high conceptual level, we calculated the students' *conceptual score* by counting the number of topics in which they attained a high conceptual level (both explanation and prediction are correct). Because we changed the teaching method for the treatment group partway through the semester, we calculated two conceptual scores for each student – a score for Part I of the course (topics 1-7, maximum score = 7), and a score for Part II (topics 9-13, maximum score = 5). By looking primarily at the high conceptual level we also minimize the effect of random guessing, because the chances of correctly guessing both the prediction *and* the explanation are between 1:10 and 1:20.

To determine the effect of the experimental change in teaching method, we need to compare the two groups' conceptual score in Part II, in which passive lecture demonstrations were used with the treatment group. Because the groups are not necessarily equivalent, we need to control for any disparity that might affect the difference in this conceptual score between the two groups. We expected, and found, a statistically significant correlation between the students' conceptual scores on part I and on part II, with $R^2 = 0.26$, and $p < 0.001$ (this means that 26% of the variance in the score on part II can be explained by the variance in the score in part I). It is safe to assume that the students' scores on Part I were not significantly affected by the different treatments they received in Part II. We can therefore use the conceptual scores in Part I as a covariate in ANCOVA, and thus account for possible disparity between the groups. The conceptual score in part II is the dependent variable, and interactivity in the teaching method is the independent variable. The results of the ANCOVA are summarized in Table 1, and show a statistically significant difference in conceptual score between the groups ($p < 0.001$). There is a medium positive effect ($d = 0.48$) of the interactive method over passive lecture demonstrations.

Table 1. ANCOVA results for the effect* of interactivity on students' conceptual achievement score (0-5) in Part II of the course.

Adjusted Means ± SD			
Interactive LD	Passive LD	*p*	*d*
2.55 ± 1.16	2.02 ± 1.10	0.0002	0.48

* *d* is Cohen's effect size. 0.48 is considered a medium effect.

To better understand the meaning of this difference, it is instructive to see how the distribution of conceptual levels changes when interactivity is discontinued, as shown in Table 2. In the fully interactive course (control group), only ~30% of students' responses are at a low conceptual level, and more than 50% of the responses show a high conceptual level. Similar numbers appear in the first part of the treatment, which was also taught with ILD. However, when interactivity is discontinued in the second part of the treatment course, this situation reverses – as many as 51.8% of the responses are at a low conceptual level, and only 38.3% are at the high conceptual level.

Table 2. Percent distribution of conceptual levels, in each part of the two runs.

	Interactive Throughout		Interactivity Discontinued	
Conceptual Level	Part I (ILD)	Part II (ILD)	Part I (ILD)	Part II (LD)
High	58.6	52.8	51.9	38.3
Medium	15.1	12.8	15.9	9.9
Low	26.3	34.4	32.2	51.8

LD = passive lecture demonstrations.

It is also interesting to note that in all four cases a large majority of the students' responses is either at a high or a low conceptual level, and only a small part (10%-15%) is at a medium level.

Discussion

Answer to first research question

The first research question in this study was: "*What are the possible effects of the cognitive conflict, triggered by the lecture demonstrations, on students' conceptual change process?*" Our results show that the effects are varied, and conceptual change can be an evolutionary, rather than revolutionary, process. When confronted with a discrepant event, students may respond in different ways, and attain different levels of conceptual change, that are in overall agreement with the *taxonomy of responses to anomalous data in science* proposed by Chin and Brewer (1998). However, there are a few points in which this taxonomy falls short of describing important features that are relevant to teaching with lecture demonstrations, which we would like to emphasize.

The high conceptual change level matches *theory change* in the taxonomy, in which individuals abandon their former belief in favor of a new one. We noticed that the term ‘abandon’ might be too strong, as some students who attained this level for the lecture demonstration still used their previous model in other contexts (the near-transfer question). As novices, they probably still lack the ability to recognize novel situations in which the newly acquired model would be applicable and fruitful. Nevertheless, after accepting the new model in one context, it was fairly easy for them to apply it, upon prompting, in other contexts. When students attained a high level of conceptual change in a specific topic, they often associated this achievement with their positive experience in resolving the cognitive conflict induced by the lecture demonstration.

The medium conceptual change level matches *peripheral theory change*, in which individuals make minor changes to their theories without giving up the core components. These students were aware of the conflict between their existing model and the outcome, tried to change their explanation to accommodate the outcome, but still did not accept the consensus model. This was because the students found it hard to relinquish their prior beliefs, or because of poor understanding of the consensus model. This process was accompanied by a feeling of struggle between the two models and evident discomfort, which were a direct result of the unresolved cognitive conflict. The quantitative data shows that this level is the least populated – only 10%-15% of the answers to the conceptual test fall in this category, in which the student remembers the outcome, but fails to explain it using the consensus model. This might indicate that students do not stay in such a state of discomfort for a long period of time. However, we can’t tell if this means that these students resolved their conflict by embracing the consensus model, or by receding to a lower level and rejecting the anomalous data.

The most surprising to us was the large percentage of responses which fell into the low level of conceptual change. At this level, students fail to recall the outcome of a demonstration that was performed in front of their eyes, and contradicted their expectations. This matches several of the low level responses in the taxonomy – *ignoring*, *rejection*, and *exclusion*, in all of which the individual does not accept the data. The students at this level hold so strongly to their existing models, that they fail to experience the cognitive conflict. To use a cliché, instead of saying “*I had to see it to believe it*”, such students should say “*I had to believe it to see it*”. They are probably aware of the conflict at the time of the demonstration, but their inability to formulate a meaningful explanation for what they saw leads to rapid fading of any memory of the discrepant event. It seems that the cognitive conflict method fails for those students who need it the most – students who have a difficulty to change their conceptions.

Answer to second research question

The second research question was “*what is the contribution of the interactive part of the ILD method, as compared with passive lecture demonstrations?*” Our results show that the interactive component of the lecture demonstration plays an important role in promoting students’ conceptual change. Its discontinuation at the middle of the semester resulted in a statistically significant drop in students’ conceptual score. The rate of high conceptual level answers decreased, and the rate of low level conceptual answers increased. Without the interactive component, more than half of the students saw a demonstration which should have contradicted their expectations, but had no meaningful recollection of this as a discrepant event. This result is in agreement with the work of Crouch et al. (2004) who studied different modes of lecture demonstrations in physics. They found that just observing a demonstration gave students little advantage over not seeing a demonstration at all, especially in terms of their ability to explain the outcome of the demonstration. Asking the students to predict the outcome of the demonstration before it was carried out had a significant impact on their ability to repeat the prediction correctly and give an acceptable explanation at the end of the course.

The contribution of the interactive component of the lecture demonstrations can be attributed to two factors. The first is that the prediction and discussion steps make the students explicitly aware of their existing models. This increases their awareness to the conflict, and their need to resolve it. It is harder to ignore an unexpected result after you have committed to it in writing, and explained it to your friends. The second is that ILD can be classified as an Interactive Engagement teaching method – designed to promote conceptual understanding through interactive engagement of students in minds-on activities which yield immediate feedback through discussion with peers and/or instructors. Such methods have been shown to consistently produce better conceptual understanding over traditional passive lectures in physics teaching (Hake, 1998, 2002). It is possible that the social interaction and active learning are responsible for the positive effect of ILDs, and not the cognitive conflict generated by the discrepant event.

Conclusions

1. We know that chemistry demonstrations are fun to do, provide concrete examples of abstract concepts, and are a potential source of anomalous data that can trigger conceptual change (Bodner, 2001). However, much of this potential is lost if a demonstration is simply carried out in front of a passive audience. To be effective, lecture demonstrations have to engage all students in activities such as prediction and discussion.
2. Cognitive conflict is not a magic wand that can solve all of the difficulties associated with conceptual change. It helps many students to achieve a high level of conceptual change, but it also fails for many others. Still, ILDs can provide a perfect setting for supporting classroom discussions, without emphasizing confrontation with students' prior conceptions (Ashkenazi and Weaver, 2007). Therefore, both supporters of cognitive conflict strategies and their opponents (such as Smith et al., 1993) can find use for them.
3. ILDs can be used without prediction sheets, just by collecting students' votes with an electronic classroom response system (for example: Wood and Brayfogle, 2006). However, we encourage instructors who use ILDs to ask students to write down their predictions, and collect the prediction sheets at the end of class. Not only does this make students more committed to their prediction, it is also an invaluable source of information for the instructor. It is a rare opportunity for lecturers in large classes to get to know their students' ways of thinking in a very detailed way. Such use of ILD combines its effectiveness as a teaching method for enhancing conceptual change, with its helpfulness as a research instrument for exploring this process and improving one's practice as a teacher.

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Educational research

A rubric to characterize inquiry in the undergraduate chemistry laboratory

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Abstract: Consensus does not exist among chemists as to the essential characteristics of inquiry in the undergraduate laboratory. A rubric developed for elementary and secondary science classrooms to distinguish among levels of inquiry was modified for the undergraduate chemistry laboratory. Both peer-reviewed experiments in the literature and commercially available experiments were evaluated using the rubric, revealing a diversity of uses for the word inquiry. The modified rubric provides a valid and reliable standard of measure for chemists to examine their laboratory curriculum. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 212-219.]

Keywords: Undergraduate chemistry laboratory, inquiry laboratory, experiment evaluation, rubric, laboratory curriculum

Introduction

For over 30 years, chemists have debated the appropriate uses of the laboratory in the undergraduate curriculum (Fuhrman et al., 1978; Pavelich and Abraham, 1979; Tamir and Lunetta, 1981; Furhman et al., 1982; Hofstein and Lunetta, 1982; Domin, 1999a, 1999b; Johnstone and Al-Shuaili, 2001; Garratt, 2002; Lederman, 2004; Jalil, 2006). Domin (1999b) discussed the relative merits of inductive vs. deductive laboratories and whether students should develop general principles from specific observations or vice versa. Garratt (2002) cautioned against defining chemistry as a laboratory-based science, but instead argued for the importance of 'purposeful observations'. Jalil (2006) noted the opportunity that laboratory provides for students to make connections between theory and practice, but emphasized that such instruction should also support the cognitive development of students. Martin-Hansen (2002) claimed that the effectiveness of laboratory as a method of instruction stems from the opportunity that students are given to ask questions, form hypotheses, collect and analyze data, and draw practical conclusions that can enable them to answer their questions.

Constructivism and inquiry

Constructivism as a theory of learning posits that "*knowledge is constructed in the mind of the learner*" (Bodner, 1986). Learning occurs when the student utilizes higher order thinking skills by connecting new knowledge to prior knowledge. Constructivism advocates instructional activities that encourage student-initiated and student-directed learning. Activities that engage students in scientific inquiry facilitate their construction of knowledge.

Martin-Hansen argued (2002) that students who participate in asking questions, forming hypotheses, collecting and analyzing data, etc. are engaged in scientific inquiry. However, many undergraduate chemistry experiments present students with directions for data collection and analysis to lead to a conclusion already known by students before even beginning the ‘experiment’. Classic examples of such pre-determined outcomes would be experimentally determining the value of the ideal gas constant, or using heats of reaction to determine the stoichiometry of a reaction. What do students learn from these laboratories? Can such experiences be considered inquiry?

What are the defining characteristics of inquiry in the undergraduate chemistry laboratory? There exists no operational definition of the term. Lack of consensus has lead to popularization of the term. Identifying and characterizing inquiry in undergraduate chemistry laboratory experiments requires a reliable and valid rubric[*] to assess the level of inquiry. Since the 1960s, education researchers across the natural sciences have developed various iterations of three distinct instruments, each one designed to assess the level of inquiry at which students are engaged during instructional activities (Schwab and Brandwein, 1962; Herron, 1971; Smith, 1971; Shulman and Tamir, 1973; Tamir, 1977; Fuhrman, 1978; Fuhrman et al., 1978; Lunetta and Tamir, 1979; Tamir and Lunetta, 1981; Fuhrman et al., 1982; Lederman, 2004).

Fuhrman (1978) developed the Laboratory Structure and Task Analysis Inventory (LAI) to analyze science curricula. The LAI contains two sections: the first examines the organization of the laboratory by the instructor, while the second identifies laboratory tasks completed by the student; each of these sections is divided into four subsections containing several categories by which the laboratory activities are assessed (Fuhrman et al., 1978). Fuhrman and colleagues (1982) used the LAI to examine laboratory activities from biology, physics, and chemistry curricula in order to determine the extent to which the laboratory materials reflected the goals of the curriculum. After examining the coherence between stated curriculum goals and the structure of materials and procedures used by students, these researchers identified a low level of inquiry and independence in the laboratory activities, concluding that students commonly worked as technicians following explicit instructions, with relatively few chances for higher-level cognitive processing (Tamir and Lunetta, 1981). Lunetta and Tamir (1979) used these findings to provide a list of twenty-four skills related to the goals of inquiry and problem-solving, affirming the importance of selecting lab activities that enhance teaching goals, and making those goals explicitly clear.

The Classroom Observation Instrument was developed by Smith (1971) as a tool to analyze inquiry in earth science curriculum. Its central focus is upon observable behaviors exhibited by both the instructor and the students throughout the laboratory, during the three phases that characterize most laboratory activities: pre-lab, the experiment, and post-lab.

The ‘Levels of Openness’ framework (Schwab and Brandwein, 1962; Herron, 1971; Shulman and Tamir, 1973) and Continuum of Scientific Inquiry rubric (Lederman, 2004) characterize the degree to which students have the freedom to make choices before, during, and after the laboratory experiment, as opposed to follow prescribed directions. Lederman (2004) used this four-level continuum to analyze high school science laboratories, concluding that students are rarely asked to think for themselves during experiments.

Research question

Given the validity of Lederman’s Continuum of Scientific Inquiry in high school science classrooms, we wondered whether the levels would be valid for characterizing inquiry in

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[*] We use the word ‘rubric’ in the following sense: A rubric comprises a set of ordered categories that frame a set of evaluation criteria. Rubrics are typically used to evaluate student work, e.g., completed assignments or laboratory reports. Rubrics can also be used to classify varying levels of attributes that a document (a laboratory exercise, a website, etc.) possesses.

undergraduate chemistry laboratories. Specifically, we sought to modify Lederman's work to characterize undergraduate chemistry laboratory experiments developed under the auspices of the Research Experiences to Enhance Learning (REEL) Project, an NSF-funded Undergraduate Research Center. The goals of the REEL project include introducing authentic lines of research into first and second year chemistry laboratory courses, with an emphasis on general chemistry, environmental chemistry, and organic chemistry. We describe below our use of Lederman's system and its reliability and validity in the undergraduate chemistry laboratory.

Methodology

Twenty-eight laboratory experiments were selected to establish the reliability of our rubric. General/environmental chemistry experiments were selected from three commercially published laboratory curricula (Abraham and Pavelich, 1999; Bauer et al., 2005; Wink et al., 2005), all of which use the word 'inquiry' in the name of their curriculum. Two of these inquiry laboratory curricula were purposefully structured by their authors so as to include some experiments with lesser degrees of inquiry (e.g., guided inquiry) and other experiments offering greater degrees of inquiry (e.g., open inquiry). Organic chemistry experiments (Senkbeil, 1999; Krishnamurty et al., 2000; Ciacco et al., 2001; Wachter-Jurcsak and Reddin, 2001; Amburgey-Peters and Haynes, 2005; Baru and Mohan, 2005; Cough and Goldman, 2005; Kjonaas and Mattingly, 2005; Nicaise et al., 2005; White and Kittredge, 2005) were selected from the *Journal of Chemical Education*, by searching on the keywords of inquiry and discovery-based learning.

Experiments selected to validate the rubric were chosen to represent a broad selection of chemistry concepts, including the same concepts (e.g., sodium borohydride reductions) across sources in order to ascertain the extent to which the rubric could distinguish between chemically similar experiments. Experiments were also selected from both of the inquiry tiers self-identified by the authors to assess the capability of the rubric to make similar distinctions.

Given the structure of REEL initiatives across teams (general chemistry/environmental chemistry, and organic chemistry), inter-rater reliability (IRR) was calculated independently for the 18 general chemistry/environmental lab experiments, again for the 10 organic experiments, and then for all 28 experiments as a whole.

The method of analysis is described as follows. Experiments were examined section-by-section: pre-lab information, procedure, and calculations/results. First, the experiment was inspected to ascertain whether an explicit problem was posed, or a question asked, about a particular phenomenon. Next, experimental procedures were scored to reflect the extent to which they were prescriptive (telling students what to do and how to do it), or the degree to which experimental procedures provided opportunities for the students to decide what actions to take. Finally, by examining the variety of questions asked in the post-lab section and making comparisons to the information provided in the pre-lab section, the laboratory experiments were judged as to what extent the students were to calculate answers and craft conclusions in echo of information provided/stated in the pre-lab in advance of the laboratory.

For example, the levels characterizing both ends of the inquiry continuum were readily recognizable by certain characteristic features:

- Level 0 – The laboratory manual began with a description of the phenomenon under study (e.g. factors that affect rate of oxidation of 'X'); an explicit method of data collection was presented with no option for alternate paths by the student; the manual contained a set of instructions for analyzing data and/or drawing conclusions already explained in the section(s) outlining the problem.

- Level 3 – The laboratory manual directed the student to explore a general phenomenon (e.g. gases/gas laws); suggestions for lines of exploration were provided, but no specific procedures or methods of data analysis were given.

A team of three researchers evaluated each laboratory experiment twice. The researchers used the rubric to individually evaluate the experiments and subsequently met to discuss their evaluations. Each researcher evaluated the experiments again, allowing for changes if he/she desired. Finally, an inter-rater reliability (IRR) value was calculated for each experiment.

Results

Table 1 shows the results of inter-rater reliability calculations for the general/environmental experiments, for the organic chemistry experiments, and for all experiments. Of the twenty-eight experiments in the sample, one experiment was not rated using Lederman's rubric due to insufficient detail regarding instructions given to students.

The IRR for each sub-group of experiments and the collection of experiments overall is good, given the standard minimal value of 0.70 as a cut-off for establishing reliability. Based on discussions between the raters during the IRR process, we found more detailed descriptions were required than were provided in Lederman's continuum. For example, levels 2 and 3 needed a more specific description of the activities carried out by students in order to refine the characterization of that particular type of experiment. We found it important to be able to differentiate among experiments as to whether students were expected to develop procedure(s), decide what data to collect, and/or determine how the data should be interpreted in order to propose a viable solution. Table 2 presents modified descriptions of the levels found in Lederman's continuum to provide clear criteria for determining the relative levels of inquiry. Table 3 provides a visual comparison across the levels of inquiry.

Table 1. Calculation of inter-rater reliability.

	Final ratings		
	Number of experiments with agreement	Total number of experiments	Inter-rater reliability
General Chemistry / Environmental Chemistry	16	18	0.89
Organic Chemistry	7	9	0.78
Overall	23	27	0.85

Table 2. Rubric to identify level of inquiry.

Level of Inquiry	Description
Level 0	The problem, procedure, and methods to solutions are provided to the student. The student performs the experiment and verifies the results with the manual.
Level 1	The problem and procedure are provided to the student. The student interprets the data in order to propose viable solutions.
Level 2	The problem is provided to the student. The student develops a procedure for investigating the problem, decides what data to gather, and interprets the data in order to propose viable solutions.
Level 3	A 'raw' phenomenon is provided to the student. The student chooses the problem to explore, develops a procedure for investigating the problem, decides what data to gather, and interprets the data in order to propose viable solutions.

Table 3. Levels of inquiry across undergraduate chemistry laboratory experiments.

Level	Problem/Question	Procedure/Method	Solution
0	Provided to student	Provided to student	Provided to student
1	Provided to student	Provided to student	Constructed by student
2	Provided to student	Constructed by student	Constructed by sudent
3	Constructed by student	Constructed by student	Constructed by student

Figure 1 depicts the distribution of the twenty-seven experiments as rated across the levels of inquiry. A wide range of experiments were sampled, from those with essentially no inquiry features (Level 0) to those which require the student to define the problem of interest as well as appropriate methods of data collection and data analysis (Level 3).

