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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

Chemistry Education Research and Practice

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.

Educational research

The modelling ability of non-major chemistry students and their understanding of the sub-microscopic level

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Abstract: This case study examined the ability of three first year non-major chemistry students to understand chemical concepts according to Johnstone's three levels of chemical representations of matter. Students' background knowledge in chemistry proved to be a powerful factor in their understanding of the submicroscopic level. The results show that modelling ability is not necessarily innate, but it is a skill to be learnt. Each of the students' modelling abilities with chemical representations improved with instruction and practice. Generally, as modelling skills improved so did students' understanding of the relevant chemical concept. Modelling ability is described according to Grosslight et al.'s three–tiered level and the ability to traverse the three levels of chemical representation of matter. [*Chem. Educ. Res. Pract.*, 2007, **8** (3), 274-292.]

Keywords: Modelling ability, macroscopic, sub-microscopic and symbolic levels, chemistry non-majors

Introduction and theoretical underpinnings

Explanations of chemical phenomena rely on understanding the behaviour of sub-microscopic particles and because this level is 'invisible' it is described using symbols such as models, diagrams and equations. A minimum level of modelling ability or representational competence (Kozma and Russell, 1997) is required to use these symbols to learn and understand chemistry. Data concerning the modelling ability of a three first year undergraduate chemistry students is presented to address the research question: "How does students' modelling ability affect their use of models and their ability to understand chemical concepts?"

Research about the different levels of representation of matter, chemical models and modelling and students' modelling ability provide the theoretical framework within which this study was conducted.

Three levels of chemical representation

Johnstone (1982) distinguished three levels of chemical representation of matter. The macroscopic level is real, comprising tangible and visible chemicals, which may or may not be part of students' everyday experiences. The sub-microscopic level is also real and comprises the particulate level, which can be used to describe the movement of electrons, molecules, particles or atoms. The symbolic level comprises a large variety of pictorial representations, algebraic and computational forms of the submicroscopic representation. Chemistry is based on the theory of the particulate nature of matter – the sub-microscopic level of matter – but we 'see' the macroscopic and use models to represent the sub-microscopic levels. Harrison and Treagust (2002) point out that for many Grade 8 students, and even for some Grade 8–10 science teachers, their understanding of the particulate nature of matter, i.e. the sub-microscopic level, is poor. Research shows that many secondary school and college students, and even some teachers, have difficulty transferring from one level of representation to another (Gabel, 1998).

Chemical models and modelling

Chemical models and diagrams provide visual prompts of the sub-microscopic level. An explanatory tool such as a diagram or an image can provide the learner with a way of visualizing the concept and hence developing a mental model for the concept (Gabel, 1998). The value of a diagram in making the link with an abstract concept depends on it being consistent with the learners' needs and being pitched at the learners' level of understanding (Giordan, 1991).

Modelling has been described as making the connection between the target and the analogue (Duit et al., 2001). With general models there can be a number of analogues (i.e. a number of models) but they link to only one real target. When considering chemical models, links are formed between an analogue and the target where the analogue is a symbolic representation (of which there may be many different types) which links with two real targets – the sub-microscopic level (target 1) and the macroscopic level (target 2). So in terms of Johnstone's three levels, the symbolic representations are analogues of the macro and sub-microscopic levels, which are the targets. This duality required of models of chemical phenomena is a significant difference from general models. Teachers or textbooks do not always highlight this difference, and it is often assumed that students are able to relate a symbolic representation to both the macroscopic and sub-microscopic realities simultaneously.

The use of models and modelling in chemistry teaching is a common practice that engages students to develop their own mental models of chemical compounds. However, despite this common use of models, studies have shown that students misunderstand the reasons for using models and modelling. Many secondary students view models only as copies of the scientific phenomena (Grosslight et al., 1991) and their understanding of the role of models frequently is seen as being simplistic (Treagust et al., 2003). Even university students have limited experience with models, and only a small percentage of these students have an abstract understanding of model use in chemistry (Ingham and Gilbert, 1991). In a cross-age study, Coll and Treagust (2001) describe similar outcomes when undergraduate and postgraduate students tended to use simple teaching models learned in high school to explain chemical bonding. Because no single model provides the total evidence for the structure and function of a molecule, each student's understanding is reliant on realising the limitations and strengths of each teaching model (Hardwicke, 1995). Teachers' level of understanding of models also has been described as limited because they have a simplified understanding of models and modelling in science (Justi and Gilbert, 2002b; Justi and Van Driel, 2005). Nevertheless, modelling is a common, intrinsic behavior used in everyday life and also in the chemistry classroom.

The use of concrete models, pictorial representations, animations and simulations have been shown to be beneficial to students' understanding of chemical concepts (Tasker and Dalton, 2006). However, the extensive and accepted process of using models has made the model appear as 'fact' to many teachers and students (Boo, 1998). Frequently, students do not differentiate between models and they do not regard models differently from the observed characteristic that the model is trying to explain. For example, teachers do not emphasize the representational nature when referring to CH_4 saying that it *is* methane, whereas the phrase 'CH_4 *represents* the composition of a methane molecule' would be more accurate. This lack of emphasis reinforces the dilemma of some students viewing models only as copies of the scientific phenomena. While it is assumed that students understand the representational nature and the analogical relations within the chemical language (Duit and Glynn, 1996), the strengths and limitations of each model need to be discussed so that students can assess its accuracy and merit (Hardwicke, 1995a, 1995b). Mathewson (2005) discusses the need for "*explicit and active involvement of processes and interactions within the constituents of the modeled system*" p. 537.

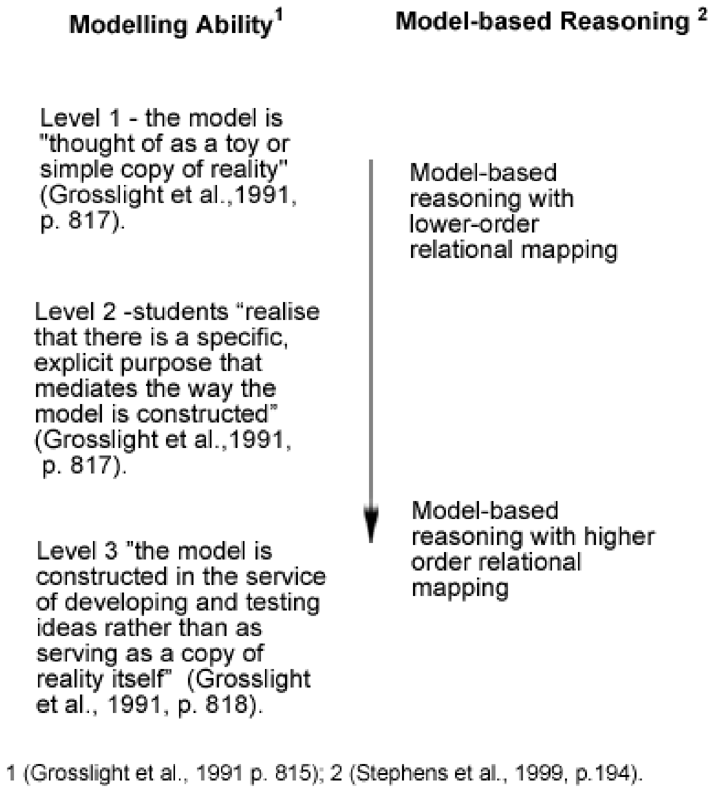
In comparing the perceptions of experts and novices on a variety of chemical representations, Kozma and Russell (1997) concluded that novices used only one form of representation and could rarely transform to other forms, whereas the experts transformed easily. Novices relied on the surface features, for example lines, numbers and colour, to classify the representations, whereas experts used an underlying and meaningful basis for their categorization. The study highlighted the need for representational competence including an understanding of the features, merits and differences of each form and showed the significance of computer animations in linking the various representations.

Modelling ability

It is necessary to define the dimension of *modelling ability* in order to address the research question. Models and modelling are explanatory tools for the learner that requires the user to relate the target to the analogue. Raghavan and Glaser (1995), working with sixth grade students, reported an improvement in the development of students' model-based reasoning skills in predicting, testing and evaluating ideas as a result of specific model-based instruction. Justi and Gilbert (2002a) identified modelling as one of the main processes in the development of scientific knowledge and as such it has the potential to drive changes in the approaches to learning. Grosslight et al. (1991) developed a scale to describe students' modelling ability consisting of three levels: at Level 1, models are considered to be "*copies of actual objects or actions*" (p. 817); at Level 2, there is a realization "*that there is a specific, explicit purpose that mediates the way the model is constructed*" (p. 817); and at Level 3, "*the model is constructed in the service of developing and testing ideas rather than as serving as a copy of reality itself*" (p. 818). In their study, Grosslight et al. (1991) based their classification on six dimensions: the role of ideas, the use of symbols, the role of the modeller, communication, testing and multiplicity. These authors found that 23% of the 11th grade students were pure Level 1, 36% were mixed 1–2 Level and 36% were pure Level 2 and no students were classified as Level 3 modellers.

Modelling ability is closely aligned to model-based reasoning as described by Stephens et al. (1999) who investigated the factors affecting electrical resistance in which the model of electron drift was used. Students used the model to explain their experimental results, engaging in model-based reasoning. The types of reasoning used by students to explain their observations were classified as: phenomenon-based, relation-based, model-based reasoning with lower-order relational mapping and model-based reasoning with higher-order relational mapping. The lower order and higher-order relational mapping is consistent with Grosslight et al.'s (1991) Level 1 and Level 2 of modelling ability. The defining of levels of modelling skill provides a scale for comparison and a useful descriptive reference (Figure 1).

Figure 1. Comparison of two schemes for modelling skills.



Modelling Ability[1]

Level 1 - the model is "thought of as a toy or simple copy of reality" (Grosslight et al.,1991, p. 817).

Level 2 -students "realise that there is a specific, explicit purpose that mediates the way the model is constructed" (Grosslight et al.,1991, p. 817).

Level 3 "the model is constructed in the service of developing and testing ideas rather than as serving as a copy of reality itself" (Grosslight et al., 1991, p. 818).

Model-based Reasoning [2]

Model-based reasoning with lower-order relational mapping

Model-based reasoning with higher order relational mapping

1 (Grosslight et al., 1991 p. 815); 2 (Stephens et al., 1999, p.194).

Harrison and Treagust (2001) consider modelling ability, conceptual status and intellectual ability to be closely related recommending that "*model-based instruction should be sensitive to the intellectual ability and needs of the students*" (p. 51). Since chemical concepts can be considered as a subset of scientific concepts, the research into models and modelling for scientific concepts can be applied to chemical concepts. In summary, the literature informs us that modelling ability is related to:

- Intellectual ability and the conceptual status of the model;
- Thinking and reasoning levels;
- Use of models for testing, predicting and evaluating ideas;
- The number and types of model or representation that can be used meaningfully;
- Ability to transfer from one model or representation to another;
- Ability to identify the representational nature – target/analogue, the mode of representation, accuracy and permanency of the model;
- Ability to identify two targets for chemical representations- the macroscopic and the sub-microscopic levels of representation of matter;
- Recognition of the limitations of each representations/model; and
- Recognition of the role and purpose of various representations/models.

These characteristics are encompassed in the definition provided by Grosslight et al. (1991), and help to highlight the significant modelling skill needed in learning chemistry.

Research question

Data concerning the modelling ability of three students who were representative of a group comprising 160 first year undergraduate chemistry students is presented to address the research question "How does students' modelling ability affect their use of models and their ability to understand chemical concepts?"

Methodology

This research comprised a series of case studies conducted with students undertaking degree courses in Environmental Biology and Health Sciences. The students were required to pass the first year chemistry unit for which there is no pre-requisite.

Sample

Of the 160 students (35% males and 65% females) enrolled in the introductory first-year university chemistry course, nineteen students volunteered to be interviewed and three of these are discussed in this paper (see Table 1). All students were required to complete pre-reading prior to participating in weekly 3-hourly laboratory sessions and write up and submit laboratory reports each week.

Table 1. Descriptive data for three case study students.

Pseudonym	Age	Experience in chemistry
Narelle	26-28 years	No experience or only Junior high school science
Alistair	18-19 years	Senior High School chemistry
Leanne	18-19 years	No experience or only Junior high school science

Data sources and analyses

The initial questionnaire gathered information about students' understanding of models, using the instruments: *Students' Understanding of Models in Science* (SUMS) (Treagust et al., 2002), and *Views of Models and Modelling in Science (*VOMMS) (Treagust, et al., 2004; Chittleborough et al., 2005)**.** Volunteer students completed four worksheets designed to investigate students' understanding of particular concepts such as solutions and ions, moles, chemical symbols and equilibrium. The primary qualitative data used were the interviews conducted at the beginning of semester 1 and at the beginning of semester 2. Three focus cards were used in the first interviews to investigate students understanding of chemical representations (see Appendix). In addition, there are the first author's observations as a participant researcher, and the reflective journal of her experiences throughout the study, and the students' laboratory reports. The data sources were processed, transcribed, collated and coded as needed. The student volunteers were identified with a single identification number that was used in both the quantitative and qualitative data. Pseudonyms have been used in this report.

Results

Since modelling is an individual characteristic, it is necessary to look at individual students, using them as case studies indicative of the larger population (Cohen et al., 2000). In responding to the research question, various available data sources are drawn upon to provide evidence to determine the modelling abilities of three students who are referred to as Narelle, Alistair and Leanne. In a previous paper (Chittleborough et al., 2005), we discussed the profiles about each of the volunteer students' (n=19) modelling abilities and their understanding of chemical concepts using the six dimensions of the role of ideas, the use of symbols, the role of the modeller, communication, testing and multiplicity, which were assessed based on observations of each students' work in the laboratory, responses on their written laboratory reports, the worksheets and interviews. In this paper, the three students were selected because they have different backgrounds and provide different perspectives about their modelling abilities and their understanding of the sub-microscopic level of representation.

Whilst student volunteers with stronger chemistry backgrounds began with a higher modelling ability because of their chemical experience and foundation knowledge, the inexperienced students rapidly improved their modelling abilities. For example, Alistair had a strong chemistry background and was already working at Level 2 in the initial interviews, and maintained that level by the end of the semester, whereas Narelle, who was a mature aged student with no chemical history, was a very poor modeller in the first interview, but improved to a Level 2-3 modeller by the end of the semester. Leanne had been in the non-chemistry group in junior high school (Year10) and had developed a negative attitude towards the subject. Initially she had no understanding of chemical models, but demonstrated skills of a Level 2 modeller by the end of the year.

Narelle – a level 2/3 modeller with initially no chemical knowledge

Narelle was a mature age student beginning university with no previous chemical knowledge, and was enthusiastic and keen to learn. Her responses to the initial interview provided evidence that she had never even considered the sub-microscopic level of matter, and that the concept of a representation was foreign to her. When first asked about the structure of atoms she replied, "*I have never thought about it*". Narelle had learnt about the structure of the atom in the first lecture and reproduced these ideas when answering a question about the inside of an atom in the initial questionnaire.

It should be noted that the interviewer was in error here by incorrectly referring to *atoms* of sodium chloride. While this may or may not have misled the student, this issue should be considered in the analysis. In the first interview Narelle was unsure about atoms.

Int.: *Can you explain how the copper atoms are arranged?*
Narelle: *Don't know, Yeah, I have thought about it. Yeah I have, I have thought how, sort of, thought how would atoms be and that. Umm Don't Know.*
Int.: *Can you tell me how the atoms are arranged in the sodium chloride? How do you picture them?*
Narelle: *I picture them as sodium cations and chlorine anions. I know that there would be some sort of bond between them but I don't know what sort of bond that would be.*

Narelle's non-existent background knowledge meant that initially she had no idea how to relate to the chemical representations. Even in the first few weeks Narelle was quickly assimilating the new terminology and concepts. When asked to classify the diagrams on Focus Card 1 (Appendix 1) into elements and compounds Narelle's answers were confused. Her first choice of an element was diagram 1.6 (metal array) and when prompted that the circles represent atoms, then she went on to choose diagrams 1.3 and 1.2. Narelle appeared to have a preoccupation with the charges associated with the atom – rather than the type of atom(s) present.

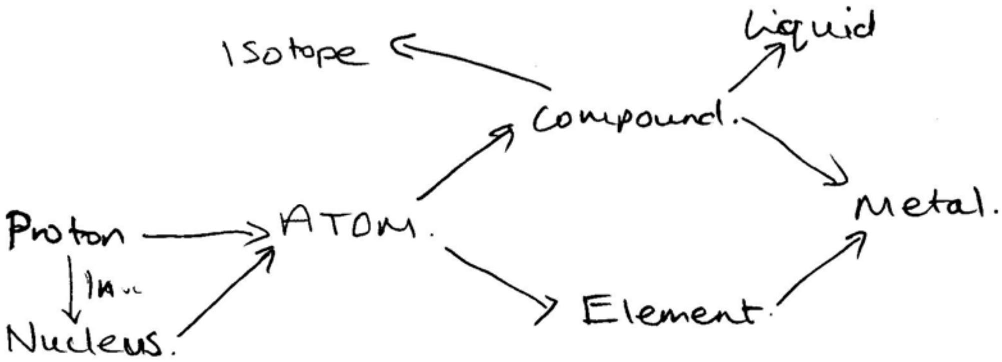
Int.: *So which one might represent a compound?*
Narelle: *7 and 8, maybe 5, I mean 3 and maybe 5.* (Referring to the diagrams on Focus Card 1)

Diagrams 1.7 and 1.8 were both three-dimensional diagrams, with diagram 1.7 representing a compound and diagram 1.8 representing an element. Narelle appeared to have difficulty transferring from the two-dimensional representation to the three-dimensional as well as understanding the basic difference between elements and compounds - with Narelle choosing diagram 1.3 to be a compound – which she had already chosen as an element. Diagram 1.4 – with positive and negative signs in the centre of adjacent circles – was not selected at all. The inconsistencies and the apparent confusion with the drawings suggests that

Narelle did not have a clear understanding of these representations of elements and compounds, and did not know which criteria to use to distinguish them. Her understanding of the subatomic level seemed to be interfering with her understanding at the atomic and molecular level. In addition, the three-dimensional drawings were causing more confusion than clarity for her. These results are consistent with Narelle's responses to a worksheet classifying states of matter and elements, compounds and mixtures.

In the initial questionnaire students were asked to draw a concept map starting with a list of chemical terms. Narelle's map (Figure 2) indicated that she did not really know what a concept map was, nor did she understand the concepts. Initially, the status of Narelle's conceptions of the sub-microscopic level was rudimentary; however, she worked hard and improved and her responses to the worksheets during the semester, and the final interview demonstrated this growth.

Figure 2. Concept map drawn by Narelle in the initial questionnaire



Narelle's responses to a worksheet on the nature of ions and solutions indicated a fair understanding of nature of ions with some lack of confidence in the reality of the sub-microscopic level. Narelle was confident with the macroscopic and familiar qualities of solutions. In a worksheet about the mole concept, students were asked to show how confident they were about twenty-two statements concerning moles. Narelle recorded "Don't Know" to six out of twenty-two questions, and indicated a lack of confidence with four other questions concerning Avogadro's number.

Towards the end of the semester, in a worksheet on chemical equilibrium students were asked to make predictions and describe what would occur in two different equilibrium situations when a change is initiated on the system at equilibrium, Narelle demonstrated a clear understanding of the sub-microscopic, macroscopic, and symbolic levels in her answer to a question on the Haber process by making predictions about the changes to equilibrium situations. The question was presented in symbolic form with an equation and a diagram; Narelles's response is summarized:

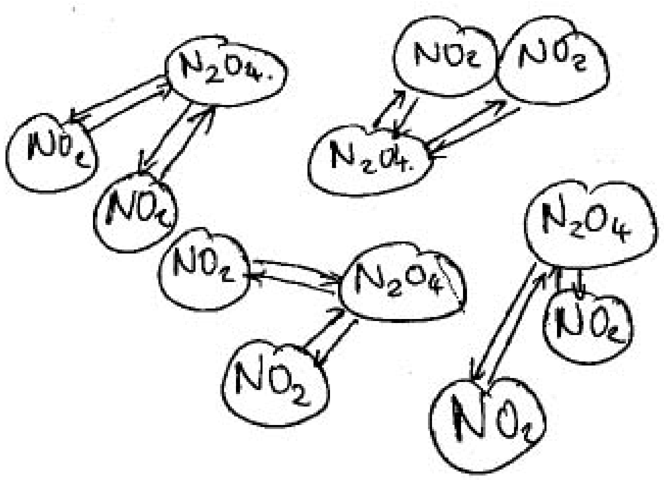
Q1b	*Predict and explain what happens to the volumes of H_2, N_2 and NH_3 at the new equilibrium position.*
Narelle:	*The volume of NH_3 will be increased. The volume of N_2 and the H_2 will decrease as the added concentration of N_2 drives the reaction in direction to lower the number of moles.*

Narelle described the effect of the changes on the macroscopic qualities of volume and concentration referring to the observable quantities and the number of moles of each component. Because the number of moles has both sub-microscopic and macroscopic perspectives; it is not possible from this comment to determine Narelle's perspective(s). This duality of chemical representations – discussed in the Theoretical Underpinnings - whereby students are able to relate a symbolic representation to both the macroscopic and sub-microscopic realities – is a common expectation in chemistry and a significant consideration in investigating students' understandings of chemical concepts.

Responding to a question about the equilibrium position of nitrogen dioxide/dinitrogen tetroxide, Narelle made incorrect predictions about the equilibrium shift for addition and removal of each substance (NO_2 and N_2O_4) and for temperature changes, but predicted correctly the effects of volume changes. Narelle's diagram to represent the equilibrium situation (Figure 3) demonstrates that she is more comfortable with the sub-microscopic level than she was at the beginning of the semester; however, her incorrect responses indicate that her interpretation of the sub-microscopic level is still developing. Despite these anomalies, a significant improvement had occurred in her use of chemical representations throughout the semester.

The data collected about Narelle provided examples of the difficulties some apparently simple concepts can produce for students with little or no chemical background, and the high probability of misconceptions occurring through the misinterpretation of simple representations. The results also demonstrate an inconsistency in understanding – understanding some concepts, and not others.

Figure 3. Narelle's diagram of the equilibrium situation.



At the beginning of the semester, Narelle was a Level 1 modeller according to Grosslight et al.'s scheme. Her initial lack of understanding of the various chemical representations corresponded to a lack of understanding of the concepts. As her modelling ability improved and she became more comfortable with chemical symbols and representations, her understanding of the chemical concepts also improved. Considering that the communication of chemical concepts is often dependent on symbols and representations, this result is not surprising. Narelle's results confirm that a students' modelling ability does affect their use of models and their ability to understand chemical concepts. Narelle repeatedly used equations and performed calculations when completing laboratory reports and preparing for tests, and so was practicing her modelling skills. Towards the end of the semester, she conceded during the interviews that she was developing a mental picture of the sub-microscopic level of matter. Her responses to the equilibrium worksheet indicated that she was working at Level 3; however, because of some inconsistencies in her responses she was assessed as a Level 2-3 modeller.

In terms of her modelling ability, Narelle improved her conception of the representational nature of matter significantly over the semester. Initially, she did not have any appreciation of the value of chemical representations. However, repeatedly using the representations to understand chemical concepts to solve problems, in laboratory write-ups and in calculations and tests she demonstrated the value of the representations. She was able to draw her own representations, create her own equations and use them effectively. She used multiple representations, used the representations to test ideas and to communicate understanding. These data provide evidence that her improved modelling ability is reflected in the use of representations in higher-order reasoning tasks that complement her ability to understand chemical concepts

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Alistair – a level 3 modeller with a good introductory knowledge of chemistry

Alistair's previous chemistry experience included Year 11 and Year 12 chemistry at high school in the previous year, but he had not taken the final examination. His strong chemistry background provided him with a good understanding of the sub-microscopic nature of matter. Below is his description of how atoms are arranged in a sample of copper from the first interview.

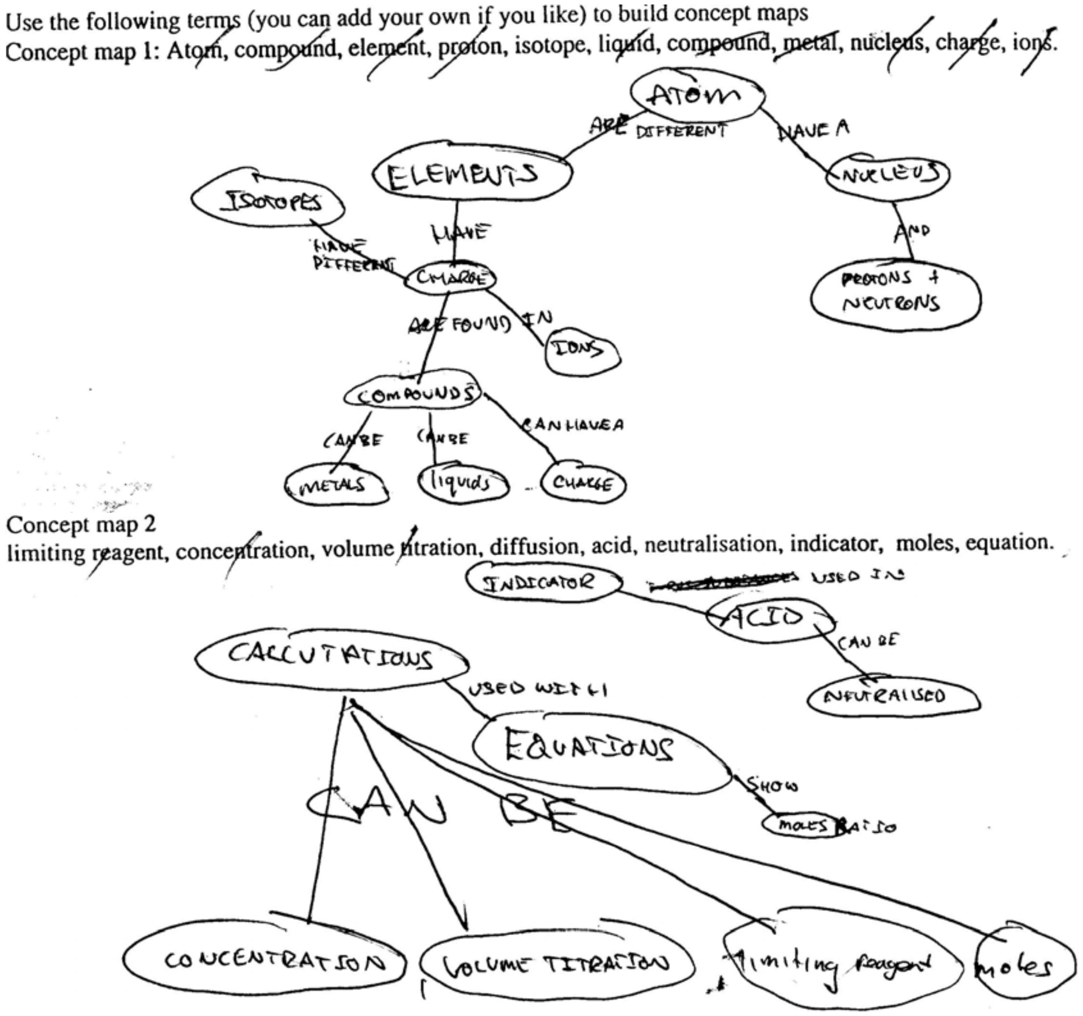
Alistair:	*I picture elements the way they show them in layers - rings of 2 and a ring of 8 electrons in orbital.*
Int.:	*And are the atoms close to each other?*
Alistair:	*No atoms are not close to each other, [they are] spaced evenly but far way away from each other. The way I imagine it is that they are in a circular formation - spaced evenly but I've heard that it's not like that so.*

Similarly with compounds, Alistair had well developed concepts about the bonding of sodium chloride. Nevertheless, the interviews revealed some misconceptions; for example, here Alistair refers to the electrons being 'owned' by particular atoms.

Alistair:	*In the same kind of way, but in the sharing of electrons in that they will either be set up between two atoms and share the electrons and then its personal electrons will be* evenly spaced around in shell formation around the outside… to make sure.

Alistair completed a concept-mapping question in the initial questionnaire (Figure 4) that showed he has a personal structure and hierarchy of chemical knowledge. He grouped common concepts together and tried to relate them with a true statement. There are some misconceptions evident (e.g., metals are compounds), but more importantly, he had the confidence to use his own understanding to build up the concept maps.

Figure 4. Alistair’s responses to the concept mapping question in the initial questionnaire.



Use the following terms (you can add your own if you like) to build concept maps
Concept map 1: Atom, compound, element, proton, isotope, liquid, compound, metal, nucleus, charge, ions.