Figure 1. Distribution of experiments across levels of inquiry.

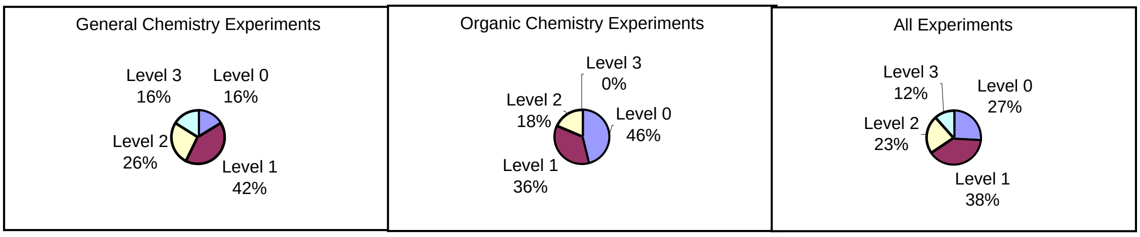
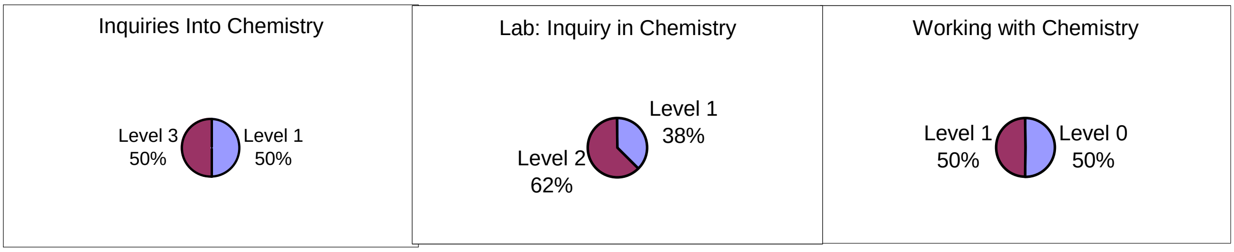


Figure 2 shows the ratings of selected experiments within the three commercially published lab manuals sampled for this research. *Inquiries into Chemistry* (Abraham and Pavelich, 1999) provides laboratory experiments characterized as either guided inquiry [“*specific instructions as to what experiments to conduct … (student) should do work in the order indicated*” (p. 3)] or open inquiry [“*designing and carrying out (student’s) own experiments … no detailed instructions on how to approach these systems*.” (p. 275)] Our modified rubric identified these different characterizations of inquiry as consistent with Level 1 and Level 3.

Figure 2. Ratings of commercially published inquiry laboratory programs.



Laboratory Inquiry in Chemistry (Bauer et al., 2005) describes its curriculum as one in which students assume the role of chemist and “*design their own experiments*”, (Bauer et al., 2005, p. v) adapting techniques to their specific problems. Analysis of the *Laboratory Inquiry in Chemistry* experiments placed them among both Level 1 and Level 2 using the modified inquiry rubric.

Working with Chemistry (Wink et al., 2005) structures laboratories in experiment groups, each one containing a skill-building laboratory that “*shows students how to use a technique*” (p. x) and an application laboratory in which students utilize concepts from skill-building labs for use in a given “*professional scenario which is more open in inquiry style.*” (p. x) Use of the modified inquiry rubric to score *Working with Chemistry* laboratories showed experiments to occupy both Level 0 and Level 1.

Discussion

Lederman's continuum was originally developed for use in high school science classrooms, including, but not limited to, chemistry. Our modifications and application of the inquiry rubric to a wide spectrum of chemistry experiments support the validity of using it to characterize varying levels of inquiry in the undergraduate chemistry laboratory. The high inter-rater reliability across both general/environmental chemistry and organic chemistry classifies this rubric as robust. The findings from this research can distinguish among levels of inquiry as identified by commercially published laboratory programs.

Significance of the inquiry rubric and its potential uses

The significance of this research lies in its ability to move forward the conversation regarding the most appropriate goals and pedagogies for the undergraduate chemistry laboratory. As of late, inquiry has gained status as a 'buzzword' of sorts, with many chemists using it (sometimes somewhat indiscriminately) to describe their instructional approach to laboratory. Case in point - each of the laboratory experiments in the sample for this research was self-identified by their respective authors as 'inquiry.' And yet, our findings clearly show that not all instances of inquiry are equivalent, i.e., they do not necessarily imply or describe the same learning opportunity for students. There exist shades of inquiry with varying degrees of freedom in the student experience.

Potential uses of this inquiry rubric include the opportunity to equip chemists with a quantitative means of comparing and debating the levels of inquiry as they design curriculum and seek to improve learning for students of chemistry. Experiments that might on the surface appear to be essentially equivalent in terms of core concepts and measurements can now be compared directly to one another as to which affords more structure and which provides more inquiry for the student experience. Faculty whose instructional goal is to move students from structured laboratory experiences to increased responsibility for decision making in the laboratory can use the rubric to arrange their experiments in order of increasing levels of inquiry.

For example, consider a laboratory where students are asked to confirm that the rate of reaction increases with temperature. Students might be given a chemical system to investigate, a data table to fill out, and post laboratory questions to answer. Using the inquiry rubric this laboratory would be a Level 0, the students are simply verifying the relationship. However, the level of inquiry could be increased by stating that the students are to investigate the relationship between temperature and reaction rate. The chemical system could still be given, but the students could be asked to develop a hypothesis, data collection and analysis procedures, and viable conclusions consistent with the data that evaluate the veracity of the hypothesis. This laboratory experiment has been transformed into Level 2.

The inquiry rubric also lends itself to use in curriculum evaluation. Departments that are engaged in programmatic evaluation can use this reliable and robust rubric to characterize the current curriculum. If results from using the inquiry rubric indicate a poor fit between the declared departmental or programmatic goals and the reality of student experience, then the rubric provides a roadmap to direct meaningful data-driven change. For example, if the general chemistry laboratory curriculum is analyzed and none of the laboratories are rated as level 2 or 3, then the curriculum can be modified. Level 0 or Level 1 laboratory experiments could be replaced with Level 2 experiments that use a more open inquiry approach. Alternatively, current laboratory activities could be modified to include experiences where the students design data collection and analysis procedures, and proposed viable solutions based upon the data.

Systematic use of the inquiry rubric to guide choices in laboratory instruction will facilitate chemists' transition from choosing laboratory experiments because they provide easy to follow directions toward choosing laboratory experiments because they provide carefully crafted opportunities for chemistry students to engage in inquiry.

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Educational research

The integration of a viscosity simulator in a chemistry laboratory

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Abstract: We integrated an interactive viscosity simulator into a pre-laboratory session in an attempt to improve training in a chemistry laboratory. The students were divided into two groups, the experimental group (EG) and the control group (CG). The students of the EG participated in a pre-laboratory session with additional instruction, including the use of the simulation on personal computers and other discussions. After the pre-labs, these students participated in the design of the experiments using the simulator as an educational tool, and then carried out the experiments; in addition, they processed their data on spreadsheets, and they pooled their results through a Local Area Network (LAN). Students of the CG performed the experiments following the traditional teaching procedure (recipe-labs), without attending the pre-lab session. Comparison of the two groups showed that the EG students valued the opportunity to question the teacher in the pre-laboratory session, and that they found this teaching procedure useful. As a result they felt more confident when they entered a laboratory and they understood better the theory behind the experiment than the CG students. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 220-231.]

Keywords: chemistry laboratory, simulations, viscosity simulator, interactive learning environments, cooperative/collaborative learning, teaching/learning strategies

Introduction

Chemistry is an experimental science and its development and application demand a high standard of experimental work. Laboratory practice is expensive in terms of equipment, consumables and the time of academic and technical staff (Bennett and O'Neale, 1998) and it should help the students obtain technical skills such as manipulation, observations, data collection, processing and analysis of data, interpretation of observation, problem solving, team work, experiment design, communication skills etc. (Bennett and O'Neale, 1998; Johnstone and Al-Shuali, 2001). Additionally, during every laboratory session, the students receive a huge amount of information, such as the location of chemicals, recognition of equipment and the associated handling, instrumentation and safety requirements in a laboratory environment etc. (Johnstone, 1997b), and they can process only a few elements of current information at any given time (Gabel, 1999; Johnstone, 2000). Moreover, the quite large number of students can cause difficulties to the academic and technical staff, and as a result most teachers use 'recipes labs' and follow the traditional way of chemistry laboratory education (Domin, 1999). As Garratt (1997) has pointed out, using such 'recipe labs' is an effective strategy for maximising both the quantity of practical experience gained by students and quality of their results. However, 'recipes labs' do not provide opportunities to learn about experimental design, investigation, critical analysis of results, and sources of error.

Students who are following a recipe lab are not ‘doing an experiment’, but ‘carrying out an exercise’, because they usually follow instructions mechanically, line-by-line, without thinking (Clow and Garratt, 1998). In order to improve chemistry education, many researchers, following constructivist theory, advocated teaching procedures that would help students understand the subject better (Bodner, 1986; Shiland, 1999; Towns, 2001).

In 1997 Johnstone claimed that there is ‘no point in putting a student into a laboratory without mental preparation’, and that ‘the nature of the preparation has to be as carefully thought out as the course itself’ (Johnstone, 1997a). Today the necessity for some kind of pre-laboratory preparation is obvious, and many researchers use IT for this purpose (Ritter and Johnson, 1997; Clow and Garratt, 1998; Nicholls, 1999; Robinson, 2000). The simulator is a computer-based program that gives students access to more facilities that they otherwise would have. For example, students can discover concepts through guided inquiry using the simulation modules (Fermann, et al., 2000) and/or can be trained in the operation of instruments (Waller and Foster, 2000). Furthermore, the use of a simulator reduces the purchase and maintenance costs of the laboratory equipment, while enabling students to perform a variety of experiments in data collection and analysis (Thomas and Neilson, 1995).

The objectives of this investigation were to find ways for students

a. to be familiarized with the theory behind the laboratory activity,
b. to feel more confident when they enter a chemical laboratory,
c. to obtain the necessary experience in order to process and analyse experimental data using Information Technology and
d. to work together as a team.

In order to help achieve these goals the students attended a pre-laboratory session before they entered a real laboratory. To verify whether this approach can assist the students to understand the chemical topics better than the traditional one, we used as reference another group of students who performed the same experiments in a chemistry laboratory following the traditional methods.

Methodology

Assumption

According to constructivism, every student ‘fits’ the new knowledge to what he/she already knows and constructs new knowledge accordingly (Bodner et al., 2001). In our investigation, we wanted all the students to have the same prior knowledge, which was considered to be the determination of mass, volume, mole fraction and concentration (% v/v and % w/w). Thus, one week before conducting the course, we informed the students that this knowledge was necessary, so that they could prepare themselves for the viscosity experiment. The teacher assumed that the students’ prior knowledge was well established in their minds, as it had been previously taught in high school and in their first year undergraduate courses.

Participants and the experimental condition

The course was conducted for two semesters in a physical chemistry laboratory in the Department of Chemistry of the Aristotle University of Thessaloniki in Greece, and the students were divided into two groups, the experimental group (EG) and the control group (CG).

Experimental Group (EG)

The students of the EG (18 male, 26 female) attended the pre-laboratory session and performed virtual experiments using the viscosity simulator. After that they entered the laboratory and performed the same experiments for real. The total time of pre-laboratory session and laboratory session was three hours.

In the pre-laboratory session, the students were divided into two-person teams who worked on a personal computer with the simulation program. The teams shared measurements, observations and conclusions about the virtual experiments with the other teams through the Local Area Network (LAN), after processing and analysing data. A LAN is a computer network covering a local area for example a classroom in which two or more computers are connected together using a telecommunication system for the purpose of communicating and sharing resources.

At the end of the laboratory session, we distributed a questionnaire to these students in order to assess their chemical knowledge about viscosity and discover their opinions about the pre-laboratory session.

Control Group (CG)

The students of the CG (16 male and 28 female students), performed the experiments only in a laboratory and they did not attend any pre-laboratory session. We explained the theory underlying the experiment to this group briefly, and we used ‘recipes labs’ in the traditional way. At the end of the laboratory session, we distributed to these students a questionnaire in order to assess their chemical knowledge about viscosity and to get their opinions about the laboratory training. The total time of laboratory session was three hours.

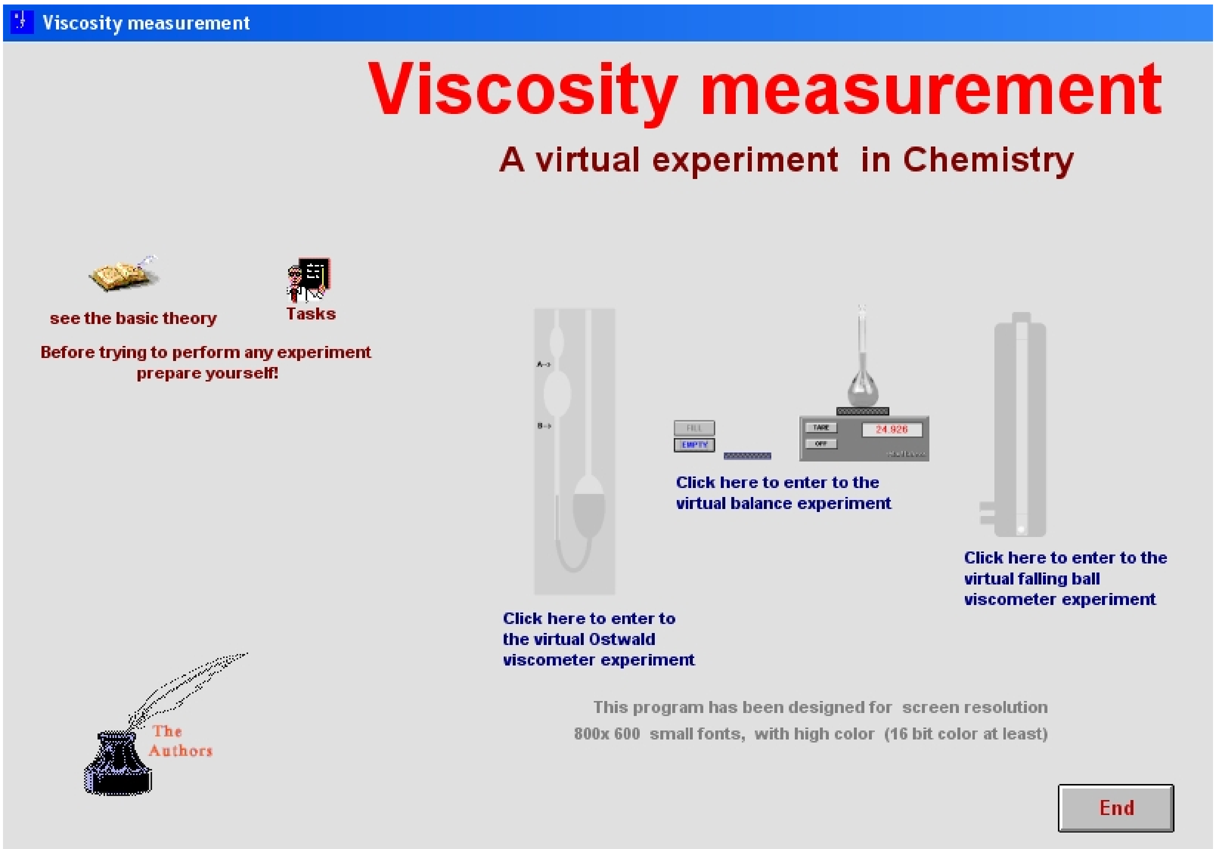
Educational tool - Educational software

During the pre-laboratory session, the viscosity simulator was used as an educational tool. The program was implemented in the 16-bit version of Microsoft Visual Basic 4.0. The software runs under Microsoft Windows 95, 98, 2000 and XP and is packaged on a CD-ROM (Papadopoulos et al., 1999). The design of this simulator is based on the cognitive load theory (Preece et. al., 1994; Quinn and Wild, 1998). Robinson (2002) has synoptically referred to the basic aspects of cognitive theory which are necessary to design a multimedia application. Pollock, Chandler and Sweller (2002) have pointed out that cognitive load theory uses some aspects of human cognitive architecture as well as the structure of information to provide instructional designs that facilitate understanding, learning and problem solving. The theory assumes the following.

1. The human cognitive system consists of two distinct channels for representing and controlling knowledge: an auditory-verbal channel and a visual-pictorial channel (Mayer and Moreno, 2002).
2. A limited working memory can process only a few elements of current information at any given time (Johnstone 1997b; Gabel, 1999). Thus, the visual-pictorial channel can be overloaded if too many pictures (or other visual material) are presented at one time. Similarly, the auditory-verbal channel can be also overloaded. Overloading one channel results in limiting the processing ability of the other one (Mayer and Moreno, 2002).
3. Active processing within the auditory-verbal and visual-pictorial channels leads to meaningful learning. Active processing includes organising relevant words and pictures into coherent pictorial and verbal models. The integration of the two channels together with previously obtained knowledge subsequently occurs (Mayer and Moreno, 2002).
4. An effectively unlimited long-term memory holding knowledge that can be used to overcome the limitations of working memory (Gabel, 1999).
5. Schemas held in long-term memory are used to structure knowledge by organising elements of information comprising lower order schemas into higher order schemas that require less working capacity (Pollock et al., 2002).

6. Automation that allows schemas to be processed automatically rather than consciously in working memory, thus reducing working memory load (Pollock et al., 2002).

Figure 1. The first screen of Viscometer Simulator.



Viscosity measurement

A virtual experiment in Chemistry

Before trying to perform any experiment prepare yourself!

Click here to enter to the virtual balance experiment

Click here to enter to the virtual falling ball viscometer experiment

Click here to enter to the virtual Ostwald viscometer experiment

This program has been designed for screen resolution 800x 600 small fonts, with high color (16 bit color at least)

Following the above theory, we have designed educational software in which the virtual objects on the screen (Figure 1) look like the same objects in the real laboratory; this makes it easier to transfer what is learned here into real use and the software provides the users with information gradually, without overloading their memory. The program includes three virtual experiments, which are designed to introduce the students to density and viscosity determinations using two viscometer types, Ostwald and Falling-Sphere Viscometer. Relevant theory, tasks and introduction sections are available in every virtual experiment. The virtual experiments are:

- The Ostwald viscometer simulator for the determination of the viscosity of a liquid with an Ostwald capillary viscometer,
- The Falling-Sphere viscometer simulator for the determination of the viscosity of a liquid using a falling ball viscosity and
- The Balance simulator for the determination of the density of a liquid.

The users perform the virtual experiments using the same actions as in the real laboratory. Additionally, the user has the opportunity to choose the solution (a mixture of ethanol-water 0-100% w/w) and its temperature (15-30°C) when carrying out the experiment. Also, in the case of the Falling Ball viscometer, the students can choose pure liquids for their virtual experiments.

Integration of the educational software with the educational procedure

We integrated the educational software into a pre-lab session. The basic points of the pre-laboratory session were that students:

a) should not receive a huge amount of information at the same time;
b) should have enough time to process and save the useful information gradually;
c) should have had prior knowledge on which they could build their new knowledge and
d) the students participated in the teaching procedure actively.

We discussed the chemical phenomena and experimental procedure with students by posing questions to them. Students gave us answers based on their prior knowledge; this way we could determine whether the students had any misconceptions. When we identified student misconceptions, we used a Power-Point Presentation which included images and animations relevant to the topic, and we posed the same questions again so that students could process the new information better.