Concept map 2
limiting reagent, concentration, volume titration, diffusion, acid, neutralisation, indicator, moles, equation.

The classification of matter into elements and compounds seems not to be associated with Alistair’s mental model of matter, but more with interpreting what the representation portrays. In this regard, Alistair classified the Focus Card 1 correctly, except for diagrams 1.3 and 1.4 (Appendix). The dialogue of the interview indicates how important it is for every part of the representation to be understood.

Alistair	*Diagram 1.4 is a compound; no it has positive and negative charges like in the nucleus or something. Don’t know if they mean atoms or whether they mean ions? Don’t know what they are trying to get at there, but I’d say that because they have two differing substances – probably means a compound.*
Int.:	*Why did you think this one was a compound (talking about diagram 1.3)*?
Alistair:	*The lines represented a bond.*
Int.:	*Oh OK and you said the bonds mean a compound and then you looked at it twice, and what did you realise?*
Alistair:	*It might not be a compound - you don’t know - you only know what the lines represent.*
Int.:	*Second time you looked at it you said it was an element – why did you say it was an element?*
Alistair:	*Simple because it could be an element or a compound – I’m not too sure.*
Int.:	*What do the circles represent?*
Alistair:	*To me they represent an element.*

Here Alistair equated lines with bonds, and he associated bonds with compounds, forgetting that elements can also have bonds. He also equated circles with elements not atoms.

Alistair: *Diagram 1.5 – a compound.*

Alistair: *Diagram 1.6 delocalised electrons in between positive charges, aqueous solution, or a metal.*

Alistair: *Diagram 1.7 a solid compound.*

Int.: *Why do you say compound?*

Alistair: *Maybe it could be NH_4 because they have got nice nitrogen and four hydrogens spaced evenly around it. That's how I imagine it too – like diagram 1.7 with three-dimensional and round shapes and so if there were two more they would be* on the front.

Alistair: Diagram 1.8 looks like a solid but an element because all bunch of the same type and the one-size balls.

Despite the fact that Alistair has a reasonably good understanding of the concept of elements and compounds, diagrams 1.3 and 1.4 did not fit his criteria. This observation supports the need for the learner to appreciate the target of all the components of a representation or analogue. Alistair's description of Diagram 1.6 suggests a memorized response. Having learnt chemistry for the previous two years at school, this is possible. Alistair repeatedly categorised the diagrams according to their state as well as their chemical status – "*solid compound*" or "*solid but an element*". These comments indicated that he had a well-established network of knowledge that included both attributes, which he was using to classify the diagrams. Alistair was familiar with chemical entities and the relationships between them as was exhibited in the concept maps. He performed well on the worksheets as expected. He is an experienced modeller and was comfortable explaining a laboratory practical using symbols and equations. Alistair had a preferred representation when asked about the various representations for water (see Appendix).

Int.: *Look at the representations of water on focus card 3. Which representation do you prefer? Why?*

Alistair: *When I think of water I think of the electron dot formula HOH.*

Int.: *Why do you think of that?*

Alistair: *It just shows me that there is oxygen, not going to have two hydrogen electrons keep them spaced apart, and all the electrons are accounted for.*

The electron-dot representation provides a logical representation – accounting for atoms, electrons and structure. Alistair could transfer easily between all three levels of chemical representations of matter: discussing a practical activity in terms of an equation (symbolic), in terms of a macroscopic quality and also at the sub-microscopic level discussing the movement of ions. On the basis of observations, he was assigned a Level 3 modelling ability.

Alistair's background knowledge and solid foundation gave him a huge advantage in this course. He had the confidence and ability to visualize, describe, envisage, and make predictions using his mental model and easily verbalized his understanding. Alistair demonstrated the importance of having a good understanding and a good mental model. In terms of the six dimensions used to evaluate modelling ability, Alistair had communicated a good appreciation of the role of representations in the process of science and the chemical content: he was confident in using multiple representations but had also a preferred representation. He used the representations to make predictions and test ideas.

Leanne – a level 2 only modeller with initially no chemical knowledge

Leanne left high school the previous year and had not studied chemistry before. She had studied science to Year 10 level where she was in the non-chemistry group. In the first interview Leanne applied macroscopic properties to the sub-microscopic nature of matter, displaying a poor modelling ability. There was obvious confusion between the representational nature and the reality of the sub-microscopic level. She was unable to understand the representational nature of the diagrams on the focus cards as is shown in the following interview excerpts.

Int.: *If I gave you a sample of copper for example. Can you explain how the copper atoms are arranged?*
Leanne: *They would be all together.*
Int.: *What would they be like?*
Leanne: *No idea.*
Int.: *Copper's hard we know that but what about the atoms?*
Leanne: *Copper's hard, then doesn't mean that they are tightly packed. They would be together.*

In this next excerpt, the interviewer has misled the student by referring to atoms of sodium chloride when in fact they are ions.

Int.: *What would sodium chloride atoms look like?*
Leanne: *It would look like little white things.*
Int.: *If you get down from the little white things and go down to the atoms what are the atoms going to look like?*
Leann*e:* *White.*
Int.: *OK*

Leanne's comments demonstrate a common assumption by learners in associating the macroscopic qualities to the sub-microscopic level (Andersson, 1990). This misconception arises because the student doesn't understand the differences between the three levels of representation of matter.

Initially, Leanne had no idea how to classify the diagrams on Focus Card 1 (Appendix) into elements or compounds, but by asking some questions and getting feedback she worked out the necessary criteria of associating different sized atoms with compounds. The diagrams acted as explanatory tools – extending her understanding of the element/compound concept.

Leanne's ability to transfer from one level of chemical representation of matter to another was rudimentary at the time of the first interview. Leanne looked at Focus Card 3 (Appendix) – displaying eight different representations of water – and was very clear about distinguishing the reality from the representation, and did not relate the two at all.

Int.: *How do you visualise the beaker with the ions mixing/dissolving in with the water?*
Leanne: *I honestly have no idea when it comes to things like that. Like I can't visualise the difference between having H_2O written down on paper and then looking at it. It doesn't look the same, it's nothing.*
Int.: *Yeah, So the real thing is so remote from the symbolic that…*
Leanne: *It's unbelievable.*

By the time of the second interview, Leanne had completed the first semester of an introductory first year Chemistry course and had just started the second semester unit course. With the experience gained in the first semester she had developed a personal understanding of the role of representations in chemistry, however she was still unsure about the sub-microscopic level.

Int.: *In laboratory work, we perform experiments and use equations to do calculations. Can you relate the equation to the experiment?*
Leanne: *No, I see the experiment – and I see the equation.*
Int.: *Do you fill in the blanks in the calculations?*

Leanne: *I do more than just fill in the blanks now but I still couldn't do the calculations without help from Barry (demonstrator); I need help to know where to start.*

Int.: *Do you have a mental picture of the reaction occurring?*

Leanne: *I do not really have a mental picture of the reaction in my head. I see it in the lab and then I understand the equation represents it, but I do not picture it at the atomic level. I liked the electron dot formula and I suppose they give me a mental picture to think about.*

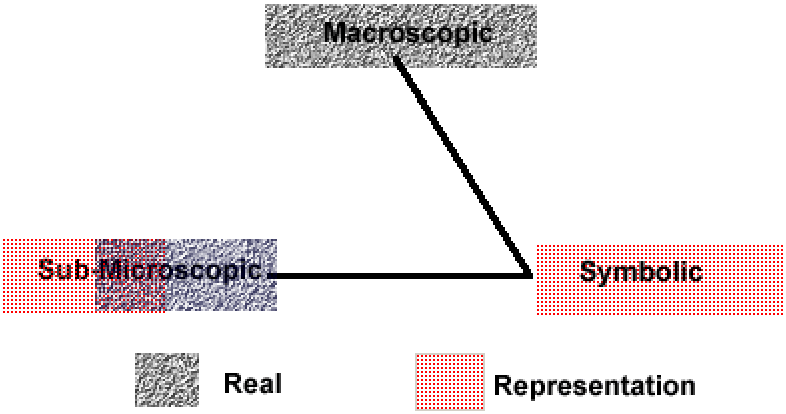
Leanne's modelling skills had improved as a result of the laboratory and theoretical work. Initially, in the first interview, Leanne was confused about the representational nature and the reality of the sub-microscopic level. The distinction between reality and representation is not always obvious in chemical contexts, because in the course of instruction teachers often refer to representations as though they are real entities, resulting in confusion. This outcome is not surprising considering that the model should have properties of the real entity and these properties are accurate. However, the teacher needs to emphasise that it is not an exact copy. The disparity between these ideas leads to misconceptions of the nature of the sub-microscopic level.

During laboratory experiments, Leanne demonstrated a competent use of chemical equations and an understanding of how they relate to the laboratory experiments, being evaluated as a Level 2 modeller. In terms of the six dimensions used to evaluate modelling ability, the data for Leanne is less consistent. While she used chemical symbols writing up practical lessons, her acceptance of the reality of the sub-microscopic level is questionable. Leanne successfully linked the symbolic level with the macroscopic level, and the symbolic level with the sub-microscopic level independently of each other. That is, Leanne had not necessarily linked the macroscopic level to the sub-microscopic level, although she had mapped the symbolic representation to both. The limitations of Leanne's understanding are shown in Figure 5. Her reticence in using the sub-microscopic level could hinder her understanding, since most chemical explanations are at the sub-microscopic level. Leanne's situation supports Johnstone's (1991) warnings of the difficulties students experience in comprehending the sub-microscopic level, and handling all three levels of chemical representation of matter simultaneously.

Leanne's reactions to comments provide an insight into her understanding. She demonstrated a clear understanding of the difference between the symbolic and the sub-microscopic levels, but demonstrated a persistent lack of conviction as to the reality of the sub-microscopic level with comments such as, "*It can't be seen with the naked eye.*" Her logical response is justifiable when considered in her practical, naïve and somewhat simplistic terms: the sub-microscopic level is not visible, in class no proof had been provided for its existence, the scale is extremely small, the idea that it is mostly empty space refutes her personal experiences of the macroscopic nature of liquids and solids. Leanne understood that the symbolic chemical representations provide the visual stimulus for how best to envisage the sub-microscopic level – but to her, it was not reality.

Leanne's level of understanding is common. The idea of relating a macroscopic observation to the invisible sub-microscopic level is understandably 'unbelievable', impossible, and foreign to some students, and contrary to common sense. Leanne's non-existent chemistry background meant that she had not been trained to think about matter in a particulate way, while most science students have been taught to think about matter in this way repeatedly every year from a young age. With common macroscopic experiences supporting an apparently continuous nature of matter, it is not surprising that there is a conflict with the particulate nature of matter, as reported in the literature (Andersson, 1990; Johnson, 1998). However, the repeated referencing to the sub-microscopic level that provided explanations of macroscopic observations gives the sub-microscopic level credibility. The sub-microscopic level promoted and required a chemical way of thinking – a chemical epistemology.

Figure 5. The links that Leanne demonstrated between the three levels of chemical representation of matter.



Conclusion

The research has shown how students' ability to model plays a significant and unique role in learning chemistry. However, while models are ever-present as tools in explaining chemical concepts, the nature of the explanatory tool itself and the skills of modelling are not usually taught directly, but rather indirectly as needed to explain content. Teachers may assume that modelling is an instinctive skill (Duit and Glynn, 1996), though the data from the three students in this study show that this is not the case when learning chemistry. Practice with models and consideration of different levels of representations did improve students' modelling ability which in turn was instrumental in students learning the chemistry concepts. Also, work with these three students has highlighted a range of difficulties and misconceptions that can arise in using models and representations to understand the abstract nature of the sub-microscopic level of matter. This was particularly the case with Narelle and Leanne who began the unit with little or no chemistry knowledge.

The unique duality of chemical models and representations – linking to both the macroscopic and sub-microscopic levels simultaneously – highlights the complex nature of chemistry. Students such as Narelle and Leanne, with little or no background knowledge in chemistry, had to learn how to interpret representations and chemical models and link them to the sub-microscopic level. Application and practice with chemical representations and models was necessary for these students to become proficient with the three levels of representations and gain a deeper understanding of the chemistry concepts in the unit. Learning through instruction and practice is not unique to models; rather the importance of this study is that it illustrates the way the ability to model impacts on students' mental models of matter. Identifying and focusing on the characteristics of good modelling ability promoted the process of thinking and using models effectively.

Based on the case studies of Narelle, Alistair and Leanne, the students' understandings of the role of models in relation to both the macroscopic and submicroscopic levels have been shown to be significant in their depth of understanding of chemical concepts. The study has demonstrated that these students who used models and the different levels of representation, with modelling ability of levels 2/3 or level 3, were able to develop higher order thinking processes about the chemistry they were learning because they were able to: use models for testing, predicting and evaluating their ideas; develop mental pictures of the submicroscopic level of matter; transfer ideas between different levels of representation; create symbolic representations from observed reactions; and appreciate the target of representation or analogue. For Narelle and Leanne especially, their developing modelling abilities were important in the development of their understanding of chemical concepts.

In brief, the conclusion from this study is that students' abilities to use and interpret chemical models do influence their abilities to understand chemical concepts. These modelling skills should be taught rather than be an incidental consequence of the teaching of chemical concepts, by being incorporated in instruction, and by students given practice in the application of multiple representations of chemicals and their interactions.