For example, in order to introduce students to viscosity theory, we posed questions about the liquid's properties and the liquid's motion. One of the questions was "*what does it mean that a liquid flows, and how do you know that a liquid flows*?" Students gave us several answers from which we realized that they had misconceptions about this topic, although they have been previously taught this subject during the course of their studies. For instance one student answered as follows:

> *Student: That means that it runs.*
> *Teacher: What do you mean it runs, explain it or give us an example.*
> *Student: When something runs, it is in motion and you need force to stop it.*
> *Teacher: Ok you are partially correct, but you do not answer my initial question, maybe you should think at the microscopic level.*
> *Student: What do you mean in a microscopic level? The molecules are like balls and as such they run like balls.*

As the discussion continued and the students did not give us any clear answers, we used animations in a Power-Point Presentation to explain to them the motion of the liquid. Then we asked them again to explain how they now understood the liquid's motion in order to make students repeat it using their own words and consolidate it. Another area in which the students had misconceptions (where their knowledge was confused) was about the definitions of density, mass and concentrations. Using the above teaching procedure, we identified and clarified their misconceptions.

After that procedure, when the students understood the experimental theory better, they performed the virtual experiments in a classroom equipped with personal computers by using the simulation program. The students, who were divided into teams, suggested and designed their experimental procedures with our help, and after they processed the data on their Personal Computer (PC), they sent their results to our PC using LAN. The aim of this virtual experimentation was to get students to collaborate in order to design the experimental procedure and to obtain necessary data analysis and processing skills, as learning is more effective when students collaborate and participate actively during the teaching procedure (Shiland, 1999).

During the virtual experimentation, the simulator of the Falling-Sphere viscometer was used first to introduce students to the related experimental procedure for viscosity measurements. This was followed by the Ostwald viscometer simulator and the balance simulator, which were used to find the coefficient of viscosity of a solution. In this way the students received and processed the information about the experimental procedure gradually (they did not receive huge amount of information, such as the theory behind the experiment, the instrument manipulation, the sample preparation, the laboratory equipment, etc.).

During the pre-lab session-virtual experimentation, students studied

a. the influence of temperature on the coefficient of viscosity and
b. the existence of intermolecular forces in the aqueous solutions of ethanol in different concentrations (0-100% w/w).

With the same approach as above (posing questions), we designed the experimental procedure jointly with the students. For example, we posed questions to students about the influence of temperature on the coefficient of viscosity. The students suggested to us an experimental procedure using the simulator, a spreadsheet program and the LAN.

Experimental Procedure

Specifically, using the viscosity simulator, every team determined the coefficient of viscosity of a specific ethanol-water solution for different temperatures (15°C, 20°C, 25°C and 30°C). Next, every team collected its data in a spreadsheet on its PC, and a graph showing the relation between the coefficient of viscosity and temperature was plotted. At the end of the virtual experimentation, every team transferred its results to our PC using the LAN to give us 11 Excel files, one from each team, which referred to water-ethanol mixture (concentration range 0 to 100% w/w) for different temperature values.

The next virtual experiment the students performed was the study of the intermolecular forces in the mixture ethanol-water. After the discussion about the intermolecular forces, the conditions in which intermolecular forces appear, the influence of intermolecular forces upon viscosity and its coefficient and how by using viscosity measurements we confirmed the existence of intermolecular forces in ethanol-water solutions, the students suggested to us the experimental procedure in order to calculate the number of solvent molecules that interact with one solute molecule using measurements of the previous virtual experiments.

Every team, which had access to our computer, transferred all data from the previous experiment to its computer using the internal network. Then every team selected a specific temperature and using the data of the coefficient of viscosity of the previous experiment, made the appropriate calculations to find the relationship between the molecules. The students produced graphs using a spreadsheet in order to find the relationship and obtained ratio between solvent and solute molecules.

After the end of pre-laboratory session, the EG students entered the laboratory in order to perform real experiments. Every team measured the viscosity coefficient of a specific solution of ethanol-water (0-100% w/w) at 25°C (every team performed only one experiment using the Ostwald viscometer). They exchanged their results and processed the experimental data as homework. We should point out that during the real laboratory, we did not explain anything about the experiments or how to perform them, thus the students performed the experiments without any instructions, we just told them to do only one experiment as they were trained on the pre-laboratory-simulation program. This was evidence that we did achieve one of our objectives, which was to increase the students' confidence when they enter a laboratory.

The CG students performed experiments in the laboratory following the teacher's instructions. Specifically, we introduced these students to viscosity without posing them any questions, and every team of students (2 students/team) performed 11 experiments using the Ostwald viscometer for the mixture of ethanol-water (0-100% w/w) at 25°C. Finally, the students of the CG processed their experimental data as homework.

The questionnaires

At the end of the course, we distributed questionnaires to the students of both two groups (EG and CG). The aim of these questionnaires was to evaluate the students' knowledge about viscosity and to provide students with an opportunity to express their views about the teaching and learning method. The questionnaires were divided into two parts. The first part was common for both groups and referred to viscosity and chemical phenomena, and consisted of five open questions. Table 1 shows the questions. The researchers evaluated each answer using a one-to-six–points marking scheme: one point: = incomplete and wrong answer, six points: right and complete answer).

Table 1. The five chemical (content) questions of the first part of the questionnaire.

Q1	*Assuming that you would like to produce a shampoo, is it necessary to measure the coefficient of viscosity in your solution? Explain your answer (think of what kind of properties your shampoo should have).*
Q2	*How can we measure the coefficient of viscosity of a solution, when using an Ostwald viscometer? Explain exactly the experimental procedure. Why should we record the time between the 'A marker' and the 'B marker' (markers on Ostwald viscometer before and after small reservoir)? If we do not know the volume of the small reservoir, how can we calculate the coefficient of viscosity?*
Q3	*There is an inverse relation between the coefficient of viscosity and temperature. When the temperature increases by 1°C the value of the coefficient of viscosity reduces by 2%. Explain why it happens and what that change means for someone who wants to produce a shampoo.*
Q4	*Solution ethanol/water 50% w/w and the mass of the solution is 150g. Calculate the moles of ethanol and water and their molecular fractions. Can you describe the relationship between mole fractions and the coefficient of viscosity?*
Q5	*In a mixture ethanol/water, the experimental value of fluidity is different from the theoretical value. Explain why this happens. Can you describe the conditions under which the experimental value of a mixture will be the same as the theoretical value? Give one example of a mixture in which the two above values are the same and one example in which they are not the same.*

The second part of the questionnaire distributed to EG students provided a number of statements, and students were asked to show the extent of their agreement on a one to six point, Likert-type scale: six-points = I strongly agree; one-point = I strongly disagree). The questions of this evaluation are given below in the Results section (see Table 3). In contrast, the second part of the questionnaire distributed to CG students asked them to express their opinion about the specific laboratory training.

Results

First part of the questionnaire: Content knowledge

We found that there was no significant difference between the answers of male and female students from either group of students.

For the chemical questions, we used analysis of variance (ANOVA) as a statistical analysis in order to compare the performances of the EG and the CG of students.[1] The results of this comparison as well as the percent means and the percent standard deviations of the performances are shown in Table 2.

It follows from Table 2 that on all five questions the EG outperformed the CG. Not only do all comparisons are statistically significant at p=0.000, but also the absolute differences between the two means were large (from 23 to 29%).

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[1] Since in each case we compare two independent means, ANOVA here is equivalent to the student *t* test for independent samples.

Table 2. Scores (%) on the chemical (content) questions of the experimental (EG) and the control group (CG) and statistical comparison by means of ANOVA.*

Question	Mean and SD results (%)	ANOVA results (α=0.05)
Q1	EG (M=92, SD=9.8) CG (M=68, SD=16.2)	$F(1, 86)$=71.8, MS_W= 0.649, p=0.000
Q2	EG (M=93, SD=13.1) CG (M=70, SD=12.4)	$F(1, 86)$= 69.9, MS_W= 0.586, p=0.000
Q3	EG (M=88, SD=13.7) CG (M=64, SD=12.4)	$F(1, 86)$= 75.5, MS_W=0.617, p=0.000
Q4	EG (M=83, SD=14.8) CG (M=57, SD=12.1)	$F(1, 86)$= 81.9, MS_W=0.660, p=0.000
Q5	EG (M=71, SD=20.0) CG (M=52, SD=13.6)	$F(1, 86)$= 26.9, MS_W= 1.05, p=0.000

* α is the limit of significance level, MS_W is the mean square within groups, F(a,b) is the variance between groups/ MS_W , p is the significance level.

Second part of the questionnaire: Student evaluation

In this part of the questionnaire, the students of the EG were asked to assess the viscosity simulator, to give their impressions about the pre-laboratory and to evaluate how well the group exercise gave them the opportunity to cooperate with their fellow-students. We repeat that the students had to make a choice on a six-point Likert-type scale: strong agreement with a statement being six points, while strong disagreement being just one point). Table 3 has the questions and the descriptive statistics of the evaluation by the students, expressed as percent mean values and the corresponding standard deviations..

Table 3. Descriptive statistics* of the experimental group students' opinions about the simulation program, computer experience and the effectiveness of course.

Questions for educational software and the pre-laboratory session	Mean (%)	SD (%)
Using the viscosity simulator, did you carry out the virtual experiments with accuracy and repeatability?	89	14.8
Do you believe that you understood the theory behind the experiment before you enter the laboratory?	85	14.1
Do you believe that you have obtained more computer experience after the pre-laboratory session?	91	9.8
Did you have the opportunity to pose questions and have a discussion with the teacher in the pre-laboratory session more interactive than during traditional teaching?	89	12.9
How useful did you find the simulation program in order to understand the theory behind the experiment?	82	12.7
Did you exchange views and information with other peers?	83	13.2
How useful did you find the collaboration with the other peers?	86	12.8
After the pre-laboratory session, did you feel more ready to carry out the experiment in laboratory?	85	13.1
How do you find the idea to have other similar simulation programs created about other chemistry phenomena and experiments?	86	13.1

* Percent mean values and percent standard deviations derived from students' choices in a Likert-type scale (1-6) (1: not al all; 6: very much).

In all cases, the EG students strongly agreed (mean values from 82-91%). The students valued the opportunity to question the teacher in the pre-laboratory session, and they found the simulation program useful in order to understand the theory behind the experiment. As a result they felt more confident when they entered the laboratory. They also found useful the collaboration with their peers. Finally, they agreed with the idea to have similar simulation programs created about other chemistry phenomena and experiments.

In their own second part of the questionnaire, the CG students were asked to express their opinion concerning their laboratory training. These students had to perform the experiment several times and thus they did much more experimental work, which they found tedious enough and eventually grew tired of. Hence, in the second part of their questionnaire, their response was not as favourable, as many complained that repeating the same experiment several times was pointless, and that routine procedures like repositioning and cleaning of the capillary were tiresome enough. On the other hand, the EG performed the experiment only once, therefore a similar negative attitude towards the experimental procedure was not observed. In conclusion, by taking into account the students' responses we realize that students find more constructive and less tiresome spending time to both pre-laboratory and laboratory sessions rather doing three full hours of experimental work at the lab only.

Discussion

"*Learning only occurs when students create their own understanding; but teachers are needed to create the environment in which this can happen*" (Shiland, 1999). In this investigation, the EG students discussed with the teacher more thoroughly topics relevant to viscosity. By using the simulator and a Power-Point presentation they could be better familiarized with the theory behind the experiments before they entered a real laboratory. As we posed questions to these students, so that discussion could take place, we could identify students' misconceptions and clarify them. For example, when we asked students about the difference between the density and the mass, the students were confused; they could not explain the concepts of mass and density, although they knew the mathematical relationship between the two concepts. Therefore, by using the Power-Point Presentation we projected some appropriate images and asked the students to explain them to us. Moreover, by using the balance simulator, we asked them to calculate the mass and the density of several solutions and to explain the difference in their results. In this way the students could come to a personal understanding through the virtual experiments and they had the opportunity to understand better the theory behind the experiment before they entered the laboratory.

In addition, the EG students had the opportunity to perform both virtual experiments in pre-laboratory session and real experiments in the laboratory, in order to consolidate the experimental procedure. During the pre-laboratory session, we did not give the students exact instructions, but the students suggested to us the experimental procedure and we posed to them questions about it in order to get students to think about it in greater depth. Thus, the students participated actively in the experimental design. This explains the significant difference between the performance of the EG and the CG, in which the students used only 'recipes labs', followed the instructions step-by-step and performed the experiment mechanically. The above procedure demonstrates that the "*learning of science is about the student being initiated into the ideas and practices of the scientific community and it is not the simple transmission of facts from teacher to student, but a continuous and active process on both sides*" (Shiland, 1999).

Using the viscosity simulator, the EG students performed the virtual experiments with accuracy and repeatability and therefore they could perform numerous experiments easily and with accuracy and they were focused on the analysis, process and the interpretation of experimental data. As EG students declared after the pre-laboratory session, they felt ready to perform the corresponding laboratory activity and were not intimidated by the laboratory environment and experiment. On the other hand the CG students followed the instructions step-by-step using ‘recipes labs’ without any opportunity to clarify their misconceptions and as they struggled to operate the equipment during the laboratory session, they failed to make important observations, and therefore gathered poor data (Johnstone and Al-Shuali, 2001). The CG students just carried out the experiments in the laboratory without analysing the experimental data and processed the experimental data as homework.

“Learning has a social component. Knowledge construction is primarily a social process in which meaning is constructed in the context of dialogue with others. Learning is aided by conversation that seeks and clarifies the ideas of learners” (Shiland, 1999). In our investigation, the EG students, who were divided into teams, shared data, exchanged views explored several different aspects of the same questions, and students with more computer experience helped their less experienced colleagues. Additionally, as they exchanged data using the LAN, the whole class worked as a team and every wrong result influenced the final conclusions. In a classroom usually there are students who are shyer than others and they are afraid to address questions directly to the teacher. We observed that there were long conversations between the EG students before giving us their final answers or their experimental results. This collaboration helped them to exchange information and learn from their peers, or because they had the opportunity to ask us questions, they could clarify their misunderstandings. During this collaboration the students had the opportunity to process only a little information at a given time and to think on a specific topic. Therefore, they could develop the critical thinking instead of attending a lecture passively. This collaboration in combination with the use of the simulator in the pre-lab session led them to perform the experiments in the real laboratory without following the teacher’s instructions mechanically line-by-line without thinking. According to Kirschner (2001), collaborative learning supports the use of the effective learning methods (make explicit, discuss, reason, etc.) while allowing for the acquisition of essential social communications skills.

A simulator is a multimedia application, which can be used as a tool but cannot by itself replace an instructor and the laboratory training. Teachers will always be essential to address the human, creative and artistic parts of teaching, and this makes a major difference in how well students learn and more importantly how well they build up their knowledge (Bunce, 2001). Consequently, we adopted an active, stimulating role by posing a problem to the learners where the teacher was very much a facilitator rather than a direct provider for student learning. Students of the EG had to think and to suggest to us the experimental procedure they should follow for every virtual experiment and to perform the real experiments in the laboratory after the pre-laboratory session; therefore, we increased their confidence for when they enter the laboratory. This was obvious as these students entered the laboratory; they performed the experiments without our instructions. In this way, learning takes place in an active mode and the teacher has a facilitator’s role rather than a being ‘sage on the stage’ (Kirschner, 2001).

During the course of undergraduate studies all students should be able to select and use the appropriate software for a particular task: spreadsheets, which facilitate calculations, and scientific graphic packages, which can visualise the meaning of a figure. The easiest way to introduce the computation into a chemistry curriculum is by simulation and data reduction programs (Zielinski and Swift, 1997). In this investigation, as the EG students performed the virtual experiments, they could obtain experience on the information technology such as the use of Excel and the LAN. Also, a recent survey conducted in England (Duckett et al*.*, 1999), tried to identify the key skills which were mostly needed by recently employed chemistry graduates, and how well their chemistry courses have prepared them in order to use these skills in their job. The chemists who participated in this survey, pointed out the essential technical skills which should be included in chemistry courses in order to better prepare the chemists for their future employment. Some of these were: computing/IT, team working, problem solving and communication skills. Our investigation was focused on the acquisition of some of these skills.

Conclusions

The integration of the simulation program into pre-laboratory session was inspired by the cognitive load theory of learning and constructivism. During the pre-laboratory session the teacher discussed with students of the experimental group (EG) the relevant chemical phenomena, designed experimental procedure with students and encouraged team-work by utilising the Personal Computer (PC) and Local Area Network (LAN), which allowed students to solve more complex problems. The result of this procedure was that EG students obtained experience on the design of the experimental procedure, the use of spreadsheets and LAN and the interpretation of the data. After the pre-laboratory session, these students were able to perform experiments in a chemical laboratory without any further guidance. In contrast to those following traditional laboratory training, these students understood better the theory behind the experiment as they had time to connect the common points between new knowledge and their previous knowledge and to clarify any misconceptions. With the integration of computer applications into a chemical laboratory, the teachers had the opportunity to create a more stimulating and motivating teaching environment where learning could be both challenging and, at the same time, pleasing.

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Practice

Advancing Chemistry by Enhancing Learning in the Laboratory (ACELL): a model for providing professional and personal development and facilitating improved student laboratory learning outcomes

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Abstract: The Advancing Chemistry by Enhancing Learning in the Laboratory (ACELL) project aims to improve the quality of learning in undergraduate laboratories through two interlocking mechanisms. The first is to build a database of experiments that are both chemically and educationally sound by testing them in a third-party laboratory, usually through an ACELL workshop involving both academic staff and students, to ensure that they work. The second mechanism provides personal and professional development for staff and students through a workshop process, and reinforced through on-going engagement with the ACELL community via the project website and experiment assessment and evaluation. The ACELL workshops include discussion of educational issues, both in abstract (through discussing laboratory learning in general) and concrete (through debriefing of each experiment tested) terms. This paper discusses the design of the ACELL project, and illustrates some of the successes of the staff and student personal and professional development aims. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 232-254]

Keywords: Undergraduate chemistry laboratories, hands-on learning, student-centred learning, personal development, professional development, ACELL project, ACELL workshops

Background and context

Chemistry is an 'enabling science' because its core concepts are essential for almost every area of science (White et al., 2003). Students study chemistry as a discipline in its own right and as a central component of other degree programs. Thirty-five Australian universities teach chemistry and over 20,000 students per year pass through these courses (Barrie et al., 2001a). Here, students learn about the microscopic and macroscopic world of molecules; the bonds that hold them together, how and why they react, and how to design molecules with properties that enhance our standard of living. Chemistry is highly conceptual, and students can find it difficult to relate the molecular level of explanation to macroscopic properties of everyday substances. Understanding the language and symbolism of chemistry is critical for students to be able to engage with the concepts of the discipline (Marais and Jordaan, 2000; Bucat, 2004). For example, Kozma et al. (2000) have reported on the contribution of symbolic representations and tools used in chemistry to the way students mediate between theoretical and material-world contexts, a topic that has also been examined by others (Treagust et al., 2003; Wu, 2003).

Laboratory work is integral to bridging the gap between the molecular and macroscopic levels of chemistry. Good laboratory programs provide a learning environment where students can forge links between theoretical concepts and experimental observations (Hegarty-Hazel, 1990). Moreover, learning goals that can be achieved through laboratory experiences include (Moore, 2006): subject-matter mastery; improved scientific reasoning; an appreciation that experimental work is complex and can be ambiguous; and an enhanced understanding of how science works. Skills that can be developed in high quality laboratory exercises include (Boud et al., 1986; Bennett and O'Neale, 1998): manipulation of equipment; experiment design; observation and interpretation; problem solving and critical thinking; communication and presentation; data collection, processing and analysis; laboratory 'know-how', including developing safe working practice and risk assessment skills; time management; ethical and professional behaviour; application of new technologies; and team work.

An extensive literature describes up-to-date chemistry laboratory exercises for students that extend beyond the traditional 'follow the recipe' format (Domin, 1999).[1] Bennett and O'Neale (1998, p. 59) have commented that students following a recipe, "*are not 'doing an experiment', but 'carrying out an exercise'*". They argue that 'recipe experiments' make limited intellectual demands on students, who "*often seem to go through the motions…with their minds in neutral*". By contrast, in a well designed laboratory exercise students can experiment and engage, both individually and collaboratively (Shibley Jr. and Zimmaro, 2002), in open-ended labs (Psillos and Niedderer, 2002) and inquiry-based learning activities (Green et al., 2004) that apply theoretical concepts to relevant, real life problems. Equally, pure discovery approaches can be ineffective (Mayer, 2004; Kirschner et al., 2006), in part because they can lack sufficient structure necessary to support student autonomy (Skinner and Belmont, 1993), and in part because they can foster behavioural rather than cognitive engagement (Byers, 2002).

In a well designed laboratory, students interact closely with teachers and peers, so learning can be enhanced, monitored and assessed effectively (Boud et al., 1986; Hegarty-Hazel, 1990; Vianna et al., 1999 ; Johnstone and Al-Shuaili, 2001; Psillos and Niedderer, 2002). It has been recognised that students find a well-designed laboratory program stimulating and motivating (George et al., 1985; Paris and Turner, 1994); moreover, they allow students to 'scaffold' each other's learning (Coe et al., 1999). Well designed laboratories can be a popular component of science courses (Hegarty-Hazel, 1990; Deters, 2005) and can promote quality learning (Teixeira-Dias et al., 2005). Poorly designed laboratory exercises have also been shown to result in working memory overload and can to push students towards a 'going through the motions' approach (Johnstone and Wham, 1982; Johnstone, 1984, 1997a, 1997b; Johnstone et al., 1994).

According to the recent *Future of Chemistry* report (Royal Australian Chemical Institute, 2005), 48% of student time is spent in laboratory work, and so it is imperative that the opportunities afforded by this substantial learning environment are realised. Notwithstanding an extensive literature describing the benefits of laboratory learning, the value of laboratory activities beyond developing technical skills (such as handling glassware) has been questioned, most recently by Hawkes (2004). Hawkes argues that laboratory activities are expensive and time consuming, and that the costs involved are not justified (particularly for non-science majors) by the technical skills developed. This position has been criticised (Baker, 2005; Morton, 2005; Sacks, 2005; Stephens, 2005), yet it reinforces the challenge to chemistry educators to provide compelling evidence that laboratory classes achieve more than Hawkes implies.

Concerns such as these are certainly not new – in fact, according to Lock (1988) and Hodson (1993), discussions of the value of laboratory work have been occurring since the late nineteenth century – and others who have recently raised concerns about the value of some laboratory work include Marthie et al. (1993) and Bennett (2000). Some research [such as Rigano and Ritchie (1994), Markow and Lonning (1998), and Hofstein et al. (2005)] has been undertaken in an attempt to address ways in which laboratory work can be made more effective for promoting student learning. Nevertheless, as Hofstein and Lunetta (1982, p. 212) note *"researchers have not comprehensively examined the effects of laboratory instruction on student learning and growth in contrast to other modes of instruction, and there is insufficient data to confirm or reject convincingly many of the statements that have been made about the importance and the effect of laboratory teaching"* and that there *"is a real need to pursue vigorously research on learning through laboratory activities to capitalize on the uniqueness of this mode of instruction"* (p. 213). Despite the progress that has been made in developing our knowledge of learning and instruction in the twenty-five years since these statements were made, these comments remain true today (Tobin, 1990; Hart et al., 2000; Nakhleh et al., 2002; Hofstein and Lunetta, 2004).

Promoting effective learning in the laboratory

The literature highlights the benefits to learning that should accrue when students engage actively in the discovery of knowledge through experimental investigation. However, this literature also notes that the potential for 'deep' learning is often not realised for reasons that include inappropriate experiments (Bennett and O'Neale, 1998), poor educational design (Boud et al., 1986; Hegarty-Hazel, 1990), and/or inadequate resources (Gibbs et al., 1997). Moreover, an undergraduate laboratory setting is one that can induce anxiety in students (Bowen, 1999) drawing undue attention to relatively simple activities, and reducing the available working memory needed for meaningful learning (Johnstone and Wham, 1982; Johnstone et al., 1994; Johnstone, 1997b) by introducing extraneous cognitive load (Chandler and Sweller, 1991; Paas and Van Merrienboer, 1994; Sweller, 1994; Kirschner, 2002). To some extent, such problems can be reduced by appropriate sequencing of activities (Wickman, 2004).

The challenge remains to provide students with laboratory programs that are relevant, engaging and offer effective learning outcomes. The Australian Physical Chemistry Enhanced Laboratory Learning (APCELL) project[2] (Barrie et al., 2001a, 2001b, 2001c) and its all-of-chemistry regional successor, the Australasian Chemistry Enhanced Laboratory Learning (ACELL) project[3] (Read, 2006a; Read et al., 2006a; Read et al., 2006b; Jamie et al., 2007) are examples of contemporary efforts designed to tackle this challenge. Very recently ACELL has undergone a change of name to Advancing Chemistry by Enhancing Learning in the Laboratory, motivated, in part, by a growing level of international interest in the project.

The APCELL project was developed when it became apparent to chemistry academics in Australia that no single institution had been successful at overcoming barriers to student engagement imposed by limitations on physical resources, specialist expertise, pedagogical expertise, and student involvement in laboratory exercise design. A collective effort involving the resources of multiple institutions offered an excellent chance to overcome these problems. In 2004 the APCELL concept expanded into the all-of-chemistry ACELL project. APCELL generated a range of tangible outcomes, including chemistry education research articles, a database of freely available peer- and student-reviewed experiments,[2, 3] workshops showcasing innovative experiments, and experiment development tools (all materials are available online in the Document Library on the ACELL website). These outcomes have contributed to academic staff development by, for example, providing educators with a framework to identify and integrate intended student learning outcomes from the outset of designing and/or reviewing a laboratory exercise.[4] Further staff development opportunities were initiated in APCELL through the active involvement of staff delegates as 'students' during the project workshops. This resulted in a new-found insight on the part of some staff delegates into the student perspective of learning. Nonetheless, limited data are available describing student views on the impact of APCELL on their learning; this became a priority for ACELL. Objective evidence is also required to support the putative notion that the A(P)CELL concept is of benefit to educators as they design and evaluate laboratory programs. Collection and evaluation of such empirical data is essential if the concerns raised by Hawkes (2004) and others are to be effectively addressed. In this paper we report on the views of staff and student delegates who participated in the ACELL Educational Workshop held in early 2006.

Advancing Chemistry by Enhancing Learning in the Laboratory (ACELL)

The ACELL project has three principal aims: (*i*) to make available, via a public database, materials relating to undergraduate chemistry experiments which are educationally sound and have been evaluated by both students and academic staff. These materials consist of everything needed to introduce the experiment into another institution, as well as evaluation data relating to both the chemical and the educational aspects of the experiment (see, for example, the associated article by Read and Kable (2007) in this issue); (*ii*) to provide for the professional development of chemistry academic staff by expanding the understanding of issues surrounding student learning in the laboratory; and, (*iii*) to facilitate the development of a community of practice in chemistry education within the broader academic community.

A significant problem arising within the collaborative nature of ACELL is that at the teaching/learning interface, in the main, chemists are discipline experts, but not well read in educational research. Such research, like any other field of enquiry, has its own language and methodologies that are not always transparent to those outside the field, and is published in journals not usually accessed by chemists. ACELL, therefore, initially seeks to engage academics in reflecting on their own curriculum decisions about teaching and design of laboratory practice (Brew and Barrie, 1999), whilst simultaneously providing an accessible entry point or bridge into educational concepts (Read, 2006b; Buntine and Read, 2007).

The ACELL project methodology has identified the need, in the first instance, to engage academics from the participating universities at the level of their teaching and learning principles, rather than at the level of teaching behaviours. Processes that encourage academics to design student laboratory exercises from a learner-focussed perspective are used. This strategy has required that the project start with the participants' own concepts of teaching, even if these are teacher-focussed, then reflect on, and challenge these ideas in developing the parameters for the design of laboratory programs. An intensive workshop-style format, preceded by academics submitting what they consider to be exemplar experiments for peer and student feedback and comment, has been used to initiate this engagement and reflection process. The first APCELL workshop was held in February 2000. The first all-of-chemistry ACELL workshop was held in February 2006. Both events were held at the University of Sydney.

To assist academics in their reflective practice, ACELL modified an 'Educational Template'[4] originally developed under APCELL. The Educational Template serves several purposes, one of which is to act as a guide to submitters of an experiment for reflection on the learning objectives of their experiment. A second purpose is to provide users of the ACELL database with evidence that the experiments are high quality learning resources. The Template is divided into four sections, which present (*i*) a general summary, (*ii*) an analysis of the educational objectives, (*iii*) empirical data relating to student experiences, and (*iv*) relevant documentation. All four sections are rigorously reviewed prior to acceptance of an experiment into the database. The focus of this report is not to discuss the Educational Template in any detail. However, part of the review process undertaken at the ACELL workshop includes feedback to submitters on how their Template content can be improved to better serve ACELL's second purpose described above. This feedback plays a critical role in the academic reflective cycle and is relevant to the workshop analysis that is the focus of the current report.

The ACELL workshop format involves an early morning discussion session focussing on a particular educational theme, with mid-morning and early-afternoon laboratory sessions. Each day concludes with a focussed debrief and discussion session where delegates critically evaluate the experiments they undertook in both the morning and afternoon sessions. At the February 2006 workshop, delegates (staff and students alike) worked with different people in each laboratory session, providing the opportunity for delegates to work with colleagues and students from a range of sub-discipline areas of expertise, geographic locale, and/or university contexts. This format provided valuable delegate networking opportunities, furthering the ACELL 'community of practice' (Wenger, 1998) aims. Academic staff delegates were deliberately assigned to test experiments in areas both inside and outside their fields of sub-discipline expertise, forcing them to move beyond their comfort zone. In this way, the evaluation of each experiment drew on the specialist expertise of staff, whilst still allowing them plenty of opportunity to experience other experiments from the perspective of a student. Likewise, student delegates were mixed so that they were able to undertake experiments across a broad range of chemistry sub-discipline areas and undergraduate year levels. In general, each experiment was tested in both sessions on a particular day, with mixed student/staff teams used in one session, and student/student or staff/staff teams used in the other.

A design feature of the ACELL workshop format was to promote the stated academic staff professional development aims through (*i*) the formal panel discussions of educational issues, (*ii*) developing insight into the student's perspective afforded by participating in the laboratory sessions with student delegates as equals, together with undertaking experiments outside of their area of specialist expertise, and (*iii*) encouraging reflection on the Educational Template submissions of other delegates as a means of developing skills to self-evaluate critically a staff member's own submission. It was intended that this involvement also provided students with a rare opportunity to interact with staff from multiple institutions over several days, providing them with intensive networking opportunities and offering them some insight into the staff members' perspectives. Delegate evaluations were undertaken to determine the extent to which the ACELL project objectives were met through this educational workshop format.

Evaluation Methods

The February 2006 Workshop was held over 3 days[5] and involved thirty-three academic staff (excluding the eight Project Directors) and thirty-one student delegates from twenty-seven tertiary institutions across Australia and New Zealand, supported by three technical staff. All delegates were surveyed extensively during the workshop for their views on the chemical and educational aspects of the experiments they undertook, and again at the very end of the workshop where their evaluation of the workshop as a whole was sought.

In this final survey, staff delegates were asked to respond to eleven 5-point Likert scale items while student delegates were asked to respond to six 5-point Likert scale items, the first four being in common with the staff. All delegates were also asked for responses to four additional open-ended items. The distributions of delegate responses to the Likert-scale items have been compared using non-parametric χ^2 hypothesis testing where appropriate, and also by assigning each response a value (Strongly Agree = +2, Agree = +1, Neutral = 0, Disagree = -1, Strongly Disagree = -2) and using the resulting means for comparative purposes. If delegates were unsure of their attitudes to any particular item they were asked not to make any response, ensuring that the 'neutral' midpoint is not used in cases where the respondent is 'unsure'. This approach is in line with standard ACELL practice described in our 'Guidelines' document (ACELL, 2007), and reflects the belief (as described by Andrich (1978) and others) that the probative insight provided by the use of means for comparative purposes justifies the careful use of interval scale analysis methods (Michell, 1986), notwithstanding the near-interval (but technically ordinal) nature of this Likert scale.

In addition to the Likert-scale items, the survey solicited delegate responses to the following four open-ended items:

- What did you find to be the most valuable aspect of the ACELL workshop? Why?
- What area of the workshop do you think most needs to be improved? What improvements would you suggest?
- What was the thing at the workshop you found most surprising?
- Please provide any additional comments on the workshop here.

Delegate responses were entered into a database as thematically distinct comments prior to being subject to a content analysis; the first part of this analysis involved coding the comments following the general approach described by Miles and Huberman (1994). According to this approach, there are two types of coding reliability: inter-coder reliability, where two investigators independently code a section of the data set [a process also known as investigator triangulation (Sidell, 1993)], and intra-coder (or code-recode) reliability. In each case, reliability can be defined as the proportion of the total number of comments which are coded consistently, and it is expected that coding is not complete until reliability exceeds 90%. In this work, inter-coder reliability was initially low due to inconsistent coding approaches having been taken, although there was immediate agreement on the six broad categories or themes that emerged from the data. Once a common coding approach had been agreed, both inter-coder and intra-coder reliability rapidly exceeded 90% as recommended by Miles and Huberman (1994, p. 64). Every comment was coded; most comments were allocated to one category only, and on occasion a given comment was included in, at most, two categories. The relative scarcity of dual-coded comments provides indirect evidence that the themes identified are indeed non-overlapping. Whilst not being definitive evidence for the validity of the analysis, this fact, coupled with the concordance found during the investigator triangulation phase of coding, does provide credibility for the analysis approach taken. In fact, different types of triangulation are widely used in part because the can contribute to establishing credibility for methodological and analytical choices made (Moschkovich and Brenner, 2000).

Once categorised, all comments were identified as being either a 'positive' or a 'negative' response, allowing statistical analysis in addition to the qualitative analysis from the content analysis of the comments in each category. Together, the delegate responses from the two parts of the survey provide a rich vein of both quantitative and qualitative data against which to assess the efficacy of the ACELL workshop format in achieving the project's aims. The six broad categories, together with their coding type, and number of positive and negative delegate responses are listed in Table 1.

Table 1: Broad coding categories (or themes) emerging from a content analysis of delegate responses to open-ended items in the 2006 ACELL workshop evaluation survey, together with the number of staff/student positive/negative responses in each category.

Category	**Staff Comments**			**Student Comments**			**Total Comments**
	Pos.	**Neg.**	**Total**	**Pos.**	**Neg.**	**Total**	
Delegate Interactions	14	2	16	18	1	19	**35**
Educational Aspects	33	3	36	34	8	42	**78**
Workshop Design	7	17	24	12	22	34	**58**
Project Design	2	6	8	3	4	7	**15**
Project Impact	16	0	16	7	0	7	**23**
Miscellaneous	4	2	6	3	0	3	**9**

The workshop survey data have been augmented with interviews of both staff and student workshop delegates held after the workshop had concluded. A total of six interviews have been undertaken, involving four staff (pseudonyms: James, Kate, Stephanie, and Ted) and two student (pseudonyms: Dace and Luke) delegates (both student delegates interviewed are male). The structure of each interview allowed for in-depth investigation of issues which arose, whilst remaining consistent with an overall semi-structured framework (Minichiello, 1995; Mason, 2002), in accord with Burgess's (1984) description 'conversations with a purpose'. An examination of the interview data related to ACELL processes in general, and to the workshop in particular, shows that most comments fall comfortably within the broad coding categories shown in Table 1, providing further evidence for the robustness of this coding scheme. The interviews have been drawn upon to augment the workshop survey data: They also include substantial material relating to individual experiments and to issues of laboratory design; these data have been disregarded as going beyond the scope of the workshop evaluation that is the focus of the current report.

Methodological triangulation can be defined as "*the use of a combination of methods to explore one set of research questions*" (Mason, 2002, p. 190), and can provide for a more comprehensive understanding of a phenomenon, provided it is used with care (Silverman, 2005). In social contexts, it is common for meaning to be context-dependant and to vary between individuals, so that there is no single 'truth' to be discovered (Jaffe and Miller, 1994), and for that reason triangulation should not be used in a search for truth (Sidell, 1993; Silverman, 2005), nor as a means to judge the efficacy or validity of different methods (Mason, 2002). In this work, the qualitative and quantitative approaches described above arise from different methodological frameworks, and yield a mixture of hard (quantitative), medium-textured (coded qualitative), and soft (interview) data. Each data source illuminates different aspects of the workshop process and the delegates' experiences, and no single data source should be viewed as having primacy over any other. Triangulation of these differently textured data has been used solely to provide a more holistic view of the actual experiences of the delegates, providing a deeper understanding than would be possible from either source individually, and thus a more detailed and comprehensive answer to the research questions (Sidell, 1993; Denzin and Lincoln, 1994).

Results and discussion

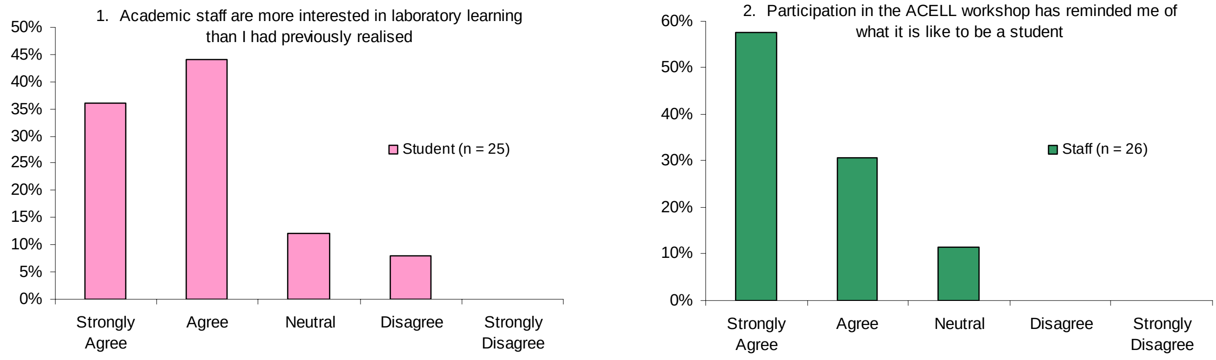
A discussion of the results obtained from this study is presented for each of the broad thematic categories listed in Table 1, with the exception of the 'Miscellaneous' category.

Delegate interactions (DI)

Delegate responses to the open-ended survey items in the DI category include comments on themes including: 'delegates' perceptions of one another', 'personal/professional development and networking', and issues of 'discussion, collaboration and feedback'. In particular, student delegates developed an awareness of the extent to which the participating academic staff were genuinely interested in their laboratory learning experiences, whilst staff delegates found that participating in the workshop reminded them of what it is like to be a student in the lab. As shown in Table 1, both students and staff provided significantly more positive than negative responses in this category ($\chi^2 = 24.2$, df = 1, $p = 8.64\times10^{-7}$). However, there is insufficient data to carry out a valid statistical test to ascertain whether there is any difference in the pattern of positive responses between the two cohorts.

Staff and student delegates were each asked one Likert-scale item relevant to the DI category. In Figure 1 the delegate responses to these items are presented, which were designed to determine how each cohort's perceptions of the other had changed as a result of participating in the workshop. Consistent with the thematic data discussed above, the quantitative data highlight strong positive responses to the questions posed: Responses to Question 1 highlight an increased student-delegate awareness of the academic staff commitment to improving student learning. These data also imply a significant improvement in the personal development and attitudes to learning of student delegates as a result of participating in the workshop, and suggest that their greater awareness of staff commitment to improving laboratory learning can enhance the quality of the student feedback and review of experiments submitted to the project.