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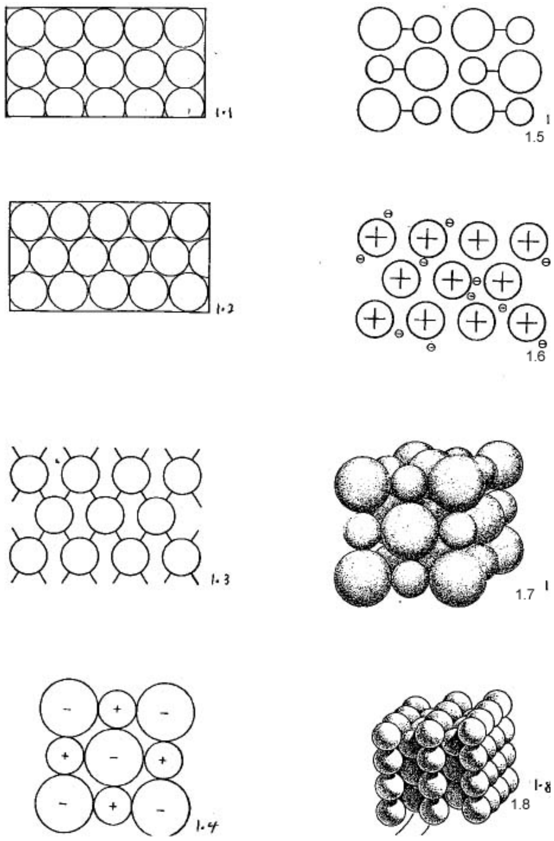
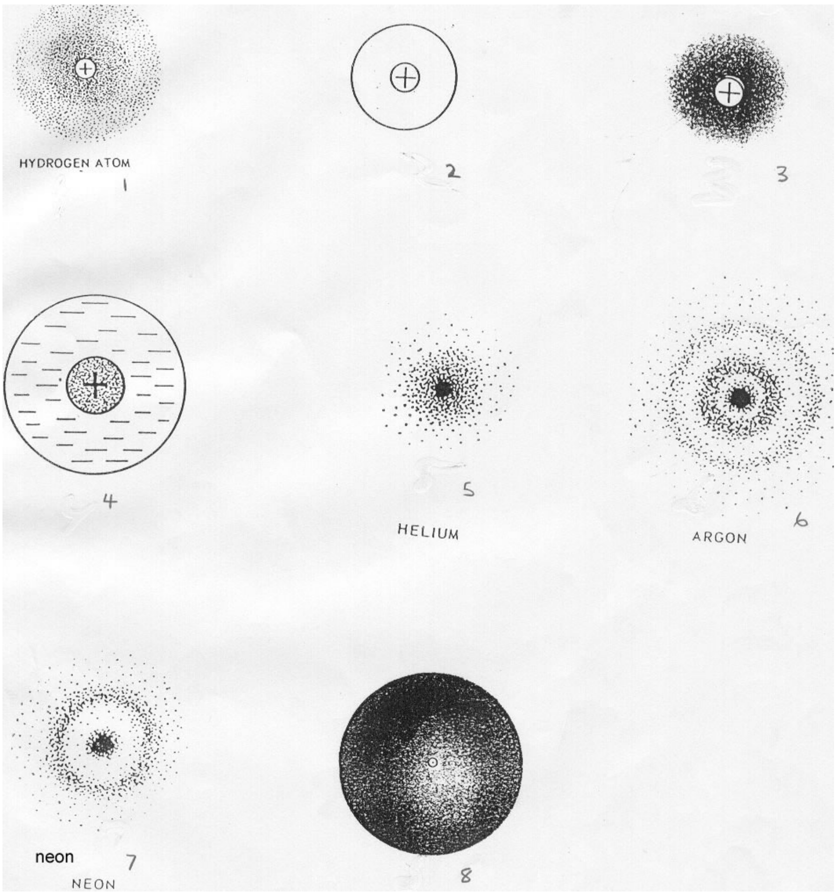
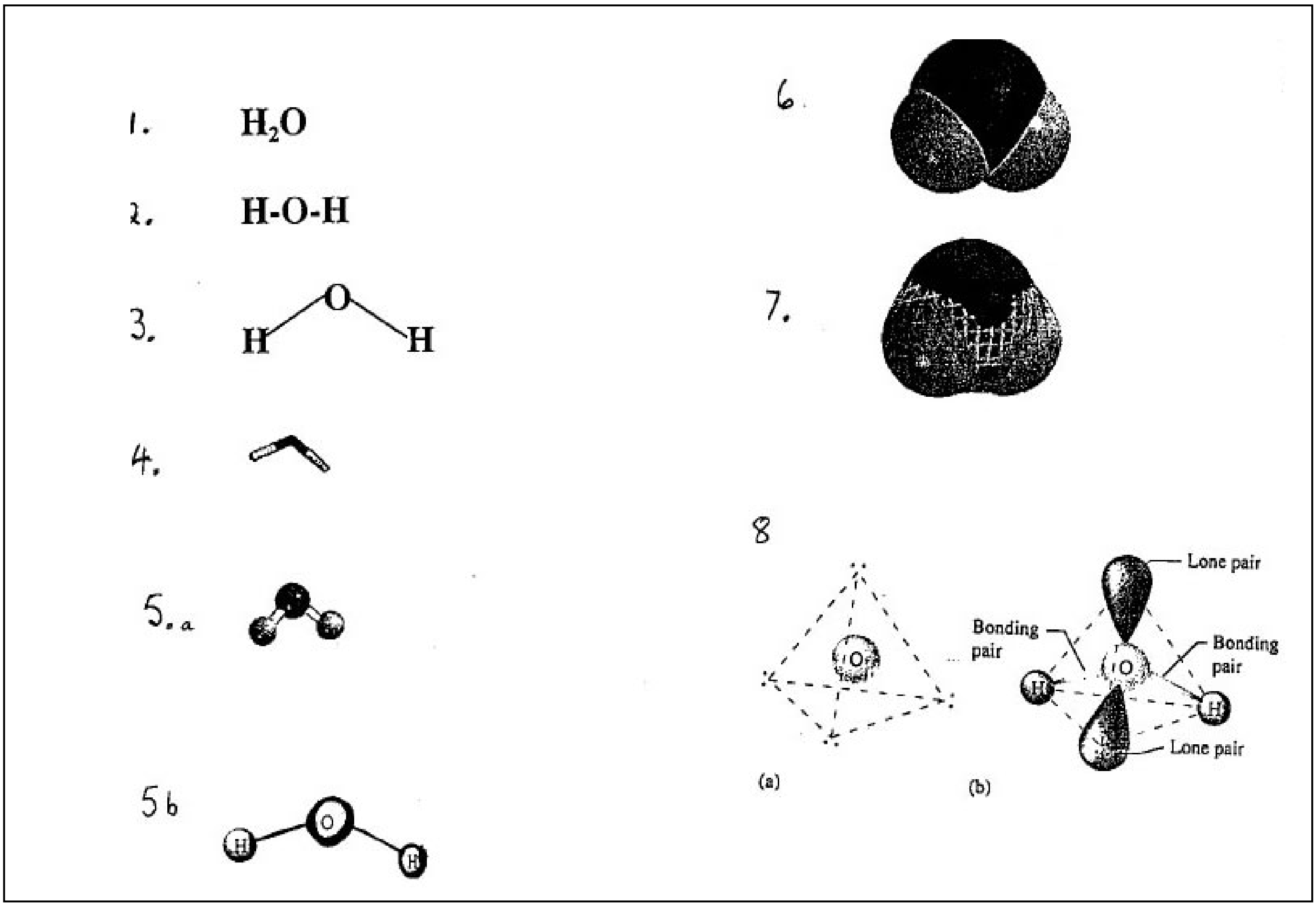
Appendix



Focus Card 1



Focus Card 2



Focus Card 3 Diagram #8 copied from Zumdahl (2000 p.358)

Educational research

The development of a two-tier multiple-choice diagnostic instrument for evaluating secondary school students' ability to describe and explain chemical reactions using multiple levels of representation

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Abstract: A 15-item two-tier multiple-choice diagnostic instrument was developed to evaluate secondary students' ability to describe and explain seven types of chemical reactions using macroscopic, submicroscopic and symbolic representations. A mixed qualitative and quantitative case study was conducted over four years involving 787 Years 9 and 10 students (15 to 16 years old). The instrument was administered to sixty-five Year 9 students after nine months of instruction to evaluate their use of multiple levels of representation. Analysis of the students' responses demonstrated acceptable reliability of the instrument, a wide range of difficulty indices and acceptable discrimination indices for 12 of the items. The teaching program proved to be successful in that in most instances students were able to describe and explain the observed changes in terms of the atoms, molecules and ions that were involved in the chemical reactions using appropriate symbols, formulas, and chemical and ionic equations. Nevertheless, despite the emphasis on multiple levels of representation during instruction, 14 conceptions were identified that indicated confusion between macroscopic and submicroscopic representations, a tendency to extrapolate bulk macroscopic properties of substances to the submicroscopic level, and limited understanding of the symbolic representational system. [*Chem. Educ. Res. Pract.*, 2007, **8** (3), 293-307.]

Keywords: chemical reactions, macroscopic, submicroscopic and symbolic representations, student conceptions

Introduction

The theoretical basis of this study is a constructivist approach that is grounded in the belief that what a learner already knows is a major factor in determining the outcomes of learning (Ausubel, 1968). Learners are provided with opportunities to develop new understandings with the teacher acting as a facilitator of learning rather than as a transmitter of knowledge. The complex and abstract nature of chemistry makes the study of the subject difficult for students (Ben-Zvi et al., 1987, 1988; Johnstone, 1991, 1993; Nakhleh, 1992; Gabel, 1998, 1999; Treagust and Chittleborough, 2001). As a result, students tend to hold particular idiosyncratic views about scientific phenomena and concepts that they bring with them to science lessons. These conceptions that students develop (referred to as student conceptions) are the result of several factors, such as their sensory experiences and the influence of their cultural background, peers, mass media as well as classroom instruction (Duit and Treagust, 1995). Very often, the conceptions that students develop about the behaviour of matter tend to differ from the views that are held by the scientific community (Osborne et al., 1983). It is likely that students are satisfied with their own conceptions as a result of viewing material that is presented by their teachers or textbooks "*through the lenses of their preinstructional conceptions*" (Duit and Treagust, 1995; p. 47).

The unique conceptions about natural phenomena that are held by students are often resistant to instruction. One reason for this resistance to change is the tendency for these conceptions to become firmly entrenched in students' minds as coherent but mistaken conceptual structures (Driver and Easley, 1978), especially when students' conceptions are deeply rooted in their everyday life experiences. As a result, when the new concepts do not make sense to them, students tend to adhere firmly to their own views (Treagust et al., 1996). Consequently, it is beneficial to identify students' conceptions so that appropriate strategies may be formulated that will challenge their understandings in order to help them develop more scientifically acceptable views of science concepts.

One of the reasons for the difficulties that students experience in understanding the nature of matter is related to the multiple *levels of representation* that are used in chemistry instruction to describe and explain chemical phenomena (Yarroch, 1985; Andersson, 1986; Ben-Zvi et al., 1986; Gabel et al., 1987; Johnstone, 1991, 1993; Nakhleh and Krajcik, 1994). For the purpose of this study the three representations relevant to understanding of chemistry concepts are: (1) *macroscopic representations* that describe bulk properties of tangible and visible phenomena in the everyday experiences of learners when observing changes in the properties of matter (e.g. colour changes, pH of aqueous solutions, and the formation of gases and precipitates in chemical reactions), (2) *submicroscopic (or molecular) representations* that provide explanations at the particulate level in which matter is described as being composed of atoms, molecules and ions, and (3) *symbolic* (or *iconic*) *representations* that involve the use of chemical symbols, formulas and equations, as well as molecular structure drawings, diagrams, models and computer animations to symbolise matter.

The acquisition of knowledge by students without a clear understanding may be attributed to the confusion caused in having to deal simultaneously with the macroscopic, submicroscopic and symbolic worlds of chemistry. From observations of the macroscopic changes that are observed, students have to explain these changes at the particulate level. The particulate level in turn is represented by symbols and formulas. As a result of having to deal with these three levels of representation simultaneously, learners generally experience difficulty in explaining chemical reactions (Gabel, 1998).

In order to help students develop conceptual understanding of chemical representations, several studies conducted over the past few decades (Ben-Zvi et al., 1986; Keig and Rubba, 1993; Kozma and Russell, 1997) indicate that students experience difficulty in understanding the submicroscopic and symbolic representations because these representations are abstract and cannot be experienced (Ben-Zvi et al., 1986, 1988; Griffiths and Preston, 1992). Students' thinking, on the other hand, is heavily influenced by sensory information that they are able to experience. Also, students often are not able to translate one given representation into another due to their limited conceptual knowledge and poor visual-spatial ability (Seddon and Eniaiyeju, 1986; Keig and Rubba, 1993).

Similarly, research also has shown that many high school teachers do not integrate the three representations in their teaching but move between representational levels without highlighting their inter-connectedness (Gabel, 1999). As a result, students are often unable to see the linkages between the three levels of representation although they may know the chemistry at the three levels. For improved conceptual understanding, it is important to help students see the connections between the three levels of representation (Gabel, 1999). A convenient way of studying students' ability to make use of multiple levels of representation when describing and explaining chemical phenomena involves the use of two-tier multiple-choice diagnostic instruments. The advantages and successful use of these instruments in several studies are discussed next.

As a result of the limitations of the clinical interview method that is time consuming and not convenient for use by classroom teachers, science education researchers have recognized the need for short paper and pencil tests for obtaining data from large whole class or samples of students. These tests included multiple-choice items that initially evaluated only content knowledge without considering the reasoning behind students' choices of responses (Duncan and Johnstone, 1973). As an improvement of this methodology, Tamir (1971) proposed the use of multiple-choice test items that included responses with known student alternative conceptions, and that also required students to justify their choice of option by giving a reason. Tamir (1989) found the use of justifications when answering multiple-choice test items to be a sensitive and effective way of assessing meaningful learning among students and addresses, to some extent, the limitations of traditional multiple-choice test items.

The positive outcomes of findings related to students' justifications to test items led to the development of two-tier multiple-choice diagnostic tests specifically for the purpose of identifying students' alternative conceptions in limited and clearly defined content areas. These short paper and pencil tests are convenient to administer and not time consuming to mark. Treagust (1988, 1995) has provided useful guidelines for the development of these instruments specifically for the purpose of identifying students' alternative conceptions about various concepts. The first tier of the items consists of a content question, while the second tier elicits a reasoning response. The need to select a justification in these multiple-choice items affords a sensitive and effective way of assessing meaningful learning among students and also serves as an effective diagnostic tool (Tamir, 1989). To date, several diagnostic tests have been developed and are described in the literature (Haslam and Treagust, 1987; Peterson et al., 1989; Odom and Barrow, 1995; Tan and Treagust, 1999; Tan et al., 2002; Chou and Chiu, 2004; Wang, 2004; Treagust, 2006).

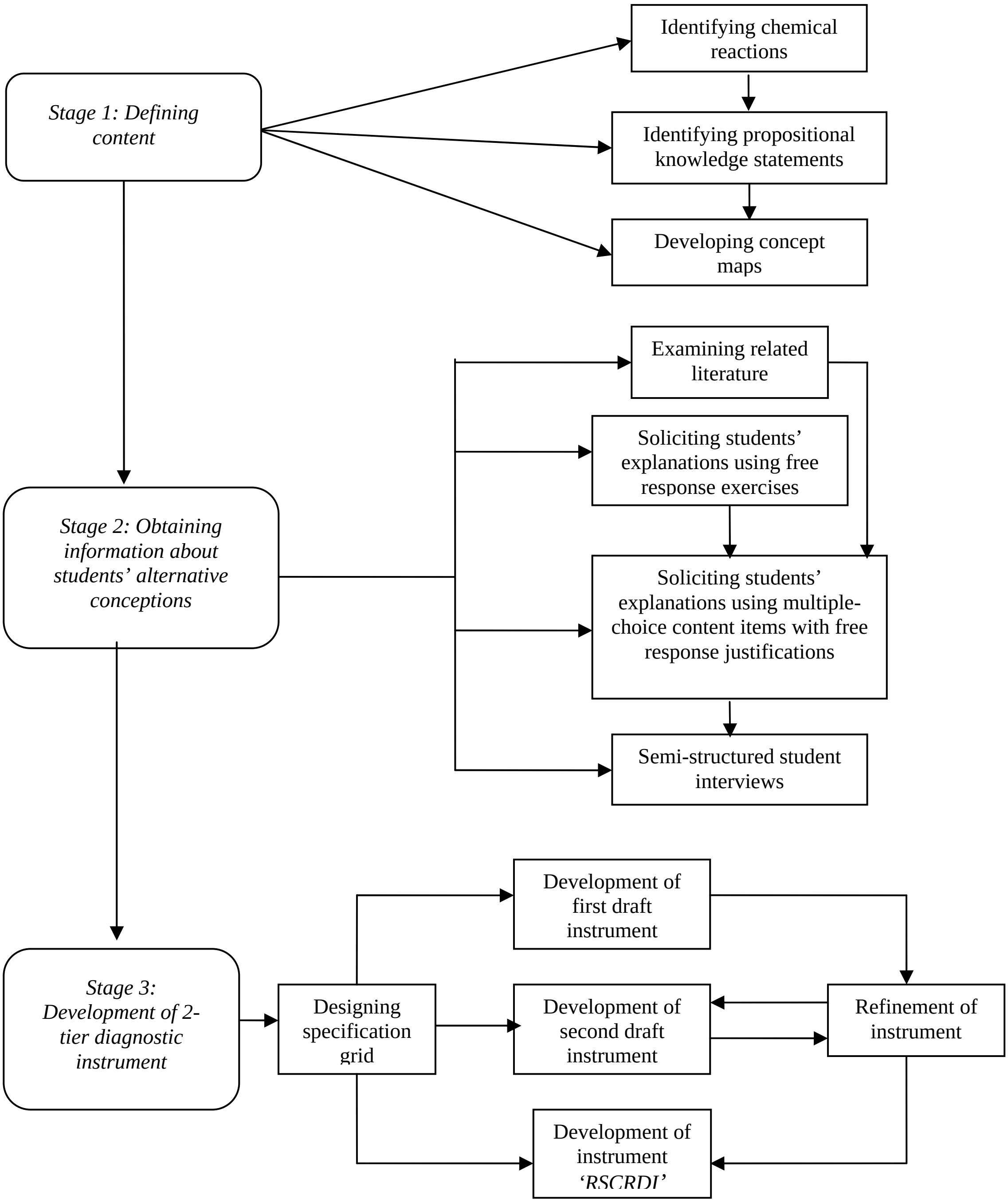
The purpose of the study

The observed changes during chemical reactions include colour changes, gas evolution, 'disappearance' of solid reactants, and formation of precipitates. The purpose of this study was to develop a two-tier multiple-choice diagnostic instrument in order to assess the ease with which 15 to 16 year old students in Years 9 and 10 were able to explain the observed changes in chemical reactions (macroscopic representations) in terms of atoms, molecules and ions (submicroscopic representations) as well as with the use of chemical symbols, formulas and equations (symbolic representations). Seven types of chemical reactions that were frequently encountered in their chemistry course were included in this study.

Methods and procedures

This case study, incorporating both qualitative and quantitative methods, involved a convenience sample (Merriam, 1998) of 787 Years 9 and 10 students aged 15 to16 years old from a Singapore secondary school who were selected during the course of the study over a period of four years. The instrument was developed in three stages (see Figure 1) using the procedure proposed by Treagust (1995). Stage 1 involved defining the content area of the study. Stage 2 involved identifying students' conceptions when describing and explaining chemical reactions using multiple levels of representation (based on responses solicited from two groups consisting 515 and 95 students). Stage 3 involved several steps in the designing of test items and the validation of the final version of the two-tier multiple-choice diagnostic instrument (based on responses solicited from 177 students).

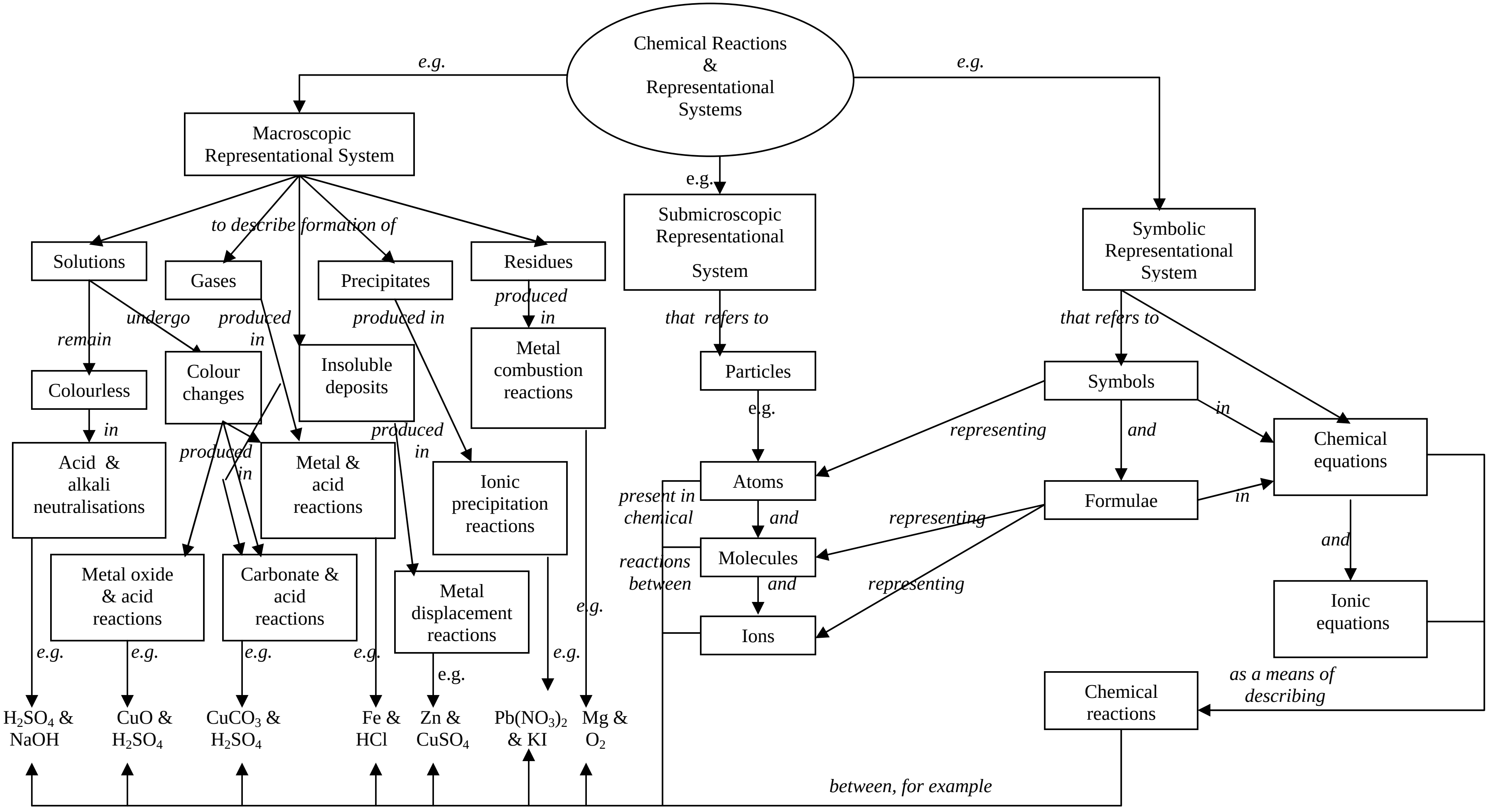
Figure 1. Scheme of development of the Representational Systems and Chemical Reactions Diagnostic Instrument (RSCRDI) based on Treagust (1988, 1995)



Stage 1 – Defining the content area of the study

Based on inspection of the chemistry syllabus, seven types of chemical reactions that were frequently encountered by Years 9 and 10 students (15 to 16 years old) were identified. All seven types were introduced to the students in the chemistry scheme of work for Year 9 and were included in three major topics, namely, the properties of acids and bases, the metal reactivity series and qualitative inorganic analysis. These seven types of chemical reactions were: combustion of metals, reactions between dilute acids and reactive metals, neutralisation reactions between strong acids and strong alkalis, neutralisation reactions between dilute acids and metal oxides, chemical reactions between dilute acids and metal carbonates, ionic

Figure 2. Concept map of representational systems for describing chemical reactions



precipitation reactions, and metal-ion displacement reactions. The content area was defined using thirty-nine propositional statements that were encapsulated in a concept map (Chandrasegaran, 2004) in Figure 2. As a reliability check, in order to ensure that the underlying concepts and propositional knowledge statements referred to the same topic area, seven concept maps were developed, one for each of the chemical reactions that were included in this study. All the concept maps were validated by two colleagues of the first author who were also involved in teaching chemistry in Years 9 and 10, as well as by two tertiary level science education professors and a chemistry lecturer.

Stage 2 – Identifying students' conceptions when describing and explaining chemical reactions using multiple levels of representation

An important aspect of this study involved identifying their conceptions when students described and explained the seven chemical reactions using multiple levels of representation. Apart from reviewing the research literature, students' conceptions were identified from their written responses in 11 exercises that included semi-structured and free response questions. These exercises were administered by the first author and six of his teaching colleagues to 515 Years 9 and 10 students. The chemical reactions that were referred to in these exercises were each demonstrated to the students prior to their attempting the exercises. An example of one of these exercises for the chemical reaction between aqueous solutions of lead(II) nitrate and potassium iodide is reproduced in Figure 3.

Figure 3. Worksheet VI: Reaction between aqueous solutions of lead(II) nitrate and potassium iodide.

You have seen what happens when a colourless aqueous solution of potassium iodide is added from a dropping pipette, with shaking, to some aqueous lead(II) nitrate in a test-tube, until no further change occurs.
A bright yellow precipitate is instantly produced.
On allowing to stand, the yellow precipitate settles to the bottom, with a colourless solution above it.
The changes that occur can be represented by the chemical equation,
$Pb(NO_3)_2(aq) + 2KI(aq) \rightarrow PbI_2(s) + 2KNO_3(aq)$

Question 1: Name the yellow precipitate produced.
Question 2: What does the chemical equation tell you about the changes that have occurred?
Using your knowledge about atoms, molecules and ions, answer Questions 3 - 8.
Question 3: Name the particles present in aqueous lead(II) nitrate.
Question 4: Name the particles present in aqueous potassium iodide.
Question 5: Name the particles present in the yellow precipitate.
Question 6: Name the particles present in the colourless solution finally produced.
Question 7: Name the particles that have remained unchanged in solution.
Question 8: Deduce the ionic equation for the changes that have occurred.

When the experiment is repeated using colourless aqueous solutions of lead(II) ethanoate, $(CH_3COO)_2Pb$, and sodium iodide, a yellow precipitate and a colourless solution are again produced.
Question 9: Write a balanced chemical equation for the changes that occur, indicating all state symbols.
Question 10: Write a balanced ionic equation for the changes that occur, indicating all state symbols.
Question 11: On allowing the yellow precipitate to settle, what colourless solution would you expect to see above the precipitate?

Subsequently, 33 multiple-choice items were developed consisting of two, three or four responses, one of which was the expected answer. The distractors in the items were based on student conceptions that were identified from the research literature as well as from students' responses to the 11 written exercises referred to in stage 2. The 33 multiple-choice items were content-validated by two science education professors and a chemistry senior lecturer. For each item a space was provided for students to supply a reason for the response that they had selected (Treagust, 1995).

The 33 items were trialled by administering to ninety-five students in three Year 10 classes that were taught by the first author. Following analysis of more than 1,000 justifications that were provided by the students, semi-structured interviews were conducted with seventeen students. These students were selected because of ambiguities in several justifications that were provided by them. A list of students' conceptions was then compiled from their responses to the written exercises and the justifications that were provided to the 33 multiple-choice items. Several of these student conceptions were subsequently used in the construction of the two-tier multiple-choice diagnostic instrument discussed in the next section.

Stage 3 – Development and **validation** *of the two-tier multiple-choice diagnostic instrument*

After studying the justifications that were provided by the students to the multiple-choice items in the previous section, 33 two-tier multiple-choice items were developed. The second tier elicited a reasoning response (for the selection made in the first tier) that had to be chosen from two, three or four responses. One of the responses was the expected reason while the distractors consisted of incorrect reasons as well as scientifically unacceptable conceptions held by students. The item options were chosen from students' responses to the written exercises in stage 2, the research literature and from the first author's teaching experience.

The items were validated by a teaching colleague of the first author and two science education professors. The 33 items constituted the first draft of the two-tier diagnostic instrument. After two successive trials (involving 177 Year 10 students), the final version of the instrument, the *Representational Systems and Chemical Reactions Diagnostic Instrument* (RSCRDI) consisting of 15 items was developed incorporating 30 student conceptions that were identified in stage 2 of the study. In deciding on the final 15 items, consideration was given to items that elicited a wide range of responses, apart from ensuring that all the chemical reactions were adequately included in the instrument. The draft and final versions of the instruments were developed based on a specification grid designed to ensure that the instruments satisfactorily incorporated the propositional knowledge statements relating to the chemical reactions involved. Examples of two items in the RSCRDI are found in Figure 4. A complete version of the RSCRDI may be obtained from the first author.

Figure 4. Examples of two-tier multiple-choice items from the RSCRDI.

Item 10

Dilute sulfuric acid is added to some black copper(II) oxide powder and warmed. The copper(II) oxide disappears producing a blue solution.
Why is a blue solution produced?

A The copper(II) oxide dissolves in the acid producing a blue solution.
B Copper(II) oxide reacts with dilute sulfuric acid, producing a soluble salt, copper(II) sulfate.
C Copper(II) oxide is anhydrous. When the acid is added the copper(II) oxide becomes hydrated and turns blue.