Figure 1: Delegate responses to the respective Likert-scale items on 'Delegate Interactions' posed in the ACELL workshop evaluation survey.



Question 2 was specifically designed to gauge the level of impact of the workshop on staff-delegate professional practice. Responses to this question highlight that staff were reminded of what it is like to be a student, suggesting prior difficulty for them in judging the quality and effectiveness of experiments from the student perspective. This renewed awareness of the student learning perspective for staff delegates at the ACELL workshop partly explains an anecdotal observation from the earlier APCELL project where post-workshop revisions to Section 2 (Educational Objectives) of the APCELL Educational Template include descriptions of 'indicators of student learning outcomes' that are more clearly written from the student perspective.

The value of delegate interactions and being reminded of what it is to be a student was highlighted in interviews conducted with staff delegates Ted and Kate. Ted found that being reminded of the student perspective was a particular highlight of the workshop:

> It certainly was a bit of an eye-opening experience to actually be in the lab again, and think from a student perspective again, which is… no matter how hard you try, it gets harder and harder as the years go by to recall what it was like. So, yeah, that was certainly enjoyable, for the most part – maybe I experienced a bit of frustration with not clicking in to some of the experiments as quickly as I thought I should have, but that's good in and of itself as a learning experience.

These views were reinforced by Kate:

> And because of the way the workshop was run, you got to know people – I went over there knowing very few people because I don't network, but I came away thinking that I was quite happy to talk to anyone there. … It was very collegial, so, that's what I'll take away … [and it] reminded me of what it was like to be a student doing an experiment.

Staff and student feedback within the DI category also highlight the 'discussion' and 'networking' aspects mentioned earlier. For example, the following comments from staff and students (in response to the open-ended survey item asking them to identify the most valuable aspect of the workshop) illustrate the positive impact the workshop in this regard:

> *Staff:* "Participation with other academics from other institutes and being able to work with students. Why? It gave me insight into the working of other universities and students opinion of things."
>
> *Student:* "Being able to give feedback on the labs as a student. It was a rare opportunity and I did not realise how interested the demonstrators were in student opinion."

The quality of delegate interactions, particularly those between staff and students was found to improve significantly as the workshop progressed. The workshop format was designed to break down staff-student barriers from the outset. Interviews with student delegates Dace and Luke highlighted that the workshop structure (including staff and students working together to undertake experiments, and daily debrief sessions at a local hotel) engendered professional and social interactions that promoted to staff-student discussions of educational issues, which, in turn, had a particular positive impact on student perceptions of academic staff as educators. For example Luke stated:

> Actually I was quite surprised with some of the staff. I would always assume, like, most Professors and what not – they're not into teaching at all. They're just there because they have to teach so they can conduct their research, and… but, that wasn't the case at all. Like, all the staff that I met at ACELL, they are actually interested in teaching chemistry. That was a… bit of a revelation for me, actually.

Luke suggested that the debriefing sessions were not long enough (it is noteworthy that Luke was just about to begin his final (Honours) year at the time of the workshop); these sentiments are reinforced by Dace, who, when asked about any particular highlights from attending the workshop, commented:

> There was the social aspect – I think that was very well organised, high fives all around. Because, nobody really knew each other on the first day but by the third day, everyone knew everyone, and was… I think that made the labs easier on the third day than the first day, because you're more than happy to go 'oi, such-and-such, chuck me a beaker of this' instead of going over and getting it yourself, or whatever. Umm, and that camaraderie, and the development thereof early in the program – I think is something that should be continued.

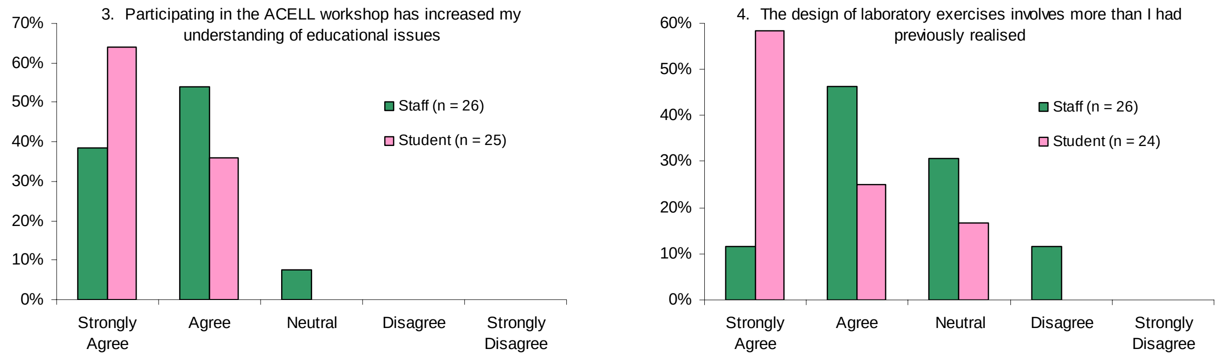
Overall, the survey and interview data illustrate the effectiveness of the ACELL workshop format as an effective mechanism for improving academic staff and student perceptions of each other in terms of (*i*) the former's appreciation of what it is like to be a student in the undergraduate laboratory, and (*ii*) the latter's appreciation of staff commitment to providing quality laboratory exercises. As we will present in following sections, the in-depth staff-student interactions promoted throughout the workshop have a demonstrable positive impact on the quality of the student laboratory learning experience.

Educational aspects (EA)

Delegate responses to the open-ended items in the EA category include comments on 'delegate educational awareness', 'the quality/effectiveness of laboratory exercises for improved student learning', and 'delegate reflection and reflective practice'. Again, as evidenced by the data contained within Table 1, both students and staff provided responses in the EA thematic category that are significantly more positive than negative ($\chi^2 = 41.1$, df = 1, $p = 1.45\times10^{-10}$). Interestingly, there is no difference between the response patterns of the staff and student delegates in this category ($\chi^2 = 1.84$, df = 1, $p = 0.175$).

In Figure 2 we present delegate responses to two Likert-scale items designed to inquire into development of educational awareness as a result of participating in the ACELL workshop. Both staff and students report an overwhelmingly positive attitude to their understanding of educational issues (Question 3), with any difference between the groups being borderline in terms of reaching significance. The mean staff delegate response to Question 3 is 1.31 ($\sigma = 0.62$) and the mean student response to this item is 1.64 ($\sigma = 0.49$) on the +2 to -2 scale. Student responses to Question 4 (concerning the amount of effort involved in the design of laboratory exercises) shows a significantly more positive response pattern ($\chi^2 = 12.3$, df = 2, $p = 2.11\times10^{-3}$), suggesting that the student cohort has gained an increased awareness compared to the staff delegates. Indeed, the stronger level of agreement amongst the students is indicated by a response mean of 1.42 ($\sigma = 0.78$) compared with that of 0.58 ($\sigma = 0.86$) for staff on the +2 to -2 scale. This minor divergence of views is not surprising and is most likely attributable to the considerable lack of prior exposure of students to issues surrounding educational awareness, also seen in an increased student awareness of the teaching content of laboratory exercises – more than 80% of student delegates agreed or strongly agreed that laboratory exercises are intended to teach more than they had previously realised.

Figure 2: Delegate responses to the Likert-scale items on 'Educational Aspects' posed in the ACELL workshop evaluation survey.

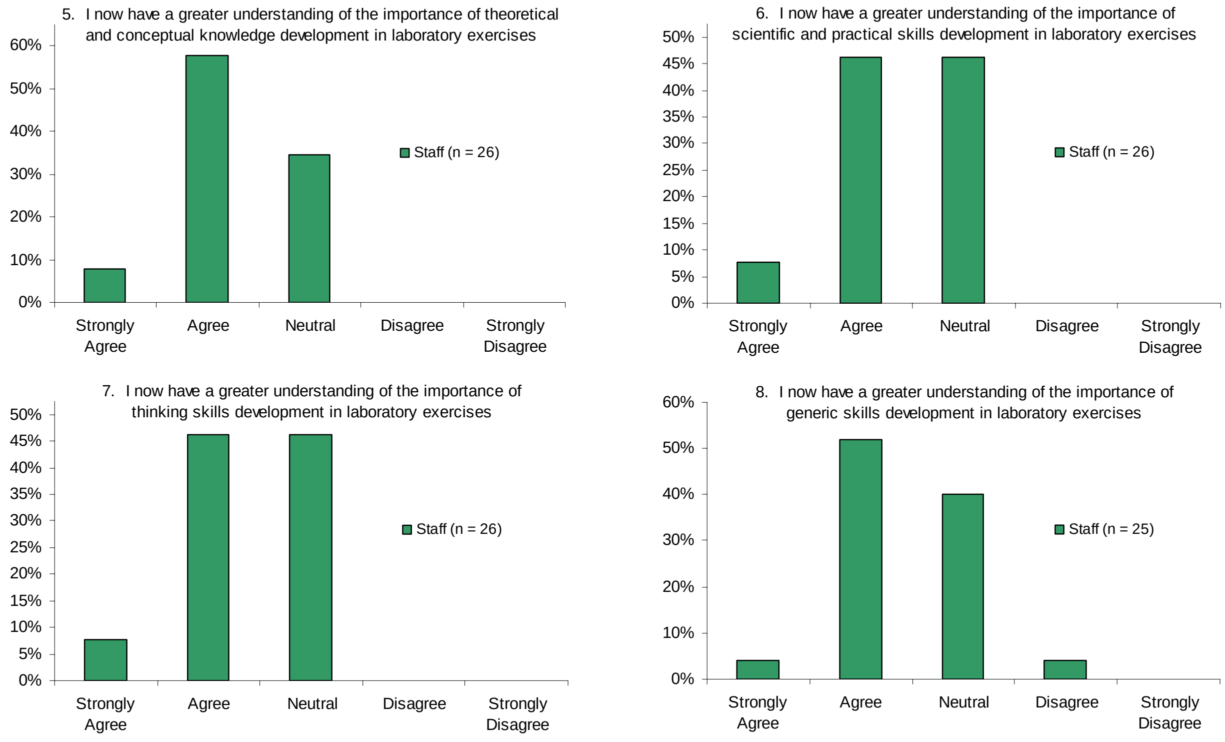


The previous APCELL participation of some staff delegates may also contribute to the difference in staff and student responses to Question 4 (Figure 2). In this context a staff response of 'disagree' with the item does not necessarily imply that the design of laboratory exercises is easy or straightforward. Rather, staff members could hold the view that laboratory exercise design is difficult, but they already knew this. For example, Stephanie was interviewed as a staff delegate who attended both the APCELL and ACELL workshops. Stephanie commented on the continuing value of the workshops:

> I have to say…I liked the idea – it was something different that people were interested in, and initially it was physical chemistry, so I liked the idea that somebody was going to try and do something about physical chemistry experiments, probably because I had some bad experiences. Also, at that stage, I was involved in running physical chemistry labs. So, it was timely. It was something I was interested in. That was my initial reason for involvement [and continuing, as] it gives me an opportunity – it forces me to develop some good experiments.

In Figure 3 we present the staff-only responses to the Likert-scale items on educational awareness posed in the workshop evaluation survey. These items were included in the survey instrument because they had been designated as the learning outcome areas for consideration in the version of the Educational Template used at the ACELL workshop. In other words, having been asked to consider these issues prior to the workshop when completing the Template, staff delegates were subsequently surveyed on their attitudes after participating in the intensive workshop process.

Figure 3: Delegate responses to the staff-only Likert-scale items on 'Educational Aspects' posed in the ACELL workshop evaluation survey.



The data in Figure 3 highlight a range of staff opinions inclined towards an overall positive sentiment, providing further evidence that the workshop is a useful professional development format in the quest to seek ways in which to improve student laboratory learning outcomes. The data in Figure 3 are not as positive as the student responses discussed earlier, where a more positive improvement in student educational awareness is demonstrated. We again attribute this minor difference in views to the lack of prior educational awareness of the student delegates.

The positive delegate sentiment towards educational aspects of the ACELL workshop evident in the quantitative data is reflected in the open-ended responses provided in the workshop survey. Examples of positive comments (in response to the open-ended item asking them to identify the most valuable aspect of the workshop) include:

> *Staff:* "It made me sit down and think carefully about what I wanted my students to get out of my experiment, and how I could judge if they had been successful."
>
> *Staff:* "Educational issues – as a scientist, I felt lacking in educational knowledge."
>
> *Student:* "Most of all though, I was shocked to find that the academics at the universities really want to make our laboratory experience as worthwhile as possible."
>
> *Student:* "That was one of the best chemistry experiences I have had in the last 4 years – knowing that there are people that are concerned with teaching in labs and what makes a great lab and how they can be improved has given me ideas that I can take back when I demonstrate [to] students."

Within the EA category, staff and student comments of a negative nature were in a remarkable degree of agreement as exemplified by the following comments on the size of the workshop's discussion forums (made in response to the question asking to identify ways in which the workshop could have been improved):

> *Student:* "Smaller groups facilitating an open discussion."
>
> ***Staff:*** "It would be great to have a session, very earlier in the program, to sit down with a small group of people to discuss why laboratory lessons are not living up to their potential. One would feel more comfortable in a small group setting to air their opinions, and this would lead to fruitful discussion."

In her interview, Stephanie comments on how, in going about designing a new experiment she draws upon the APCELL/ACELL approach as a framework for ensuring quality and validity in terms of educational outcomes:

> Well, for me, first of all: being able to write a – what I, well what other people as well, view as a quality experiment. I certainly never went through that process, I knew, you know, I think I've always known what's a good experiment, what a good experiment should have – you know demonstrator notes and technical notes, and so on, and educational background and objectives and so on. [But,] I didn't know how to put it all together, didn't have a template, I didn't have time. So, for me, having reached a quality experiment which has been tested by students, peer reviewed, and so on, that I feel confident…

Thus far we have contrasted staff and student delegate attitudes within the EA category in terms of students having a less well developed educational awareness. However, as illustrated in the following interview extract with Dace, students have a quite well-developed sense of when and how they actually learn:

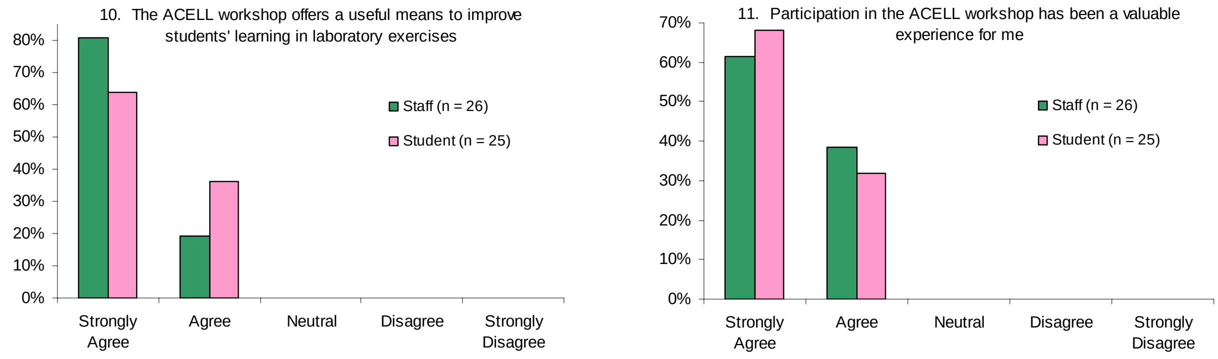
> You don't learn in the lab – you learn before the lab, and you learn after the lab, but you don't learn in the lab. You 'do' in the lab. If you're learning in the lab, it's a top experiment.

In conclusion, the survey and interview data illustrate the effectiveness of the ACELL workshop format as an effective mechanism for improving academic staff and student educational awareness, thereby contributing to the professional and personal development of all delegates.

Workshop design (WD)

In Figure 4 we present delegate responses to two Likert-scale items designed to determine delegate views on the structure and design of the ACELL workshop. Both staff and students report an overwhelmingly positive attitude to the design of the workshop, with no statistical difference evident in the response patterns of the two groups for either question (Question 10: χ^2 = 1.80, df = 1, p = 0.180, Question 11: χ^2 = 0.233, df = 1, p = 0.629). The mean staff delegate response to Question 10 is 1.81 (σ = 0.40) while the mean student response to this item is 1.64 ($\sigma = 0.49$) on the +2 to -2 scale. Similar response patterns are seen for Question 11, with the mean staff response being 1.62 ($\sigma = 0.62$) with a mean student response of 1.68 ($\sigma = 0.48$).

Figure 4: Delegate responses to the Likert-scale items on 'Workshop Design' posed in the ACELL workshop evaluation survey.



In terms of the open-ended items, the WD category includes responses that comment on the 'workshop program: format, timing and impact on delegates', 'venue and facilities', 'delegate laboratory exercise allocations', and 'laboratory exercise time allocations'. In contrast to the quantitative data presented above, the qualitative responses of both students and staff are significantly more negative than positive ($\chi^2 = 7.11$, df = 1, $p = 7.67\times10^{-3}$). Again, there is no difference between the response patterns of the staff and student delegates in this category ($\chi^2 = 0.24$, df = 1, $p = 0.624$).

The negative commentary of issues relating to workshop design might, at first glance, seem at odds with the quantitative data. However, most of the negative comments relate to infrastructure matters including the quality of the budget college accommodation used by delegates and the lack of air conditioning and other environmental controls during a humid summer period. Constructive negative comments relating to educational aspects of the workshop design focus on the non-stop intensity of the three-day program. Several staff delegates commented on how tired they were and suggested a less dense program in future. In her interview, when asked about the merit of allowing for 'visiting' of other experiments, Stephanie suggested:

> Yeah, I was thinking about that. Yes and no. Yes, because then I would get – I would choose the ones that would be appropriate for my units, probably. But, no, because, I may be biased – I'm interested in those anyway. So, I may not be as critical maybe of the actual experiment. So, maybe it was good that you gave – and like you said, putting people out of their comfort zone was very, very useful

In contrast to staff feedback which focussed on the conduct of the laboratory sessions, most negative student comments related to the format of the morning and evening discussion sessions that bracketed each day's laboratory program. By and large, student delegates expressed a desire for smaller, more focussed, discussion groups, and some variation in the discussion forums, including the possibility of including 'student only' discussion sessions on occasion. The constructive nature of the negative comments can be interpreted in terms of positive level of delegate engagement with the workshop process; delegates enjoyed the workshop, and the feedback given is offered in terms of making subsequent activities even better educational experiences. From the six interviews conducted, all interviewees have said that they would recommend future ACELL activities to colleagues and peers.

Representative delegate comments highlighting the views expressed in terms of suggesting improvements to the workshop format include:

> *Staff:* "Not enough time to look at other experiments – could staff be "students" for only 2 half-days instead of 2 full days?"
>
> *Student:* "More discussion time i.e. the panel discussions in the morning – perhaps break into groups (half size) – one morning session, one afternoon."
>
> *Student:* "Apart from doing the labs themselves, there should be a brief discussion prior to this about the context of the lab and the theory that surrounds it."

As stated earlier, a key objective of the ACELL project is to build a community of practice amongst staff and students. A deliberate design feature of the 2006 workshop was to quickly establish and promote an informal, collegial atmosphere in which staff and student delegates could learn to appreciate each other's points of view without focusing on each other's rank and station in the education hierarchy. The earlier discussion regarding Delegate Interactions highlighted the success of the workshop format in contributing to this objective. The following student comment in response to being asked to identify the most surprising aspect of the workshop is indicative of delegate attitudes:

> I was surprised at how relaxed the atmosphere was. I had expected the 3 days to be stressful and put my skills to the test. I was glad that I was able to analyse the experiments in the relaxed atmosphere.