The ***reason*** *for my answer is:*
1 The ions in copper(II) sulfate are soluble in water.
2 Cu^{2+} ions have been produced in the chemical reaction.
3 Hydrated salts contain molecules of water of crystallisation.
4 Cu^{2+} ions originally present in insoluble copper(II) oxide are now present in soluble copper(II) sulfate.

Item 14

When powdered zinc is added to blue aqueous copper(II) sulfate and the mixture shaken, the blue colour of the solution gradually fades and it becomes colourless. At the same time a reddish-brown deposit is produced.
The chemical equation for the reaction that occurs is,

$$Zn(s) + CuSO_4(aq) \rightarrow ZnSO_4(aq) + Cu(s),$$

while the ionic equation is, $Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s)$.

Why did the solution finally become colourless?
A Copper has formed a precipitate.
B Zinc is more reactive than copper(II) sulfate.
C The copper(II) sulfate has completely reacted.
D Zinc has dissolved, just like sugar dissolves in water.

The ***reason*** *for my answer is:*
1 Zinc ions are soluble in water.
2 Zinc loses electrons more readily than copper.
3 Soluble, blue Cu^{2+} ions have formed insoluble, reddish-brown copper atoms.
4 In aqueous solution Cu^{2+} ions produce a blue solution, while Zn^{2+} ions produce a colourless solution.

Evaluation of the RSCRDI

The RSCRDI was evaluated for its usefulness in assessing students' proficiency in using multiple levels of representation. The instrument was administered to a sample of sixty-five students from two Year 9 classes after nine months of instruction during which time they were introduced to the seven chemical reactions relevant to this study. The two classes that were selected for this study were the only two Year 9 classes (out of a total of 10 classes involved in the learning of chemistry) that were taught by the first author.

Statistical Analysis of RSCRDI

The responses of the sixty-five students to the 15 items in the RSCRDI were analysed using a SPSS statistics software program. The students obtained a mean score of 11 out of 15. The answer to an item was considered to be correct if both content and reason parts were correctly answered. The reliability of the instrument was established by a Cronbach alpha coefficient of 0.65 for the 65 cases and 15 items. This value is acceptable as it is greater than the threshold value of 0.5 for multiple-choice items quoted by Nunally (1978). The difficulty indices of the items ranged from 0.35 to 0.94 providing a wide range of difficulty in the items. The discrimination indices ranged from 0.35 to 0.59 for 12 of the 15 items. A discrimination index greater than 0.3 is considered acceptable (Lien, 1971). Three of the items that did not meet this criterion would require further refinement.

Item analysis of two-tier test items in RSCRDI

Analysis of students' responses revealed that of the 30 student conceptions that were incorporated in the items in the RSCRDI, 14 were held by at least 10% of the Year 9 students to whom the instrument was administered after nine months of instruction using a specially designed program that provided opportunities for students to perform the chemical reactions themselves, and to discuss in small groups the submicroscopic and symbolic representations used to describe and explain the observed macroscopic changes. Despite efforts to facilitate the use of multiple levels of representation during instruction, it was not surprising that several student conceptions were resistant to instruction. The 14 student conceptions and the percentage of students who held these conceptions are summarized in Table 1. Students' responses to the items in which these conceptions emerged are discussed next.

Table 1. Several non-scientific conceptions held by students (N = 65) when using multiple levels of representation to describe and explain chemical reactions.

Chemical reactions	Item no.	Students' conceptions	Percentage of students
Burning of magnesium	2	Mg^{2+} ions are present in magnesium ribbon. (mac, **sub, sym**)	14
		The symbol for the element magnesium is Mg^{2+}. (mac, sub, sym)	14
Iron powder and dilute HCl	3	Atoms of iron and chlorine become green when they combine together. (mac, sub)	15
Dilute acid and aqueous alkali	8	Na^+ ions and NO_3^- ions react in aqueous solution to produce sodium nitrate. (**mac**, sub, sym)	20
	9	The ionic equation for the reaction between a dilute acid and aqueous alkali depends on the stoichiometry of the chemical equation. (mac, **sym**)	11
Metal oxides and dilute acid	10	Cu^{2+} ions exist only in aqueous solution, not in the solid and liquid states. (mac, sub, sym)	25
	11	Iron(III) oxide dissolves in dilute hydrochloric acid. (mac)	15
		Individual Fe^{2+} ions in aqueous solution are green (mac, sub, sym)	15
Aqueous lead(II) nitrate and aqueous solutions of iodides	12	The ionic equation for the reaction of aqueous potassium iodide with lead(II) nitrate displays all the ions present in the reactants and products. (sub, sym)	11
	13	The ionic equations for the reactions of aqueous lead(II) nitrate with aqueous potassium iodide and with aqueous sodium iodide depend on the stoichiometry of the two chemical equations. (mac, **sym**)	12
Zinc and aqueous copper(II) sulfate	14	Cu^{2+} ions in aqueous solution are blue. (mac, sub, sym)	31
		Copper atoms are reddish-brown. (mac, sub)	31
		Copper atoms are insoluble in water. (mac, sub, sym)	31
		A reddish-brown precipitate of copper is produced when zinc is added to aqueous copper(II) sulfate. (mac)	11

Note: The abbreviations mac, sub and sym denote the macroscopic, submicroscopic and symbolic representations

The burning of magnesium ribbon

Item 2 in the RSCRDI referred to the symbol for magnesium that is present in magnesium ribbon. A relatively high proportion of students (75%) made the correct selection indicating that the symbol for magnesium in magnesium ribbon is 'Mg' because the particles in magnesium ribbon are neutral atoms. These students were able to represent magnesium using a symbolic representation in terms of the neutral magnesium atoms that are present (submicroscopic representation).

Fourteen percent of students, however, held the conceptions that Mg^{2+} ions (submicroscopic and symbolic representations) were present in magnesium ribbon (macroscopic representation) and that the metal magnesium had a charge of +2 (symbolic representation). The suggestion that magnesium ribbon consists of Mg^{2+} ions may have been associated with the explanation for the structure of metals in which the presence of metallic bonding is regarded as resulting from the electrostatic attraction between positive nuclei of metal atoms and the 'sea' of mobile valence electrons. However, the suggestion that magnesium (instead of the particles in magnesium) has a charge of +2 indicates confusion between the macroscopic and submicroscopic levels of representation.

Chemical reactions of dilute acids

Item 3 in the RSCRDI involved explaining the formation of a light-green solution when dilute hydrochloric acid was added to iron powder. Only 66% of the students made the correct selection, suggesting that the colour of the solution could be attributed to the formation of iron(II) chloride in aqueous solution (macroscopic representation). The students justified their choice by explaining that the green colour was due to the presence of Fe^{2+} ions in aqueous solution (submicroscopic and symbolic representations). Fifteen percent of the students, however, held the conception that chlorine and iron atoms turned green when they reacted to produce iron(II) chloride in aqueous solution.

In Item 4 students were required to explain how hydrogen gas was produced in the chemical reaction between dilute hydrochloric acid and iron powder in Item 3. Forty-three percent of students incorrectly suggested that acids produce hydrogen when they react with *all* metals, although they correctly explained that in this reaction iron displaces hydrogen ions (submicroscopic level) from aqueous solution because iron is more reactive than hydrogen (macroscopic level). However, the incorrect factual statement was not included as a student conception in Table 1 as the statement does not involve students' facility with the use of multiple levels of representation.

Item 8 in the RSCRDI involved the chemical reaction between dilute nitric acid and aqueous sodium hydroxide. The net change that occurred was the removal of equal numbers of H^+ ions and OH^- ions to produce water molecules (submicroscopic and symbolic representations). Although 91% of the students suggested that the resulting solution was neutral (macroscopic representation), only 71% of the students indicated understanding of the macroscopic change as involving a reaction between equal numbers of H^+ ions and OH^- ions in aqueous solution at the submicroscopic level of representation. The reference to an equal number of the two ions indicated additional understanding at the symbolic level of representation about the stoichiometry of the chemical reaction between nitric acid and sodium hydroxide. Twenty percent of the students, however, held the conception that Na^+ ions had reacted with NO_3^- ions (submicroscopic and symbolic representations) to produce aqueous sodium nitrate (macroscopic representation). This inappropriate explanation may have been the result of students knowing that, at the macroscopic level of representation, sodium nitrate was a product of the chemical reaction.

Item 9 of the RSCRDI required students to compare the ionic equation for the reaction in Item 8 with that when dilute hydrochloric acid reacted with aqueous potassium hydroxide. A high proportion of students (88%) correctly suggested that the macroscopic change produced by either pair of dilute acid and alkali would be similar as the net change at the submicroscopic representational level involved the same ions (H^+ and OH^- ions). Despite the similar net reaction that occurred in both cases involving the removal of equal numbers of H^+ ions and OH^- ions to produce water molecules (submicroscopic and symbolic representations), 11% of the students failed to see the common feature in the two chemical reactions at the symbolic level represented by the identical ionic equation. They suggested that the ionic equations for the two neutralisation reactions would depend on the reaction stoichiometries of the two chemical reactions.

Item 10 in the RSCRDI required an explanation for the formation of a blue solution as a result of the chemical reaction between dilute sulfuric acid and copper(II) oxide. Despite 91% of the students selecting the correct content choice that soluble copper(II) sulfate had been produced (macroscopic representation), only 66% selected the correct reason. These students indicated the correct view that the formation of the blue aqueous solution of copper(II) sulfate could be explained in terms of the Cu^{2+} ions that were now present in aqueous solution (submicroscopic and symbolic representations). Twenty-five percent of the students, however, held the conception that Cu^{2+} ions could only be present in aqueous solution, but not in the solid state.

Item 11 in the RSCRDI involved the reaction of iron(III) oxide powder with dilute hydrochloric acid and with dilute sulfuric acid. A high proportion of students (72%) could identify the similarity in the chemical reactions between iron(III) oxide and the two acids. These students agreed that the macroscopic change in both chemical reactions involved the same interaction between H^+ ions and O^{2-} ions (submicroscopic and symbolic representations). However, 15% of the students held the conception that the solid iron(III) oxide had dissolved in the dilute acid (macroscopic representation) and that *green* Fe^{2+} *ions* (macroscopic, submicroscopic and symbolic representations) were present in aqueous solution after the chemical reaction.

Chemical reaction between an aqueous solution of lead(II) nitrate and aqueous solutions of iodides

Item 12 in the RSCRDI involved deducing the ionic equation for the ionic precipitation of lead(II) iodide in the reaction between aqueous solutions of lead(II) nitrate and potassium iodide. A very high proportion of students (91%) was able to select the correct ionic equation. Yet, only 75% of students displayed understanding of the reason for not including the 'spectator ions' K^+ and NO_3^- in the ionic equation. Eleven percent of the students held the conception that the ionic equation included all the ions that were present in the reactants and products (submicroscopic and symbolic representations), displaying lack of understanding of the net chemical change involving merely the removal of Pb^{2+} ions and I^- ions from aqueous solution.

Item 13 in the RSCRDI involved the chemical reaction between aqueous solutions of lead(II) nitrate and sodium iodide. Students had to decide whether or not the ionic equation for this chemical reaction was the same as that in Item 12 when aqueous potassium iodide was used instead of sodium iodide. Seventy-four percent of the students displayed understanding of the significance of the balanced chemical equation at the symbolic level of representation and the involvement of only the Pb^{2+} ions and I^- ions at the submicroscopic level represented by the ionic equation. However, 12% of the students held the conception that the ionic equation would be different for the two chemical reactions as the number of ions present in aqueous solution had an influence on the ionic equation, even though there was no difference in the two reaction stoichiometries in this case.

Displacement of copper(II) ions from aqueous copper(II) sulfate by metals

Item 14 in the RSCRDI required an explanation for the change in colour of the solution from blue to colourless and the formation of a copper coating resulting from the chemical reaction between zinc powder and aqueous copper(II) sulfate. Only 40% of the students were successful in answering this item. These students believed that the blue solution turned colourless because the copper(II) sulfate had reacted completely (macroscopic representation). They also agreed with the explanation that the blue solution that was due to the presence of Cu^{2+} ions, had turned colourless because the Cu^{2+} ions were no longer present in aqueous solution. The solution now contained Zn^{2+} ions resulting in the formation of a colourless solution (submicroscopic and symbolic representations).

On the other hand, 31% of the students indicated an extrapolation of bulk macroscopic properties of matter to the submicroscopic level of representation in their reasoning. Their choice of response indicated their belief that individual Cu^{2+} ions were blue in aqueous solution. At the same time they implied that copper atoms were reddish-brown and were insoluble in water. Also, 11% of the students showed ignorance of the definition of the term precipitation, by suggesting that a reddish-brown precipitate of copper was produced as a result of the chemical reaction. (The term *precipitation* is used in the chemistry course to refer to the formation of an insoluble salt that is produced by mixing two or more aqueous solutions together).

Conclusions and implications for teaching and research

Despite the limitations of this study that involved students from a single school, the findings about the efficacy of the diagnostic instrument make a significant, albeit limited, contribution to our knowledge about evaluating high school students' proficiency in using multiple levels of representation when describing and explaining chemical reactions. Analysis of students' responses to the items in the RSCRDI has shown, that despite efforts during instruction to facilitate students' use of multiple levels of representation, several student conceptions still persisted among the students who were involved in this study. Administration of the RSCRDI to evaluate students' understandings about the use of multiple levels of representation will provide useful information to teachers in the planning of classroom instruction by incorporating strategies that challenge students' conceptions in order to engender more meaningful understandings.

The resistance to change of students' conceptions is not unexpected as these conceptions are deep-rooted and often "*difficult to shift, and can offer a serious barrier to effective teaching*" (Tytler, 2002; p. 15). For example, students in this study demonstrated confusion between macroscopic and submicroscopic representations when they suggested that the metal magnesium (instead of the particles in magnesium) has a charge of +2 (please see the earlier section on the burning of magnesium ribbon for the likely reason for this confusion), and that iron and chlorine atoms turned green when iron powder reacted with dilute hydrochloric acid.

In other instances students displayed a tendency to extrapolate the bulk macroscopic properties of matter to the submicroscopic level by suggesting for example that insoluble, reddish-brown atoms of copper were produced in the displacement reaction between zinc powder and aqueous copper(II) sulfate. They also attributed the fading of the blue colour of the solution to the removal of individual *blue* Cu^{2+} *ions*, as a result of extrapolating the blue colour of the bulk solution to the submicroscopic level of representation.

Students were also relatively uncertain about the significance of symbolic representations, especially with regard to ionic equations. This weakness was evident in their understanding of the reactions between different pairs of strong acids and strong alkalis, different metal oxides and different dilute acids and the ionic precipitation of lead(II) iodide on adding aqueous lead(II) nitrate to aqueous solutions of different iodides. Despite a special teaching program to address these issues, it was not evident to several students that the changes at the submicroscopic level were essentially the same for each pair of reactants, and that as a result the ionic equation was identical in each case.

On the positive side, analysis of students' responses on the diagnostic test indicated, in several instances, students' ability to use multiple levels of representation to describe and explain the chemical reactions. For example, in the reaction between a strong acid and strong alkali, most students were able to relate the changes at the macroscopic level (production of a solution neutral to litmus indicator) to the changes at the submicroscopic and symbolic levels of representation (removal of equal numbers of H^+ ions and OH^- ions from aqueous solution). In another example involving the reactions of aqueous lead(II) nitrate with aqueous solutions of potassium iodide and sodium iodide, respectively, students were generally able to associate the same observed change at the macroscopic level (the production of a yellow precipitate of lead(II) iodide) in both reactions to the same change at the submicroscopic level using symbolic representations (removal of Pb^{2+} and I^- ions represented by the same ionic equation).

Several implications for classroom practice are evident from the results of this study. First, the findings about the efficacy of the RSCRDI in assessing students' proficiency in using multiple levels of representation could contribute to the professional development of chemistry teachers. The instrument could be used prior to or after classroom instruction to identify student conceptions when they use multiple levels of representation. Based on the findings, teachers could plan and institute relevant measures to reduce the incidence of their students' misunderstandings in the use of multiple levels of representation.

Second, there is a need to place greater emphasis on the correct use of multiple levels of representation when describing and explaining chemical phenomena during classroom instruction. All too often teachers take it for granted that students are able to switch back and forth between levels of representation with ease. This study has shown that this was far from the case when students described and explained chemical reactions. The findings of this study could facilitate teachers in their planning and implementation of relevant measures to reduce the incidence of their students' misunderstandings in the use of multiple levels of representation.

Third, students should be provided with opportunities to perform the chemical reactions themselves and discuss with their peers the observed changes in terms of the particles involved. Following this, discussion of the multiple levels of representation associated with the corresponding chemical equation for the reaction should be emphasized. The performing of additional similar chemical reactions by students themselves or as demonstrations by the teacher could help further consolidate students' conceptions. For example, using several metal oxides to react with different dilute acids will help illustrate the similarities in the chemical reactions although different salts are produced. Once students are aware of the similarities in the chemical reactions, deducing the ionic equations for the reactions would become a more meaningful endeavour than the common practice of 'cancelling out' the 'spectator ions' from the overall balanced chemical equation.

Fourth, classroom instruction may be organised in a manner that takes into account student conceptions similar to the ones that have been identified in this study. When directly confronted with conceptions that students realise are not scientifically acceptable and through discussions with the teacher and with peers in small groups, students may be led to arrive at more fruitful understandings of the changes that occur in chemical reactions.

Finally, the use of multi-media software and computer animations that illustrate the changes that the atoms, ions and molecules undergo during chemical reactions can further reinforce the relationship between the observed changes and the changes at the particulate level (Ardac and Akaygun, 2005, 2006; Tasker and Dalton, 2006). In addition, several commercially produced software packages and materials from the internet, after prudent evaluation to ascertain their suitability, provide additional resources for teachers. (See for example, Interactive Courseware for Chemistry, Acids and Bases, and Qualitative Analysis on http://www.cool-science.net).

For successful implementation of the suggestions discussed above, curriculum planners have the responsibility to consider the formulation of syllabuses that take into account research findings in science education that promote student learning with understanding rather than accumulation of knowledge that is rote-learned. In the absence of such considerations, efforts to engender meaningful learning during classroom instruction at all levels are unlikely to be realised.

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Use of a multimedia DVD for Physical Chemistry: analysis of its effectiveness for teaching content and applications to current research and its impact on student views of physical chemistry

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Abstract: In this study, a new multimedia learning tool for physical chemistry was implemented in a class setting, and students' attitudes and learning gains examined. The *Physical Chemistry in Practice* (PCIP) DVD contains multimedia modules that provide an in-depth description of the research of eight different scientists. Each module contains a documentary style video program of the researcher and their laboratory, HTML-based background information about the topic, problems for students to work on, and links to related information. The DVD was implemented in a physical chemistry laboratory course where students worked through a module on surface-enhanced Raman spectroscopy (SERS). Data was collected in the form of pre- and post-tests of content knowledge and surveys about attitudes and academic career choices. Students showed statistically significant learning gains after using the DVD and showed an increase in their recognition of the applications of physical chemistry to real problems. Students also showed an increased interest in further study of physical chemistry. [*Chem. Educ. Res. Pract.*, 2007, **8** (3), 308-326.]

Keywords: physical chemistry, multimedia, surface-enhanced Raman spectroscopy (SERS), DVD, attitudes, learning gains

Introduction

Great strides have been made in the field of physical chemistry that are not included in traditional college courses, such as: nanotechnology, novel materials, advances in laser techniques, and photolithography. Exposure to these topics may give students a more complete view of the field and the value of research in it. Without students being introduced to applications or current work, physical chemistry may continue to seem overly abstract to them. Many educators called for inclusion of new physical chemistry research and applications in undergraduate curricula (Moore and Schwenz, 1992; Schwenz and Moore, 1993; Zielinski and Schwenz, 2004). Others have adapted teaching and learning advances used in other courses for physical chemistry (Moog et al., 2004a; Moog et al., 2004b).

In a different area of educational research, instructional technologies have begun to see increased use and support. Using Mayer's Theory of Multimedia Learning (Mayer, 2001, 2002) and other related work (Atkins, 1993) as a basis, multimedia instruments can be developed that will allow students to learn in a learner-controlled environment. However, in order for the technology to contribute to a rich and effective learning experience, research must be done to determine how students learn from technological tools, and how the technology can be designed to benefit the student best. In this article, we examine student use of a multimedia learning tool designed for the physical chemistry course, and look at aspects of that tool that assist with student learning and student views of physical chemistry.

Physical chemistry curriculum reform

Physical chemistry has traditionally been taught as a very mathematics-intensive, conceptually abstract course. Many innovations in the field of physical chemistry have been omitted from the curriculum, and other traditional topics – electrochemistry, pressure-volume work, phase diagrams – remain. Researchers and physical chemistry educators have advocated modernizing the physical chemistry curriculum and making the undergraduate courses more relevant to the work that current physical chemists practice (Zielinski and Schwenz, 2004). It is clear that not all important topics in the area can be given in-depth coverage in a one-year course, which is the time allotted at many institutions in the US. Refocusing educational goals will ensure that the students will learn the basic information necessary for them to succeed in industry or graduate school, as well as be exposed to current topics of physical chemistry research. Topics that Zielinski and Schwenz felt were important for inclusion in the new physical chemistry curriculum included polymer chemistry, materials science, nanomaterials, Bose-Einstein condensates, computer visualization, molecular modeling and computational programs, Raman spectroscopy, atomic force microscopy, photolithography, and atmospheric chemistry.

In 1992, the decline in the number of physical chemistry students was partially attributed to the fact that the immense progress of physical chemistry was not being communicated to students (Moore and Schwenz, 1992). Moore and Schwenz wrote that if the teachers of physical chemistry informed undergraduate students about the cutting-edge topics and opportunities in research, more students might pursue physical chemistry in graduate school. The authors believed that the traditional method of focusing on the mathematics and not utilizing microscopic explanations of chemistry makes the physical chemistry course appear, from the students' point of view, to not be chemistry.

Research has also been done on what factors influence student success in physical chemistry, as well as what factors make physical chemistry a difficult course. A qualitative study was conducted at two universities in Turkey to find what undergraduate students and lecturers felt made physical chemistry a difficult course, and what solutions they would propose to lessen these difficulties (Sozbilir, 2004). Students and lecturers both agreed that difficulties in physical chemistry arose from the abstract nature of the concepts covered, an overload of the amount of course content, teacher-centered teaching, and lack of student motivation. Students overwhelmingly said that they wished physical chemistry instruction would make more links between course content and everyday life, because they believed this would make the topics easier to learn.

Based on documented difficulties that students face in the physical chemistry course (Nicoll and Francisco, 2001; Derrick and Derrick, 2002; Sozbilir, 2004), several different types of innovations for the physical chemistry curriculum have been proposed. Pentecost and James (2000) moved towards a more student-centered classroom, using small-group discussions and problem packets. Group and individual interviews showed that students felt the system forced them to study in a new and more useful manner. Two books have been written (Moog et al., 2004a; Moog et al., 2004b) for teaching physical chemistry classes based on the Process Oriented Guided Inquiry Learning (POGIL) model (Hanson and Wolfskill, 1998; Farrell et al., 1999). A group of colleges and universities implemented Physical Chemistry Online (PCOL). In PCOL activities, students grappled with authentic context-rich problems while working in cooperative groups within their institution. They collaborated with students at other institutions via a list server available on the Internet, which allowed small (ten students or fewer) physical chemistry classes to discuss problem solving strategies within a larger group (Long et al., 1996; Stout et al., 1997; Towns et al., 1998; Sauder et al., 2000; Towns et.al., 2001; Slocum et al., 2004). The richness of the on-line discussion allowed the group to generate faculty facilitation guidelines (Slocum et al., 2004). Other than this use of the internet, however, relatively little work has resulted in the development or use of instructional technologies specifically for the physical chemistry course.

Multimedia development and implementation

An early overview of multimedia educational tools revealed a disparity between current theories of learning and the format in which most multimedia tools are created (Atkins, 1993). Atkins stated that the design of multimedia educational tools followed a behaviorist approach, whereas cognitive theory had already made a shift to a constructivist view of learning. Atkins referenced cognitive theory, by which he was referring to a broad swath of theories in learning and psychology, mainly information processing and social constructivism. He argued that the design of multimedia tools should draw from the current findings of this cognitive theory.

Richard Mayer elaborated on the cognitive approach to multimedia design (Mayer, 2002, 2005; Robinson, 2004). In order for multimedia instructional tools to be most effective in promoting understanding, Mayer stated that the developers must take into consideration three assumptions about the way people learn and process information in a multimedia setting: the dual channel assumption, the limited capacity assumption, and the active processing assumption. Mayer called this the “Cognitive Theory of Multimedia Processing”. Using these assumptions to describe how the human mind receives and constructs information, Mayer proposed eight principles of multimedia learning that can be used to ensure that multimedia instructional tools are designed to promote meaningful learning (Mayer and Anderson, 1991, 1992; Mayer and Sims, 1994;; Mayer and Moreno, 1998; Mayer et. al., 1999; Moreno and Mayer, 1999, 2000; Mayer et al., 2001; Mayer and Chandler, 2001; Mayer, 2001, 2002, 2005). These were used as guiding principles to design the multimedia instructional tool for the physical chemistry course that we present in this paper.

Purpose of this study

The *Physical Chemistry in Practice* Digital Video Disk (PCIP DVD) was developed specifically to utilize new technology to inform students about physical chemistry and its applications in modern research. This study investigated the effects of the DVD on student learning of the physical chemistry content covered in the DVD and on student perceptions about the subject. In order to determine if the PCIP DVD is an effective educational tool, three research questions were posed:

1. How do students perceive the usefulness of the PCIP DVD as an assignment in a physical chemistry laboratory course?
2. How does student understanding of a physical chemistry topic differ before and after using the PCIP DVD?
3. How does the DVD affect student views on the applicability and connections of physical chemistry to life?

In this article we report on one approach to including topics from current research and incorporating the use of multimedia in the physical chemistry course. As was described above, these are issues that have been discussed among educators for some time. However, what has not been resolved is how the methods and tools for doing that will work. Therefore, this work represents one aspect of a project in which we are beginning to assess the impact of a tool to accomplish just this. The results are useful to inform us not only about this tool, but about the design and use of future tools of a similar nature.

The Physical Chemistry in Practice DVD

The Physical Chemistry in Practice (PCIP) DVD was created as a supplement for physical chemistry courses with the goals of introducing the topics of interest that curriculum reformers suggested (Moore and Schwenz, 1992; Zielinski and Schwenz, 2004), as well as helping students understand real-world applications of physical chemistry theory. The DVD comprises eight modules, each of which is based on actual research being carried out by scientists nationwide in academia or industry, and relates to some fundamental topic in physical chemistry. Each module explores the research project being carried out with respect to both the fundamental theories involved and broader applications of the work. Topics include surface enhanced Raman spectroscopy, atomic force microscopy, thin-film kinetics of photolithography, Bose-Einstein condensates, electronic structure of corrinoids and Vitamin B_{12}, single molecule thermodynamics of DNA, hydrogen fuel cells, and magnetic resonance imaging. At the time of writing this, several modules are still in development.

The PCIP DVD is different from traditional educational videos, which are designed for passive watching (see, for example, videotapes and videodiscs at JCE Online). The PCIP DVD uses a relatively new interface that allows it to be interactive and show additional information along with the video. A hybrid interface was used that allows for simultaneous and synchronized display of full-featured DVD video along with web content. The program can be used to automatically cue particular content at specific times during the video, which is useful for providing definitions or links that correspond to topics in the video. An internet connection is not necessary, as the interface uses all the files (both HTML and DVD video format) from the disc itself. (Additional information about the DVD is provided in the Appendix.)

This interface allows the DVD to contain video of the scientists explaining and showing their research, as well as textual explanations of background theory, equations and a glossary of terms. Multiple formats of graphical information can be included either embedded as part of the videos, or in the HTML-based files, including high-quality three dimensional animations of molecular-level visualizations or simulations of the internal working of instruments. Each module also contains problems for students to work on that are related to the content of the video. In some cases, they are asked to analyze authentic data from the research. A text transcription (script) of each video is also provided. The sections of the DVD are summarized in Table 1.

Table 1. Sections of the PCIP DVD.