A further aspect of informality designed to promote the ACELL community of practice and delegate equality objectives was to integrate social aspects into the educational deliberations. For example, the evening discussion and evaluation sessions were held in a local hotel, with food and drinks provided throughout the discussion periods. A relatively small number of delegates commented negatively on this aspect of the workshop, but interestingly the comments offered were almost all in terms of the inappropriateness of the venue's acoustics for simultaneous small-group discussions of the day's experiments rather than the use of a hotel *per se*. As before, these 'negative' comments can be interpreted as constructive feedback, and are indicative of the high level of delegate engagement in the educational process; delegates were commenting on the inappropriate acoustics in the hotel because it prevented them from fully participating in the discussions at hand! Positive delegate attitudes towards the hotel-based discussions are best summarised by the following comments:

> *Student:* "The half-hour discussions at the end of the day at the pub – I believe this is where the majority of good feedback to the demonstrators occurs, as 'students' could bounce ideas off each other." (In response to what was most valuable about the workshop).
>
> *Staff:* "How engaged staff and students were, even over the beer sessions" (In response to what was most surprising about the workshop).

In her interview, Kate made several references to how the ACELL workshop format has reinforced her motivation for pursuing educational excellence, by providing her with the confidence, via the ACELL instruments in general, and constructive peer and student criticism in particular, that her design and sequencing of laboratory exercises is of a very high standard, with clear objectives:

> The Template – that is a way of trying to remind – continually reminding academics: why are you doing this? What is the pedagogy? What are the learning outcomes? There's always a sense that we stick in labs just for the sake of sticking in labs and to fill space. And, I've seen it, I've seen academics saying I've got to find another lab – and really, that's not what we should be looking at. If there's no lab – if you don't think you need another lab, why run another lab?

The survey and interview data illustrate that the design of the intensive ACELL workshop, including the aspects of (*i*) staff and students working on experiments together as equals, (*ii*) the informality of daily discussion, evaluation and review sessions, and (*iii*) the social program all contributed to establishing a friendly and supportive environment in which constructive educational criticism and feedback was given and received positively.

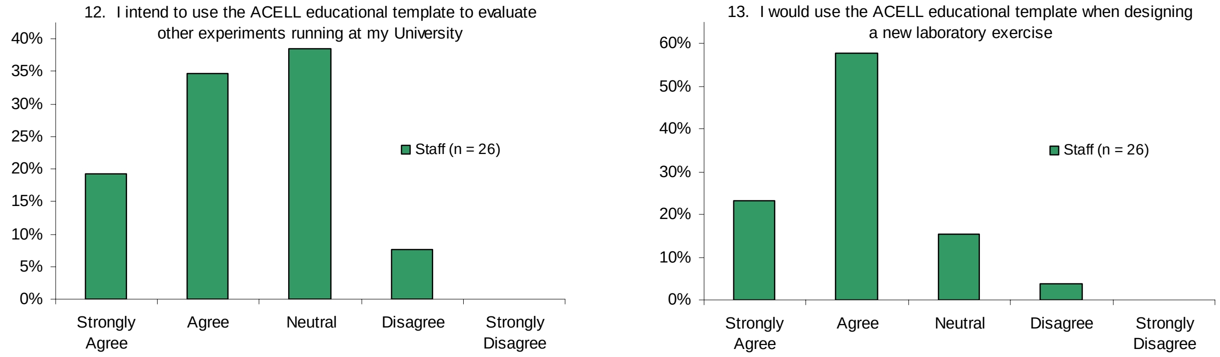
Project design (PD)

Delegate responses to the open-ended survey items in the PD category include comments on themes including the ‘Educational Template: effectiveness, scope and purpose’, and ‘quality of submissions’. As shown in Table 1, only 15 responses were allocated to this category and there is insufficient data to comment on separate staff and student response patterns. When all delegate responses are combined, there is a balanced positive and negative response distribution ($\chi^2 = 1.66$, df = 1, $p = 0.197$), suggesting a plurality of positive and negative views.

One aspect of the ACELL project to receive considerable attention is the Educational Template. The Template is an instrument originally developed during the APCELL project to assist team members in identifying and articulating the key learning aspects of their submitted experiment. Based upon APCELL participant feedback, the Template was modified somewhat for the ACELL workshop, but retained its key characteristics designed to elicit reflective practice from the workshop staff delegates. In Figure 5 we present the staff-only delegate responses to the Likert-scale items on the educational template posed in the workshop evaluation survey. These data highlight a range of opinions clustered around generally positive sentiments, which suggests that the development and use of the Educational Template is a useful tool for educators to reflect upon and ultimately articulate the educational benefits of any given experiment. The survey data indicate that ~80% of workshop delegates intend to use the Template when designing a new laboratory exercise, and over half intend to use the Template to evaluate existing experiments at their institution. Nonetheless, support for using the Template is not unanimous. We intend for the Template to continue to evolve with ACELL participant needs, and in this vein delegate feedback from the 2006 workshop has resulted in minor changes. However, we have (as yet) no feedback on whether these changes are seen by users to have addressed their areas of concern.

The quantitative data presented in Figure 5 expresses a consistently more positive sentiment than the open-ended response data. One possible interpretation of this difference is that delegates expressing some negative feeling can see the value in using the Educational Template, but are having some difficulty with using the Template with confidence, mostly attributable to a lack of familiarity with what is being asked of them. The intensive workshop format required staff delegates to submit their completed Template describing their experiment in advance of the workshop itself. As a result, delegates did not have the benefit of the workshop discussions to inform their completion these initial submissions.

Figure 5: Delegate responses to the Likert-scale items on 'Project Design' posed in the ACELL workshop evaluation survey.



From a constructivist perspective (Bodner, 1986; Phillips, 1995; Palinscar, 1998; Windschitl, 2002), the ACELL project design requiring submitters to complete the Template prior to attending the workshop, with all workshop delegates participating in that given experiment's review commenting on the clarity and usefulness of the Template, is pedagogically sound. Learning-by-doing allows delegates to make mistakes and learn from them, and leads to a much more developed understanding, albeit personalised.

To assist submitters in their reflection, a written 'how to' guide for filling in the Template was provided prior to the workshop, but it is clear that some submitters didn't fully appreciate its implications. Consideration was given to the possibility of providing more guidance, such as by including more reference to the literature of education, but this idea was discarded. The ACELL project is designed to encourage participants to engage with educational issues surrounding effective student laboratory learning – if delegates were asked to immerse themselves too deeply in educational theory prior to attending the workshop an unnecessary barrier to engagement might have been introduced.

Some delegates turned to published Templates from the earlier APCELL experiment database for guidance on completing the ACELL Template. In his interview, Ted mentioned looking for such guidance as he first wrote his Template draft and then went on to say that he felt that the Template is a useful instrument to promote the difficult task of reflection around educational issues:

> [The completed Template is] certainly something I would look at again with my particular experiment, and probably want to modify. But, yes, it's useful to be concrete about things and, try to target the various learning areas and think about the practical side, but also how the theoretical side is tying in to that. [Also], how we are assessing that is, of course, the hard part.

Positive survey feedback about the Template was also offered, by staff and student alike, in the context of a new-found educational awareness. Experience from the preceding APCELL project is that the quality of the Educational Template submissions markedly improved following the experiment critical review process at the workshop. These improved Template submissions form the basis of the public database of APCELL experiments.[2, 3] It is expected that a similar improvement in the quality of the ACELL Template submissions will result from the ACELL workshop experience. Indeed, the most comprehensive ACELL Template submissions for the 2006 workshop were provided by staff delegates who had previously participated in the APCELL project. As discussed previously, the very fact that these staff chose to participate in ACELL, having previously contributed to APCELL, attests to the value of these initiatives in providing on-going and lasting professional development value.

Representative delegate comments on the ACELL Educational Template, expressed in terms of suggesting improvements to the project design, include:

> *Staff:* "Template. The Template is good for developing an experiment as a check list, but not as good for communicating choices for aims and basis. Could be improved – but need to think about it. Templates may be a good way of disseminating info in labs."
>
> *Student:* "Perhaps outlining the Educational Template a bit better BEFORE the workshop so delegates understand what they are critiquing/analysing."

Unlike the staff delegates who had to prepare an experiment for submission to the workshop, most student delegates attended with no prior knowledge of what to expect. Although the blank Template and associated guide were provided to student delegates prior to the workshop, the absence of any concrete example appears to have made this hard to understand. Therefore, most students only appreciated the significance of the Template at the workshop itself, and the student comment above should be interpreted in this context. Interestingly, a small number of staff delegates chose to get the student delegate(s) from their institution involved in the workshop preparations, and anecdote suggests that these students adapted to the workshop environment more readily. Involving students in workshop preparation in future endeavours is well worth considering.

Project impact (PI)

Delegate responses to the open-ended survey items in the PI category address issues including 'delegate motivation, inspiration and new ideas' and 'views as to the lasting impact of the project'. No quantitative items concerning project impact were included in the evaluation survey form. With only 23 open-ended responses allocated to this category, there is insufficient data to comment on separate staff and student response patterns. When all delegate responses are combined, the pattern of responses is uniformly positive. Most delegates offered comments relating to Project Impact in response to the item asking about what they found to be the most valuable aspect of the workshop. Example comments include:

> Staff: "Ways to improve more variables into our lab to make them more 'enquiry driven'."
>
> Student: "Learning lab skills from more experienced lab partners. I am looking forward to utilising those new-found skills when I get back to Uni."

The most compelling evidence relating to the impact of the ACELL project on the quality of Australasian undergraduate laboratory programs comes from the interview data. Supporting ACELL's 'community of practice' aims, student delegate Luke commented on how attending the workshop has provided him with on-going contact with other staff and student delegates he met:

> I was a bit intimidated because I thought everyone would be really super smart, and everything, but, yeah just a bunch people who just loved chemistry – just really, really good. I wasn't really familiar with ACELL at all, before – I know they had it for physical chemistry in previous years.

Staff delegate Ted commented that attending the workshop has had an impact in terms of reinforcing his view that undergraduate laboratories are not simply 'assembly' lines that you pass students though:

> …thinking about the lab again from an educational standpoint, which, unfortunately, we often see it as a timeframe that has to be filled, and getting students in and out, sort of like an assembly line, sometimes, which…comes from the redundancy, I guess, of doing it every year, that sometimes you lose perspective on the teaching dynamic in the lab and being able to troubleshoot new problems that you really haven't encountered, as opposed to just funnelling students through the system.

Stephanie, a participant in both the APCELL and ACELL workshops, identified the project impact in terms of improving the quality of individual laboratory exercises, as well as her personal and institutional attitudes towards assessment, staffing and resourcing models for undergraduate labs:

> [ACELL] also [offers] a quality control [mechanism] that I can say to my students that the experiment that they're doing is going to provide them with a good laboratory experience. Personally, I think that that's – that's very important. I think it's fantastic that finally laboratories are being viewed as an important learning environment. I say that because, when I went through University, many, many years ago – but not too many, because I do remember – I really don't think that the lecturers viewed the laboratories as being that important. And I went through some labs that were ancient – the way they were written, the quality wasn't there – just the way the assessment was. I didn't see that it was certainly such an important learning environment, and I don't think the lecturers viewed it that way. That was my view, and – that's changing… [ACELL] is saying 'no, laboratories are important, you need to spend time designing the labs, you need to have a good demonstrator, it is a place where students are learning. … [T]he whole ACELL experience has given me the tools to create new labs, and whenever I do design a new experiment – or fix the old ones – I do it now according to the ACELL way, because I want – in future, I would like all my experiments to be ACELL experiments, that's the goal.

Apart from influencing their broader educational awareness, during their interviews, staff delegates also discussed how the ACELL project has impacted on the way that they implement new experiments and/or identify aspects of experiments that are suitable to their educational context. All staff delegates highlighted particular experiments showcased at the workshop that they would like to introduce to their institutions. All these showcased experiments are fully documented in the ACELL workshop manual, and each staff member interviewed wishes to adapt their experiment of interest to suit the specific conditions found in their institution. Nonetheless, this willingness to adopt experiments from other universities illustrates the ACELL project's impact, in that workshop delegates have the resources at hand to 'fast track' such experiment adoption. All experiments that pass through ACELL's rigorous review process will become publicly available on the project's website[3] to allow ready adaptation and adoption by all interested parties.

The February 2006 ACELL workshop involved 64 staff and student delegates, not including the 8 project Directors. One measure of the broader interest that the project is having in the higher education community can be found from the number of visits to the project's website. In the period since the website was launched near the start of June 2006, an average of over 1000 visitors to the web site each month has been recorded, with the number of *unique* web site visitors each month steadily increasing, to approximately 500 unique visitors per month over the period October 2006 – February 2007.

All the evidence presented supports the conclusion that the ACELL project is having a significant impact on the professional development of the participants in the workshops. Preliminary evidence suggests that the project's impact is extending well beyond the flagship workshop held in February 2006. The interview data, in particular, suggests that the A(P)CELL projects have, together, contributed fundamentally to the educational awareness in terms of student learning in the laboratory of academic staff who have been involved. The explicit incorporation of student commentary in the anonymous peer review of experiments that are revised following feedback provided at ACELL workshops, which is an essential component for publication of the educational aspects of an experiment (see the ACELL website for a comprehensive discussion of the entire ACELL process), is designed to ensure a student focus at every stage. Our hope is that the ACELL initiative will have lasting impact in the sector. The recent ACELL change of name, designed to accommodate a growing level of interest in the project outside of Australasia, augurs well for the future.

Conclusion

The A(P)CELL model has proved effective at engaging academic staff and students collaboratively in evaluating undergraduate chemistry laboratory exercises. The project is a practical example of how to sustain a community of practice in chemistry education. The immersive workshop approach has been demonstrated to allow both pedagogy and discipline content to be discussed; it engages staff in a scholarly approach to curriculum development, and provides a practical way for student feedback to be used in designing resource-intensive components of an undergraduate program.

Apart from the obvious academic staff professional development benefits, student involvement demonstrates and reinforces the commitment of the Australasian chemistry educational community to be inclusive, and to work collaboratively with stakeholders. Student participants benefit from tangible personal development opportunities, and have provided positive feedback that the ACELL workshops enhance their ability to ‘learn how to learn’. In short, the A(P)CELL model has strong potential to provide similar benefits to other chemistry education communities, and to other laboratory-based disciplines in the science, technology and engineering fields.

Acknowledgements

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Notes

1. Also, see, for example, any recent issue of *J. Chem. Educ.* for examples of modern undergraduate and high school experiments that promote problem solving over recipe following.
2. See http://www.apcell.org .
3. See http://acell.chem.usyd.edu.au .
4. As evaluating the educational design aspects of a laboratory exercise is new territory for many academic staff, an important feature of A(P)CELL has been the development of an "Educational Template" to guide this assessment. This Template can be used beyond the confines of the project to evaluate any existing experiment, as well as being a useful tool to use when developing new experiments.
5. Time associated with travel to and from the Workshop meant that delegates invested up to 5 contiguous days to the project, which itself is a strong indicator of their perceived worth of the activity.

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Practice

Educational analysis of the first year chemistry experiment 'Thermodynamics Think-In': an ACELL experiment

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Abstract: This paper describes an educational analysis of a First Year University chemistry practical called 'Thermodynamics Think-In'. The analysis follows the formalism of the Advancing Chemistry by Enhancing Learning in the Laboratory (ACELL) project, which includes a statement of education objectives, and an analysis of the student learning experience. The practical consists of a suite of ten well-known, short experiments on the general theme of 'thermodynamics in chemical change'. Pairs of students undertake a specified and graded set of five of these experiments. All experiments require careful observation by both students, followed by discussion between them until a common, mutually-agreed explanation for their observations can be formulated. The pair then discusses their explanation with a demonstrator, who may challenge it, point out flaws, or provide new information. Student surveys were conducted using the ACELL Student Learning Experience instrument. Analysis of the data shows that students enjoy working on the practical, and report it to be a beneficial learning experience that effectively develops their understanding of thermodynamic principles. The practical also fosters significant interest, and through a process of collaboration and cooperation aids the students in further developing their generic thinking skills. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 255-273.]

Keywords: Laboratory-based learning, practical work, first-year undergraduate chemistry laboratory, student engagement, cooperative learning, ACELL project, physical chemistry, thermodynamics

Introduction

Thermodynamics is one of the topics in the introductory chemistry syllabus that many students find difficult (Sozbilir, 2004), with a range of different approaches to teaching thermodynamic concepts having been described in the literature (Arnold and Millar, 1996; Williamson and Morikawa, 2002; Greenbowe and Meltzer, 2003). All university chemistry laboratory courses would be expected to have one or more experiments at the introductory level that teach students thermodynamics concepts. For example in Domin's (1999) review of the content of laboratory manuals for General Chemistry, all manuals examined included calorimetry experiments.

Thermodynamics Think-In is a collection of well-known, short, observational experiments that have, as a central theme, the concept of driving forces in chemical reactions. The mix is fairly eclectic, including commercial products such as a chemical hot pack, oddities such as the 'Drinking Duck' that was the subject of a recent study by Lorenz (2006), and various sets of known and unknown chemicals in sealed tubes. The practical is structured around careful observation and peer discussion, which is intended to promote cooperative learning, leading up to a demonstrator conference. We show below that in addition to the development of a deep understanding of elements of thermodynamics, the practical is strong on the development of thinking skills and other generic attributes.

Many of the ten individual experiments that make up this laboratory exercise will be undoubtedly familiar to instructors of introductory chemistry and have a long and often unknown history in chemistry demonstrations. The experiments themselves are not the focus of this paper, and so are described only briefly here. The focus of this paper is, rather, the educational analysis of the experiments to support the statements about student learning and engagement above. The educational analysis of this experiment uses the Advancing Chemistry by Enhancing Learning in the Laboratory (ACELL) project formalism. Some details of the project itself have been published previously (Read, 2006; Read et al., 2006a, 2006b; Jamie et al., 2006), and a detailed discussion of the most recent ACELL workshop is included in this volume (Buntine et al., 2007). This paper follows closely the template of the ACELL educational analysis formalism (called the 'Educational Template'), details of which are available on the ACELL website (http://acell.chem.usyd.edu.au). In brief, the ACELL educational template involves four sections: 1) description on the experiment, 2) educational objectives, 3) student learning experience, and 4) support material. The next three sections of this paper are written from sections 1–3, while the supporting material is available on-line from the ACELL website. Most of the information is freely available; however, access to materials such as demonstrator and technical notes requires an email request to the ACELL team and subsequent verification of academic, or equivalent status. This measure is simply to control access to the 'answers'.

History and brief description of the experiment

Thermodynamics Think-In has been running in the First Year Chemistry program at the University of Sydney since 1994. It was first developed by Dr Ian McNaught (now at the University of Canberra); the notes and experiments have undergone modest changes and additions since that time. The student cohort is one of the advanced streams of Chemistry 1 at this university. Students work in pairs on these experiments and discussion between students is an integral part of the learning experience (see Sections 2 and 3).

There are ten separate experiments in this practical, organised in two sets of five. Student pairs perform one of the sets of five experiments in a prescribed order, from simple to more difficult, over 3 hours. The ten experiments are described below, along with typical student observations. Full descriptions of each of the experiments are available on open access from the ACELL website.

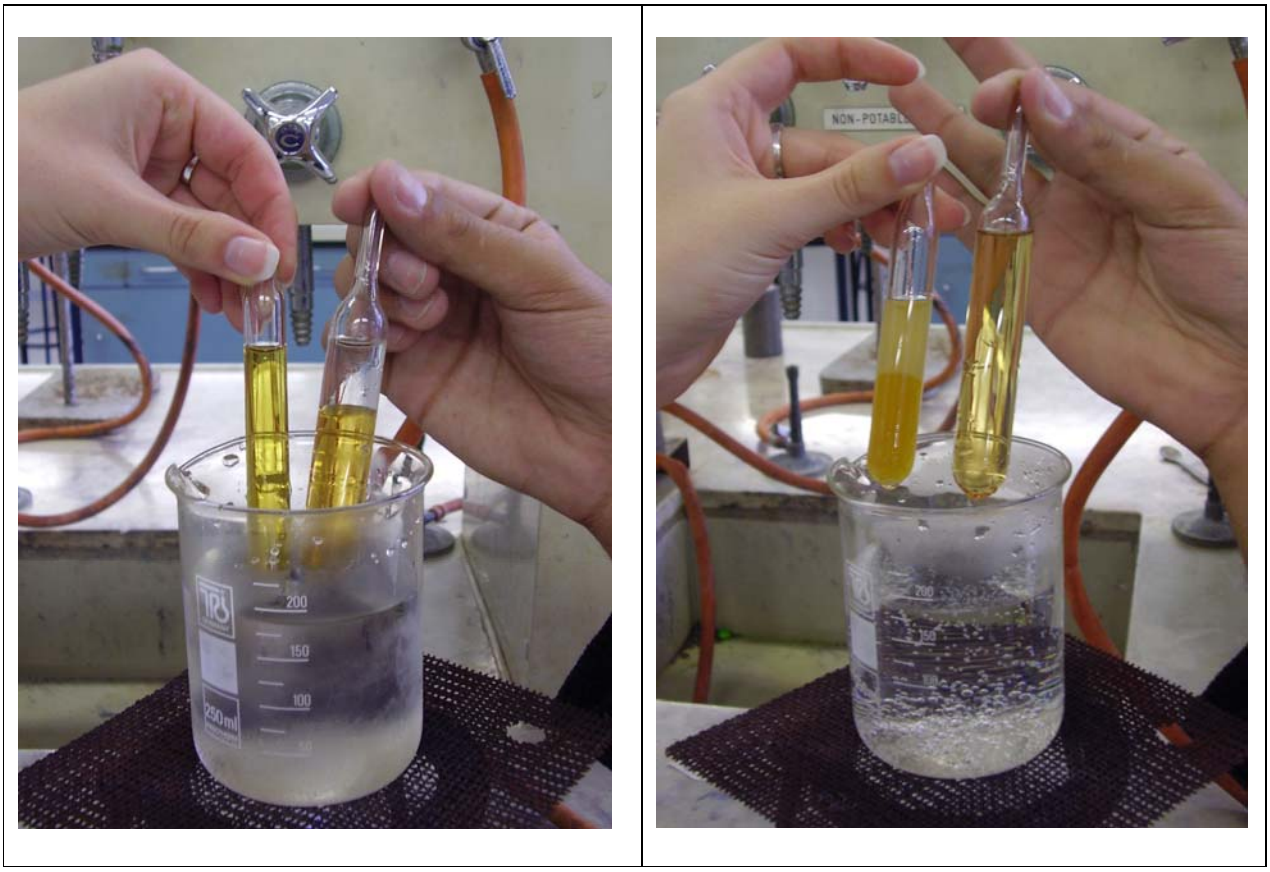
Experiment 1A (Thermodynamics of rubber bands, Part 1): Students place a rubber band against their lips and rapidly extend it so that the length is at least doubled. They then let the rubber band relax quickly, while still holding it against their lips. Students are asked whether they felt a temperature change (the change is small but distinctly noticeable). The students summarise their observations in chemical equation form by deducing the sign of ΔH for the equilibrium rubber band (extended) $\rightleftharpoons$ rubber band (relaxed).

Experiment 2A (Thermodynamics of rubber bands, Part 2): The students suspend a 1 kg block from a retort stand using 3-4 rubber bands. They then gently warm the rubber bands with a heat gun and watch whether the bands expand or shrink. Counter-intuitively, the rubber bands shrink when they are heated, as shown in the short video clip (http://www.rsc.org/images/weight_tcm18-85053.avi), which is available with the on-line article or the ACELL website. Students are provided with a generic description of polymers and some background material about entropy. The pair must explain their interpretation on both a macroscopic and microscopic level.

Experiment 3A [Heating $I_2(s)$]: Students are provided with two identical-looking tubes containing solid iodine. Using a gentle flame, each tube is warmed. The students are told that one tube is under vacuum, while the other contains air, but not which is which. In one tube the iodine sublimes, whilst in the other it melts.

Experiment 4A (Heating produces mixing and separation): Students are provided with two tubes – one contains roughly equal phenol/water which has two phases, and the other contains nicotine/water, which is miscible, as shown in the left photo of Figure 1. Students heat both tubes together in a beaker of water. At about 80 C the phenol/water mixture becomes monophasic, while the nicotine/water phase separates (Figure 1-right). Students are provided with the molecular structure of nicotine and phenol and are asked for a macroscopic and microscopic interpretation.

Figure 1. Sealed tubes of phenol / water (thick tube) and nicotine / water (thin tube). The left photo shows two-component phenol / water and a single component nicotine/water at room temperature. At about 80°C the situation is reversed (right photo).



Experiment 5A (Drinking Duck): The students must explain the thermodynamics principles behind how the famous 'drinking duck' works (see Figure 2 and a short video clip at http://www.rsc.org/images/duck_tcm18-85054.avi , and Lorenz (2006) for an in-depth analysis). The duck takes a drink from the bowl, then sways like a pendulum, slowly stopping, then tips over and drinks again. We use ethanol in the bowl rather than water to speed the duck up, especially on humid Sydney summer days! This is a good test of whether the students have developed a deep understanding of enthalpy, entropy, heat, temperature, and pressure.

Figure 2. Photo of drinking duck in action.

Experiment 1B (Effect of temperature on the equilibrium between NO_2 and N_2O_4): Students are given three identical sealed tubes containing a mixture of nitrogen dioxide and dinitrogen tetroxide. They immerse one in hot water (~50°C) and another in ice water. They are told that, in gas phase, nitrogen dioxide is brown while dinitrogen tetroxide is colourless. The colour of the contents of the hot tube darkens relative to that in the room temperature tube, while the contents of the colder tube goes are observed to become paler in colour. The experiment has been recently expanded to include cooling a tube in liquid nitrogen, in which case the formation of a bright blue product is observed (see Figure 3).

Figure 3. Photo of four tubes, originally containing an equilibrium mix of nitrogen dioxide and dinitrogen tetroxide, at four different temperatures, from left to right: 50°C, 20°C, 0°C, –196°C (liquid nitrogen). The blue colour is due to solid dinitrogen trioxide.

Experiment 2B (Effect of pressure on the equilibrium between NO_2 and N_2O_4): Students prepare their own nitrogen dioxide from the reaction between nitric acid and copper turnings. They collect the gas in two 50 mL syringes. Both syringes are then capped with blocked needles. Students quickly compress the gas with one plunger and observe the colour change. The gas initially goes darker, but then lightens over a period of a few seconds, though it remains darker than the control syringe.

Experiment 3B (ΔH and the direction of spontaneity): Students place a pool of water on a block of wood in the fume cupboard. In a beaker they mix given quantities of solid ammonium nitrate and barium hydroxide octahydrate and place the beaker on the pool of water. The beaker gets so cold that it freezes the water and the beaker sticks to the wood.

Experiment 4B (Cooling produces boiling and freezing): Students are provided with a sealed glass U-tube containing a little clear liquid. The students do not know that the liquid is water and that the tube has been evacuated. They tip the water into one arm of the tube and place the other arm in liquid nitrogen. The water will boil (often a sharp eruption), then the water will freeze.

Experiment 5B (ΔS and the direction of spontaneity and a commercial heat pack): Students are provided with a 500 mL measuring cylinder containing supersaturated sodium acetate. They place a few crystals of sodium acetate on top and watch the crystals grow until the whole measuring cylinder is solid. The cylinder gets quite hot. After explaining this phenomenon, the students set off a commercial sodium acetate portable heat pack (shown in Figure 4). The commercial pack works the same way, but is initiated differently.

Figure 4. Photo of two commercial sodium acetate portable heating packs, before and after setting off the crystallisation reaction.

Educational Objectives

As described briefly in the Introduction, our description of the education objectives of this practical is structured around the ACELL Educational Template. Section 2 of the template – the educational analysis part – is shown in Table 1. This part of the template has three categories:

2.1 Theoretical and conceptual knowledge;
2.2 Scientific and practical skills; and,
2.3 Thinking skills and generic attributes.

In each category we have described several learning outcomes (What will the students learn?). The learning outcomes marked with an asterisk are considered to be the most important in the way that we run the laboratory; however, the other unmarked learning outcomes could be accentuated in other contexts. For each learning outcome, we describe the processes in the experiments that are expected to promote student learning. Finally, we describe the indicators that will allow both demonstrator and students to recognise whether the learning outcomes have been met.

Learning Outcomes		**Process**	**Indicators**
What will students learn?	**(*)**	**How will students learn it?**	**How will staff and students know that the students have achieved the learning outcomes?**

2.1 Theoretical and Conceptual Knowledge

Students will learn that chemical change can produce a change in temperature, and that, conversely, heating and cooling can induce chemical change.	*	Students will observe a number of spontaneous and non-spontaneous processes, including • evaporation of water causing the water to freeze; • crystallisation of a supersaturated CH_3COONa solution, producing heat; • heating rubber bands to make them shrink; • a solid phase reaction that produces liquid and gas, but cools the environment enough to freeze water. • heating two mixed liquids to make them mix or separate	Students write down their observations about the chemical change, including whether the system or surroundings got hotter or colder, or whether they had to heat or cool the system to produce a change. At "conference" time, the demonstrator will check their observations, and ask the students to repeat the experiment if they have missed an important aspect.
Students will learn that information regarding the release of heat, or the supply of heat, is not enough to predict the direction of spontaneous chemical change. This leads to the development of the concept of entropy. Students will develop a physical understanding, and develop appreciation of the molecular-level interpretation of entropy.	*	Students will apply the same approach to similar systems and observe the opposite results: • heating two mixed liquids can make them mix or separate; • lowering the pressure above a liquid makes it boil and freeze • heating $I_2(s)$ produces $I_2(g)$ in one sealed tube but $I_2(l)$ in another similar-looking tube. By questioning *why* they cannot predict the direction of change and, with help from demonstrators, either apply what they know about entropy, or begin to develop their own theory of entropy. (This depends on whether the students have had lectures on entropy when they do this experiment.)	As above, students write down their observations and check with the demonstrator at "conference" time, and repeat if necessary. The concept of entropy is developed in one of the early experiments, usually with a lot of help and guidance from the demonstrator. The students apply their knowledge in later experiments to explain what they observe. Successful explanation shows both students and demonstrator that the knowledge has been transferred from one chemical context to another.

Students will learn how to interpret pressure/temperature phase diagrams, including the triple point.		By observation that heating $I_2(s)$ produces $I_2(g)$ in one sealed tube but $I_2(l)$ in another similar-looking tube. They are told that one tube is under vacuum, while the other contains 1 atm of air. This leads to the development of ideas relating pressure and temperature to the phase of a compound.	Students are asked by the demonstrator to extend what they have learned about phase diagrams to explain why 'dry ice' does not have a liquid phase (at normal T/P conditions) and why ice melts under pressure (related to skating). Successful explanation of these phenomena indicates to both demonstrator and students that they have developed a deep understanding of phase diagrams.

2.2 Scientific and Practical Skills

Practical: Safe handling of unfamiliar materials and equipment.		In their experiments, student use gas syringes, liquid nitrogen, Bunsen burners and heat guns. Demonstrators provide guidance and demonstrate techniques as needed.	Students and demonstrators will know that the students have satisfactorily achieved these skills by safe and successful completion of the experiment.
Scientific: Students practice making connections between macroscopic observations and microscopic interpretations.	*	Students are required to switch between macroscopic concepts of thermodynamics (ΔH, ΔS, etc) and the microscopic interpretation of these concepts (bond breaking, molecular structure, etc)	If the students' explanation is purely macroscopic, then the demonstrator will query the students on microscopic concepts, and vice versa. Students and demonstrator will know that they can switch between the two concepts if this facility improves as the experiments progress.

2.3 Thinking Skill and Generic Attributes

The ability to carefully *observe*, to summarise the observations, and explain complex ideas to a third party in a coherent and scientifically appropriate way.	*	In these experiments, students set up and watch various chemical processes and observe many, sometimes subtle and / or counter-intuitive, changes. Students must summarise what they saw and explain the thermodynamic principles behind their observation to a demonstrator.	By noting down all observations, agreeing with their partner on the observations and their explanations for those observations, and showing them to a demonstrator. Many experiments can be run over and over again so students can hone their skills. The demonstrator will question and probe the depth of understanding of the concepts and sometimes provide hints on how to refine the observations and / or theory.
One-on-one communication, explanation and negotiation skills with a peer.	*	Students must develop an explanation of each experiment jointly. Both must agree on the explanation, and both must be able to defend the explanation before summoning a demonstrator.	The provision of an agreed explanation shows to both students and demonstrator that this skill has been developed. (Demonstrators ask questions of both students and monitor to ensure that one student does not dominate the discussion.)
Students learn to think about the scientific principles that underpin some commercial products.		Students are provided with two commercial products and asked to explain how they work using the thermodynamics principles they have been discovering.	Explanation of the thermodynamic principles to the demonstrator's satisfaction. (Other groups' students often ask difficult questions during these sessions.)

Theoretical and Conceptual Knowledge: The most important concepts that the students will learn in this practical relate to the thermodynamic properties that allow us to predict the direction of spontaneous chemical change. These concepts range from simple Le Chatelier's Principle, to more challenging concepts of chemical entropy. Students will learn, by experiment and experience, that temperature changes are often associated with chemical change, but that spontaneous changes can be accompanied by either an increase or decrease in temperature (exothermic or endothermic processes). This leads to the introduction, or reinforcement of chemical entropy (depending on whether the students have had the lectures on entropy at this stage of the semester). The concept of entropy is developed in one of the early experiments, usually with a lot of help and guidance from the demonstrator. The students apply their knowledge in later experiments to explain what they observe, and thus need to transfer their understanding into new contexts (Salomon and Perkins, 1989; Price and Driscoll, 1997; Nokes and Ohlsson, 2005). Successful explanation shows both students and demonstrator that the knowledge has been transferred from one chemical context to another. Students also learn about phase diagrams, the thermodynamics of phase changes and the effects of pressure and temperature on equilibrium.

Scientific and Practical Skills: The development of practical skills is not a particular focus of this suite of experiments, although the students do encounter, often for the first time, liquid nitrogen and gas syringes, and get to practice their skills with Bunsen burners, glassware, and handling of acids.

As has been noted elsewhere in the literature (Russell et al., 1997; Kozma, 2003; Treagust et al., 2003; Wu, 2003; Han and Roth, 2006), an important scientific skill in chemistry is the ability to switch between a macroscopic (observational) picture of a chemical process and an appropriate molecular interpretation of the process. This practical is very strong in the development of this skill. Thermodynamic quantities and properties are often expressed in macroscopic terms as ΔH, ΔS, ΔG, etc. These are crucial properties for the prediction of chemical reactions; in the present context on the direction of chemical change. However, a deeper understanding of these principles is attained from a microscopic, molecular interpretation. Students are quizzed about their explanations at both levels.

Thinking skills and generic attributes: This practical is built around the students' ability to *observe and explain*. They make no measurements, no calculations, and are not required to prepare any chemical quantity with any accuracy. Instead, they need to work out a scientifically rational explanation for their observations through a process of cooperative learning (Cohen, 1994; Gilies, 2006). The benefits of cooperative learning have been described elsewhere (Springer et al., 1999; Bowen, 2000; Barbosa et al., 2004), as have applications in general (Kogut, 1997), organic (Carpenter and McMillan, 2003), and physical chemistry (Towns and Grant, 1997). In order to promote peer-interactions, and to take advantage of the known qualitative superiority of collective over individual reasoning (Moshman and Geil, 1998; Moshman, 2004), consensus between students is an integral part of this practical. The observed phenomenon is first discussed between the pair of students to obtain agreement about the observations themselves. Mostly, the experiments can be repeated over and over to allow multiple chances to observe the effect and to obtain agreement. Following this, the pair must devise a chemically relevant explanation that they can agree on, and that both understand. This explanation needs to be written down in clear scientific language. After this has been completed the students may summon the demonstrator to a 'conference'. The students must describe their observations and then explain to the demonstrator the basis of their theory in a coherent and scientifically appropriate fashion. The demonstrator will generally challenge their theory or observations by pointing out aspects that are not consistent, or extend their understanding by introducing new data. Questions will also be asked of each student, ensuring that both students can rationalise their observations, and ensuring that students are interacting in a truly collaborative way. Students may not progress to the next experiment before testing their theory at the demonstrator conference. Some of the experiments also have different levels of detail (and subsequent tests) to keep the most enlightened students engaged and appropriately challenged.

The whole process of this laboratory session is rich in the development of thinking skills and other generic attributes. No student, in 12 years of running this practical, has been able to explain all of the observations first time around. The thinking process is supplemented by verbal and written communication skills by the requirement that both students must agree on the explanation, and that their explanation must be written and explained to the demonstrator in clear scientific language. Sometimes this process also involves negotiation skills (!) and very often develops teaching skills in the situation where one student has grasped a concept before the other. Learners at similar cognitive levels have the opportunity to effectively co-construct an understanding of new material (Palincsar, 1998), and can also help to provide a 'scaffold' assisting each to reach a higher level of cognitive functioning (John-Steiner and Mahn, 1994; Clarkson and Brook, 2004).

In the final experiment of each set of five, the student pair is asked to explain the chemical thermodynamic basis behind what seems initially to be not a particularly chemical system. This develops the ability to apply fundamental knowledge into a general situation whilst simultaneously providing concrete examples of the 'real world' relevance of chemistry.

In this practical, students are assessed subjectively by the demonstrator based on their clarity of thought, their ability to explain their hypothesis logically to both their peer and demonstrator, and their ability to take what they have learned from one experiment to the next. There is no pre-work nor post-work associated with the experiment, aside from reading the notes beforehand.

Student learning experience

As with any experiment submitted to ACELL for evaluation, this experiment has passed through the standard testing procedures described in the ACELL Guidelines and Procedures document (ACELL, 2007), designed to demonstrate the transferability of the experiment and to evaluate it from both chemical and educational perspectives. Laboratory testing was carried out at the University of Tasmania as part of the workshop run at the 2004 Royal Australian Chemical Institute Chemical Education Division National Conference. This paper reports the educational analysis of the experiment, including discussing the students' perspective. As usual, the experiment documentation is available on the ACELL website.

Method

Data were collected using the ACELL Student Learning Experience (ASLE) survey, which was distributed to all forty students who had undertaken the experiment at the University of Sydney in semester 1, 2006; the processes described in the ethics application were followed and thus completion of the survey was voluntary, and all responses were anonymous. Responses were received from twenty-nine students, a response rate of 73%. Although the anonymity of the survey prevents any formal statistical testing to examine whether the respondents are a representative sample of the entire cohort, the fact that responses were received from a substantial majority of students allows the drawing of conclusions about the entire cohort with confidence.

The ASLE instrument includes 14 Likert scale items; a summary of the statements is included in Table 2, along with the scoring used for item. Twelve of the statements probe students' perceptions of aspects of the experiment (such as interest, skill development, guidance from notes and demonstrators, and improved understanding of chemistry); the remaining two items concern the time available for the experiment, and ask for an overall rating of the experiment as a learning experience. In addition, the instrument includes five open-response items, which are:

- Did you enjoy doing the experiment? Why or why not?
- What did you think was the main lesson to be learnt from the experiment?
- What aspects of the experiment did you find the most enjoyable and interesting?
- What aspects of the experiment need improvement and what changes would you suggest?
- Please provide any additional comments on this experiment here.

Table 2: Summary of student feedback responses to the ASLE Likert scale items.

Number	Item	Mean*	Standard Deviation	% Agree or Strongly Agree
1	This experiment has helped me to develop my data interpretation skills	+1.18	0.72	89.3%
2	This experiment has helped me to develop my laboratory skills	+1.00	0.90	75.0%
3	I found this to be an interesting experiment	+1.43	0.88	82.1%
4	It was clear to me how this laboratory exercise would be assessed	+0.64	1.03	53.6%
5	It was clear to me what I was expected to learn from completing this experiment	+1.25	0.89	85.7%
6	Completing this experiment has increased my understanding of chemistry	+1.29	0.90	89.3%
7	Sufficient background information, of an appropriate standard, is provided in the introduction	+0.79	0.88	64.3%
8	The demonstrators offered effective support and guidance	+1.54	0.69	96.4%
9	The experimental procedure was clearly explained in the lab manual or notes	+1.36	0.78	89.3%
10	I can see the relevance of this experiment to my chemistry studies	+1.39	0.79	89.3%
11	Working in a team to complete this experiment was beneficial	+1.61	0.69	96.4%
12	The experiment provided me with the opportunity to take responsibility for my own learning	+1.29	0.90	85.7%
13	I found that the time available to complete this experiment was	+0.21	0.69	
14	Overall, as a learning experience, I would rate this experiment as	+3.14	0.89	

* For items 1 to 12, a +2 (strongly agree) to -2 (strongly disagree) scale has been used, with a 0 (neutral) midpoint – for these items, the ideal response is +2. For item 13, a +2 (way too much time) to -2 (nowhere near enough time) scale has been used, with a 0 (about right) midpoint – for this item, the ideal response is 0. For item 14, a +4 (outstanding) to 0 (worthless) scale has been used, with a 2 (worthwhile) midpoint – for this item, the ideal response is +4.

Data from the Likert items were examined looking at the histograms (for distribution) and numerically by calculating the mean and standard deviation of the responses, as well as the percentage of respondents in broad agreement (agree or strongly agree), in line with standard ACELL analysis practice (ACELL, 2007). Data from the open-response items were separated into thematically distinct comments, and then coded into categories as part of a content analysis, following the procedure outlined by Buntine and Read (2007), which is broadly based on the approach of Miles and Huberman (1994). Thematic separation of comments was done with the aim of minimising the number of comments that need to be coded as relating to more than one category.

Student feedback results and discussion

A summary of the results from the Likert items is also provided in Table 2, whilst the categories used in the content analysis of the open-response items are shown in Table 3. The categories used in the content analysis are broad and distinct, and they were chosen after repeated reading of the feedback; they represent the general themes which emerge from the data, and the only real overlap between categories occurs with the miscellaneous category, which was used to code the small number of comments which did not fit within the five identified themes. Within each category, sub-categories have been used to group similar responses, and these sub-categories are also shown in Table 3.

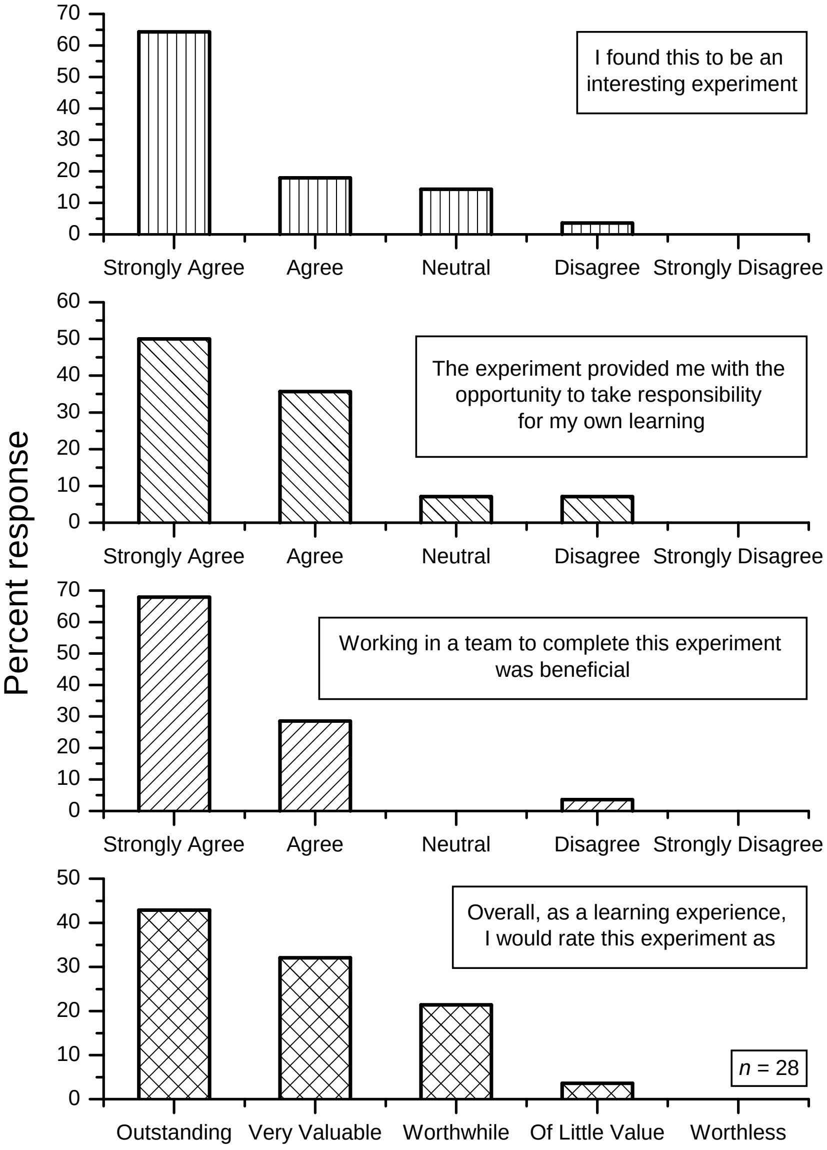
Table 3: Summary of categories used in content analysis of the ASLE open-response items.

Category / Theme	Abbreviation	Total Comments	Sub-Categories
Understanding of Chemistry	UC	31	Thermodynamic Principles (17) Thinking Skills (11) Other Areas of Chemistry (3)
Experience of Experiment	EE	39	Positive Comments (35) Negative Comments (4)
Interesting Aspects of Experiment	IAE	40	Use of Liquid Nitrogen (15) Drinking Duck Experiment (9) Heat pack Experiment (7) Other Experiments (9)
Potential Improvements	PI	12	Number of Experiments (7) Student Notes (5)
Group Interactions	GI	6	
Miscellaneous Comments	MC	5	

An examination of the Likert scale data shows that students' experiences of this experiment were extremely positive, with the majority of students agreeing or strongly agreeing with all twelve items. In fact, a positive response was provided by at least 75% of students for ten of these items, all of which also received mean ratings of +1 or higher. The other two items (dealing with assessment and background information) would be expected to receive a less positive evaluation. As mentioned above, assessment in this experiment is based on demonstrators' evaluations of student's effort and is unrelated to experimental results obtained, and thus students might be expected to be less clear about how such an evaluation is made.

Regarding the guidance provided by the background information, the experiment is intended to challenge students to provide their own qualitative explanations for the phenomena observed – and, in effect, to take responsibility for their own learning. As a consequence, the experiment is deliberately designed with the provision of comparatively little background information, with the intention that demonstrators will provide what guidance is needed in interpreting results. The strong positive responses to the related items (8 and 12 – see also Figure 5) suggest that this strategy is effective, a perception reinforced by the students' response to the items related to increased understanding of chemistry (item 6) and the overall learning experience (item 14). In addition, the strong response to item 9, dealing with the procedural aspects of the notes, indicates that students were not concerned about the general quality of the notes. Of the five comments related to the notes in the PI category, three suggested improvements to the description of the rubber band experiment, and changes to this section of the notes have been implemented.

Figure 5 Student responses to four of the ASLE Likert scale items.



The qualitative data also provides evidence that development of knowledge and thinking skills followed from the approach taken: within the UC category, 17 comments were made which identified an improved understanding of thermodynamic principles as a key lesson of the experiment – this is to be expected, as the qualitative application of these principles to explain observations is required repeatedly throughout the experiment. However, as the comments below show, different students developed appreciation for these principles at different levels of sophistication:

> "*Thermodynamic principles can be applied to qualitatively explain various chemical and physical phenomena*"
> "*Chemistry is often a power play involving entropy and enthalpy*"

> "*That reactions proceed (or don't proceed) due to a range of factors (pressure / volume, enthalpy of products / reactants, state of products / reactants) and that, overall, these processes can be explained by considering enthalpy, entropy, and the macroscopic properties of reactants and products*"

One of the goals of the experiment was the development of thinking skills, as shown in the outcomes described in Table 1. It is both gratifying and a little surprising that this aspect came through so strongly from the students' perspective, with 11 comments in the UC category on this topic. Typical comments in this area in response to the 'main lesson' item included:

> *"Think about the problem as you are attempting to solve in a variety of different ways"*
> *"How to think about certain phenomena critically without knowing all the relevant theory"*
> *"Applying our knowledge to things we observe but don't yet understand"*

These comments indicate a focus on higher-order cognitive skills – skills which are often not developed by laboratory work, according to the Domin (1999) review – and also on important metacognitive skills such as evaluation and reflection (Ertmer and Newby, 1996; Schraw et al., 2006). If the background information provided with the experiment were substantially increased, there is a significant risk that this fostering of thinking skills would be reduced. Such a change also risks having other adverse consequences for the learning experience by undermining aspects of the experiment which increase motivation and engagement. Paris and Turner (1994) discussed aspects of motivation situated within a learning environment, and concluded that the inclusion of appropriate challenge and meaningful student control increases motivation, and students' comments on reasons for enjoying this experiment picked up on these aspects:

> *"Yes – allowed me to think about the experiments and interpret the results. The results were unexpected to first years, so understanding them was fun and enjoyable"*
> *"Yes, it was challenging trying to explain why things happened rather than just following instructions"*
> *"Yes, very much. It's very different to the other experiments we had to do. It's very enjoyable to be able to work things out for yourself."*
> *"The idea of having to think about things other than just measure them."*

Analysis of the EE categories shows that the comments were significantly more positive (90%) than negative (10%); even some of the negative comments recognised the value of the experiment. One student's responses to the 'enjoy the experiment' and 'improvement' open-response items, respectively, were:

> *"The experiment was mildly enjoyable – thermodynamics really isn't my bag. However, I did find it quite entertaining insofar as I was playing with rubber bands and liquid nitrogen."*
> *"I don't think the experiment should be changed drastically at all. It achieved its objective and I learned how to apply thermodynamic principles to observable stuff, so it was a success."*

When even the critics of an experiment believe they have learned from the experiment, the argument to avoid making changes for fear of undermining its success becomes quite compelling.

Figure 5 shows the students' responses to the overall learning experience item, which shows that 96.4% of respondents rated the experiment as being at least worthwhile, with 42.9% of students rating it outstanding. This is an incredibly strong response, particularly in light of the topic area. Experiments in physical chemistry are often unpopular with students (Sozbilir, 2004), which was part of the motivation for establishing the physical chemistry predecessor to the ACELL project (Barrie et al., 2001a, 2001b, 2001c). The fact that a thermodynamics experiment, at first year level, can be evaluated so positively provides evidence for the belief that engaging experiments can be developed for any area of chemistry.

The popularity of this experiment was even supported by the data relating to experiment timing: Whilst 71.4% of students described the time available as 'about right', 25% indicated that too much time was available. It might be expected that students would be pleased to finish early, in that it provides the opportunity for an early mark. However, the open-ended responses in the PI category suggest otherwise, as seven of the twelve comments in this area suggested the desirability of being able to do more of the experiments:

> *"All experiments worked very well. It was disappointing we didn't get to do them ALL."* (emphasis in original)
>
> *"Improvement? No, but perhaps tell early finishers to try all the other ones … which they seem to do anyway."*

Another important theme that emerged from the content analysis was the importance of interest, a fact also reflected in Figure 5, which shows that over 60% of students strongly agreed that this experiment was interesting. Interest is a motivational construct that has been receiving considerable attention recently (Schiefele and Krapp, 1996; Ainley et al., 2002; Hidi et al., 2004; Hidi and Renninger, 2006). It is usually divided between individual interest, which reflects a fairly stable and enduring characteristic of an individual, and situational interest, which arises spontaneously due to characteristics of individual learning activities. Situational interest can be sub-divided into triggered and maintained situational interest, with this sub-division effectively reflecting the difference between 'caught' and 'held' attention. Tasks that are involving and meaningful (and preferably related to students' goals) having been shown to maintain a situational interest once triggered (Mitchell, 1993), with maintained situational interest having been shown to be associated with a higher level of cognitive engagement than triggered situational interest. In practical terms, this means that it is desirable for an experiment (or sequence of experiments) to include a mix of activities to both trigger situational interest and to maintain it once triggered.

An examination of the comments in the IAE category shows that three of the exercises were particularly interesting for students. Considering the triggers of situational interest that have been described by Bergin (1999), it could be predicted that colour changes, bangs and flashes, and novel situations (such as being able to use liquid nitrogen) would foster interest, and the feedback received bears this out. Encouragingly, some of these comments did indicate engagement beyond the level that might be expected if triggered situational interest were not maintained. For example, a student commenting on the interesting aspects of the experiment responded:

> *"The liquid nitrogen tests (both enjoyable and interesting), because they demonstrated an odd phenomenon and required careful thought to work out what was happening."*

This comment indicates not only cognitive engagement indicative of knowledge development, but also focuses on unexpected (discrepant) events, which are often useful in fostering an individual interest (Bergin, 1999). This focus on understanding and knowledge development, often connected to so-called 'real world' phenomena was seen in other comments in this category as well:

> *"The actual implementation of chemical theory, ie. the sodium acetate was used as a heating patch. It was enjoyable to understand how something works."*
>
> *"Wrestling with difficult concepts, elaborately demonstrated in simple experiments."*
>
> *"Applying Uni chemistry to everyday situations."*

Finally in this area, the descriptions offered of the drinking duck experiment often indicated a desire on the part of the students to understand the observations that they had made. For example, when describing this exercise as the most enjoyable part of the experiment, it was described as:

"The water-bird of confusion!"
"The drinking bird – understanding the phenomenon"
"The drinking duck, interpreting how it functioned"

It seems clear that the suite of experiments included in *Thermodynamics Think-In* does successfully trigger situational interest and maintain it once triggered, and that cognitive engagement with the activities was high. There are even indications that activities may be promoting the emergence of individual interest, although this seems likely to occur for only a fraction of students within any cohort.

The responses of students to experiments 1B and 2B reflects the extent of cognitive engagement. The colour changes observed when a nitrogen dioxide / dinitrogen tetroxide mixture is heated and cooled would be expected to be effective situational interest triggers, and yet these experiments were not particularly popular. Feedback indicates that this was because the students had seen the system before, either as a lecture demonstration or at school, and this exercise was also criticised as insufficiently challenging. However, engagement increased when one of the students tried cooling the mixture with liquid nitrogen rather than ice, and found that a blue liquid is produced (see Figure 3). This blue liquid is dinitrogen trioxide, and students were challenged by trying to explain how this came to be formed; the need to provide a reasonable explanation should prompt students to re-examine some of the nitrogen chemistry that they cover in lectures. As a consequence, in order to introduce additional novelty and challenge into this exercise, cooling with liquid nitrogen has been incorporated as one of the parts of this exercise.

One final aspect of the exercise that warrants comment is the importance of collaboration, cooperation, and teamwork, several comments about which are quoted below:

"Bonding with a team member"
"The tutor's explanations about each experiment" (in relation to most enjoyable aspects of the experiment)
"A more in-depth discussion of the explanations behind the experiments" (in relation to suggested improvements)

Although the teamwork aspect of the experiments did not feature prominently in the qualitative feedback (there were only six comments in the GI category), the students' responses to the related Likert item (item 11 – see Table 2 and Figure 5) were the most positive of any item. It is likely that the collective reasoning resulting from the cooperative learning design elements included in the practical is part of the reason that students agreed so strongly that their understanding of chemistry had increased (item 6).

Summary and conclusions

In summary, the purpose of this experiment was to create an interesting and engaging environment to promote student learning about a subject that is commonly perceived as dry, quantitative, and boring – and to do so by challenging them to apply their understanding to novel situations in order to provide satisfactory microscopic-level explanations for their observations. Each of the experiment sequences within the practical is intended to lead students on an increasingly challenging journey, qualitatively exploring different applications of thermodynamic principles. The sequences involve no quantification, but rather seek to promote scientific and critical thinking about their observations, and to model scientific communication through 'conferences' with their demonstrator. The feedback data from the students shows that this experiment is extremely successful in achieving its objectives. The summary Likert item (Q14) showed that more than 75% of the students considered this exercise to be 'very valuable' or better and 96% 'worthwhile or better'. Indeed, the score in all Likert items indicates very positive perceptions of their experiences amongst the students;

qualitative data not only supports this observation, but also provides insights into the most valuable aspects of the learning environment.

Clear evidence has been presented that this experiment fosters cooperative learning and teamwork, triggers and maintains student engagement and interest, and is perceived to be highly relevant. In addition, students recognise and value the opportunity to develop problem solving and thinking skills provided by the exercises – they find them challenging but not daunting, and are keen to undertake additional experiments from the suite included in *Thermodynamics Think-In.* Skill development in these areas is particularly important for the development of generic graduate attributes, which is a key goal of any tertiary education program. In parallel with the development of attributes necessary for life-long learning, students undertaking this exercise perceive that their participation has led them to an improved understanding of thermodynamic principles and their applications. This simultaneous (if incremental) development of attributes necessary for a scientific career, along with appreciation for and understanding of important scientific principles, is a particular strength of this exercise, especially given the stage at which it is undertaken.

The weakest scoring items in the student feedback data relate to background information and clear assessment. The relative weakness in clear assessment is likely more indicative of a mismatch between assessment goals and student expectations than of a weakness in the procedures themselves. The assessment is aimed at fostering a mastery orientation focussed on promoting understanding, rather than a performance orientation focussed on accuracy of results and grades (Ames, 1992; Wolters, 2004). This is not an approach with which students are typically accustomed. Thus, it seems likely that any changes to assessment strategies should focus on making the expectations of demonstrators clearer to the students. With respect to the background information, the exercise is intentionally designed with minimal theory provided, as this contributes to its strengths in the areas of critical thinking and problem solving skill development. Again, there appears to be a mismatch between the expectations of the students and the goals of the exercise in fostering the ability to learn independently and to judge for themselves what is relevant.

Given that the cohort that undertake this experiment are academic high achievers with demonstrated performance in chemistry, the question of how well this experiment would work with a broader first year cohort remains open (it may be more appropriate for early second year in some instances). Nevertheless, it has demonstrated potential for *engaging* students in thinking about thermodynamic *principles*.

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Themed Issue on *Research and Practice in Chemical Education in Advanced Courses*

Scheduled for publication in April 2008

Guest Editors: George M. Bodner and Gabriela C. Weaver, Purdue University, Department of Chemistry, West Lafayette, IN 47907

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Contributions are invited for a themed, peer-reviewed issue of CERP on

Research and Practice in Chemical Education in Advanced Courses

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- Students' attitudes toward and interest in advanced-level chemistry courses.
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- Assessing students' performance, progress and achievement using non-traditional modes of assessment in advanced-level courses.
- Incorporating non-traditional modes of instruction and inquiry-based instruction in upper-level chemistry courses.
- Incorporating molecular visualization and/or simulations into upper-level chemistry courses for undergraduates or graduate students.
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Papers can refer to one or more of the advanced or upper-level courses taught at the college or university level to undergraduates or graduate students. The list is intended to suggest the scope of possible contributions, but it is not exclusive.

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