Section of PCIP DVD	Information Contained in this Section	Format
Video	Multi-chapter video including scientists explaining their research, three dimensional animations, graphs, and footage of research being conducted	DVD video
Theory	Text book-like explanations of equations and theory necessary to understand the research	HTML
Glossary	Listing of terms and definitions, hyperlinked from theory pages	HTML
Animations	Animations from the video available to be viewed separately	DVD video
Problems	Homework or project-like questions, based on actual research shown in the video, including authentic data to be analyzed by the student	HTML
Script	Transcription of narration in the video segments	HTML
Timed links	Interactive links cued to specific parts of the video, allowing connection to glossary, theory, or external web pages for additional information	HTML
References and credits	List of literature references and production credits for the video	HTML

The interface design of the DVD allows students the freedom to navigate the material in myriad ways. Figures 1 through 3 show screen shots of the menu and content pages (these are discussed in greater detail in the Appendix). The video content is divided into chapters, along with the corresponding theory and glossary information. Students could choose to view the video chapters in order, then view the additional theory information later, or the video and information for each chapter can be viewed together. The format of the DVD allows students to control the way they access the material, including when and how often they view particular parts of the content, giving them the capability of interacting with and participating in their learning environment.

Figure 1. Main menu of the DVD interface, showing a link to each module. In this image, the user has rolled over the menu button for the SERS module, which becomes enlarged and outlined.

Figure 2. The module menu, showing the main components of the module (on the left) and a list of individual chapters within this module (on the right).

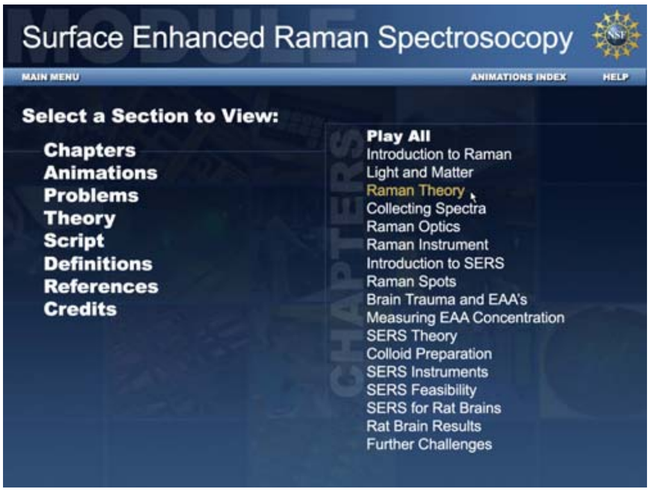
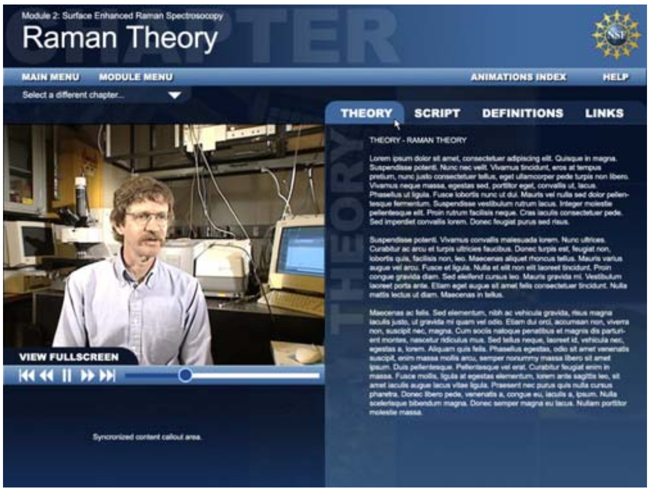


Figure 3. The main viewing screen for a module chapter. The video can be viewed here in a split-screen fashion that also simultaneously displays the theory, script, or definitions in separate tabs. The video can also be expanded to full screen view.



The PCIP DVD was designed using several of Mayer's multimedia design principles. Both the multimedia principle, which encourages the use both words and images, and the contiguity principle which suggests they should be present simultaneously (Mayer and Anderson, 1991; 1992), are evident in the design of the main chapter viewing area in which words (in both audible and written form) are present with images (either video or animations). The modality principle states that animations are more effective with narrated rather than written text (Mayer and Moreno, 1998; Moreno and Mayer, 1999). Since the PCIP DVD animations are integrated into the video, the video narration is used in explaining them. The interactivity principle suggests that students should be able to control the pace and order in which material is received in order to maximize learning (Mayer and Chandler, 2001). In the PCIP DVD, students can access any part of the material in any order that they choose. They can watch videos as often as they would like, and can scan through them using the slider bar.

Background to the present study

One of the main educational goals of the PCIP DVD is to show students the connections between the abstract, mathematical content of physical chemistry courses and real-world applications. With information about concrete applications of the concepts, students may be able to better understand the physical chemistry course. Three DVD modules (Atomic Force Microscopy, Surface Enhanced Raman Spectroscopy, and Thin-Film Kinetics) were previously implemented in courses and evaluated between Fall 2002 and Spring 2005 at two universities (Dyer, 2005; Dyer et al., 2007). In that study, students' attitudes and content learning were evaluated. Dyer found that students' content knowledge increased with the viewing of the DVD, and that the majority of students had positive attitudes about the usefulness of the DVD for their learning and showed excitement about using similar technology to learn other topics. However, in the Dyer studies the students used the DVD individually outside of a class setting, and there was no impact on their grade. All the students in that study were chemistry majors. The user interface in that study was very rudimentary, and many of the findings from that work helped us to revise the user interface into its current form. In this study, we looked at the DVD as a replacement for a laboratory activity in a course where students have a combination of majors. The first was essentially a pilot study and this study represents a step toward a more authentic use of the disc.

The module used in this study, Surface-Enhanced Raman Spectroscopy (SERS), is based on the work of Gerard Coté (O'Neal et al., 1999, 2000; O'Neal et al., 2003) at Texas A&M University. Their work explores the use of SERS as an alternative for analyzing excitatory amino acids in patients suffering from brain trauma. In some forms of head injuries, the presence of elevated levels of glutamate and aspartate in the cerebrospinal fluid indicates a need for pharmaceutical intervention. However, the interventions would be dangerous if these elevated levels are not present. The current method used for detection is often too slow to allow for effective treatment, while SERS could allow for accurate analysis in minutes. The module contains background information on the fundamentals of Raman, SERS, and metal colloid surfaces, as well as specifics about the medical applications of SERS. A comparative study is shown, in which the current method of analysis (HPLC separation, chemical tagging, and either IR or UV/visible spectroscopy) is compared to SERS. SERS requires much less time to perform the analysis, and has a slightly higher sensitivity than the current method. There is some disparity between the methods as to the quantitation of the highest excitatory amino acid concentration, which is presented to students as a data analysis problem for them to work on.

Methodology

Participants and setting

Data were collected during the spring 2006 semester at Purdue University. All participants were undergraduate students in the physical chemistry laboratory course. This course is populated by chemistry and chemical engineering students, who also take one of several physical chemistry lecture courses available. The laboratory course consists of one 50-minute lecture period per week and one 3-hour lab period per week. Two lab sessions are used to complete each experiment; the first week is used to collect most of the data, the second week is used for additional data collection, data analysis, and write-up. The 2006 spring semester course consisted of eight lab sections with three to ten students in each.

Table 2. Demographics of student participants; total number of students is 58.

Sex		**Race/Ethnicity**	
Male	33	White	46
Female	25	Asian	7
Age		Hispanic/Latino	1
19	2	African American	2
20	7	No Answer	2
21	30		
22	15	**Major**	
23	3	Chemical Engineer	25
≥24	1	Chemistry	16
Mean age	21.3 years	Chemistry Education	2
Year in school		Dual Chem/ChemE	1
2nd/sophomore	3	Biochemistry	8
3rd/junior	21	Dual Chem/Biochem	5
4th/senior	30	Other	1
5th	4		

The demographic information for those who participated in this study is detailed in Table 2. The course has a majority of male students, but has a typical distribution for a third/fourth year course with respect to age. Typical of the institution itself, the students in this course are predominantly White, non-Hispanic. The majority of the students are in major fields that are strongly allied with chemistry, which will have an impact on how they perceive and use the DVD.

SERS module implementation

During week 14 of the semester, the SERS module of the DVD was used by students during the laboratory period in place of a 'wet' laboratory experiment. Each student had individual access to a Macintosh G5 desktop computer on which the DVD had been loaded before class by the researchers. Headphones were provided so the students could listen to the narration on the video without disturbing other students. Students were able to view the DVD in any order they chose for the full laboratory period, and could take notes on the material. No printing capabilities were available to the students.

Survey data collection

Three surveys, developed by the author, were given during Weeks 2, 9, and 15 of a 16-week semester. The surveys consisted mainly of free response questions. The free response questions of Survey 1 asked students what they expected to learn in the course, what they had heard from peers about the course, and what difficulties they expected. Demographic information was also collected in Survey 1. Survey 2 asked the students what they had learned thus far in the course, what they expected to learn during the remainder of the semester, and what connections they saw between physical chemistry and real-world issues or their other coursework. On Survey 3, students were asked to compare the DVD module to other laboratory activities and to describe what aspects of the DVD were useful and not useful for their learning. This survey also asked them, again, about connections they saw between physical chemistry and other experiments. Two questions, "*would you pursue a career in physical chemistry?*" and "*would you take additional courses in physical chemistry beyond those required?*" appeared on all three surveys and consisted of a 5-part Likert-scale response ("definitely not" to "definitely"), followed by a free response explanation.

Learning gains data collection

In addition to the surveys described above, at the beginning of the laboratory period of week 14, students were given a pre-test consisting of twelve questions covering SERS and Raman spectroscopy. The students had been given a lecture earlier in the semester about Raman spectroscopy (week 12) and had performed a laboratory activity using conventional Raman spectroscopy (weeks 12 and 13). The pre-test was administered by the researchers before students were given access to view or use the DVD. If unsure of an answer, students were directed to write "*I don't know*" rather than leave the answer area blank. After completing the DVD, during the same laboratory period, they were given the post-test, which was identical to the pre-test. The students were allowed to go back to the DVD if there were questions that they could not answer based on their recollection or notes. The students were advised that their notes would be useful for studying for the final exam as well. The questions for the pre- and post-test are shown in Table 3.

Table 3. Questions for the pre- and post-test.

Questions
1. Explain how the photon/molecule interaction in the Raman process results in a signal.
2. Describe the signal enhancement process in Surface Enhanced Raman Spectroscopy (SERS).
3. Why does Raman spectroscopy require a high intensity light source?
4a. Place the following analysis methods in the order of largest detection limit to smallest detection limit: Conventional Raman, Conventional IR, and SERS
4b. For each of the analysis methods in 4a above, please include the improvement (order of magnitude) in detection limit over the previous one.
5. Of the 20 naturally occurring amino acids, what is special about aspartic acid and glutamic acid?
6a. Clinically, what is the single greatest advantage of the SERS method detection of excitatory amino acids (EAA's) over the conventional high performance liquid chromatography (HPLC)/infrared spectroscopy method?
6b. Why is that advantageous?
7. Using Raman spectroscopy, how are the two EAA's glutamate and aspartate distinguished?
8. Explain the variables that could complicate the experiment described in this module?
9. SERS might be a feasible technique to observe events other than brain trauma. What other kinds of events could be included in this list?
10. In relation to the Raman effect demonstration, explain the problem solving process involved in using Raman spectroscopy to distinguish between two samples, for example benzene and toluene.

Anonymity and scoring of student data

Students were given randomly assigned three-digit code numbers in order to keep their responses confidential. Students used their code numbers on the surveys so that each student's responses could be followed throughout all three surveys. Each survey and pre-test was worth a minimal number of points based only on completion of the instrument, and these counted towards the students' final grade. No staff associated with the course or with the assignment of grades were allowed to see the surveys. The post-test content questions were graded by the course teaching assistants and were included as a laboratory assignment score. All surveys and content tests were then scored independently by the researchers for the purpose of this study.

Data analysis

Survey responses were transcribed verbatim and coded using QSR N-VIVO® software. Each student's responses to Question 7 (Would you pursue a career in physical chemistry?) and Question 8 (Would you take additional courses in physical chemistry beyond those required?) were also analyzed for any changes in responses over the semester.

The data from the pre- and post-tests were scored in the same manner as previous DVD evaluations (Dyer, 2005; Dyer et al., 2007), based on the work of Abraham (Abraham, 1992; Abraham and Williamson, 1994). This system uses a scale of 0-5, where 0 is assigned a 'no response' answer, and 5 is assigned a fully correct answer. The scoring scheme is shown in Table 4.

Inter-rater reliability was established by having the researchers independently score three students' pre- and post-tests and then compare results. Scoring was conducted on three sets of data until 90% agreement (100% within 1) was reached. After scoring, each set of data was analyzed using Statistical Package for the Social Sciences (SPSS) for Windows®.

Table 4. Scoring scheme for pre- and post-tests.

Numeric Score	Degree of Understanding	Criteria for Score
0	No Response	Blank, “I don’t know”
1	No Understanding	Irrelevant or unclear response
2	Specific Misconception	Responses that include illogical or incorrect information
3	Partial Understanding with Specific Misconception	Responses show understanding of concept, but also make statements which demonstrate a misunderstanding
4	Partial Understanding	Responses that include at least one component of the validated response, but not all the components
5	Sound Understanding	Responses that include all components of the validated response.

Results and discussion

Connections between the laboratory course and other areas

Throughout all three surveys, several trends became apparent about what students want from this laboratory course. Students’ belief that there should be an explicit connection between laboratory and lecture material was very evident. Even though the laboratory course is designed to be a stand-alone course that students with varied physical chemistry backgrounds take, students seem to want parallels drawn for them between the thermodynamics or quantum mechanical concepts taught in their physical chemistry lecture courses. Most of these students are in their third or fourth year of undergraduate study and are beginning to consider a position in industry or attending graduate or professional school. Having a chance to see how theory applies to problem-solving situations they may be faced with in their career is important to them.

> *In this class I expect to finally see how the concepts and equations I learned in [physical chemistry lecture courses, I and II] work in practice. This includes any number of concepts in thermodynamics and quantum mechanics (Student 607).*

Students stated that they either wanted to learn or expected to enjoy learning how physical chemistry related to ‘the real world’. This phrase, or a variation of it, was often used; however, the students rarely defined it, so we do not know whether they were speaking of the world of chemical problems, everyday issues that all people face, larger societal issues, or many other possible meanings. For example, one student stated:

> *Real life stuff. Yes I might have learned what an RTD [resistance temperature detector] is but now let me use it for something real. And I guess a big problem is I am a CHE [chemical engineer], I don’t want to do research, but in a lab, so I like real things (Student 406).*

An interesting aspect of this desire is that rarely, if ever, do the students say which ‘real world’ problems they would like to solve, or how they think it should apply. Also, some students say that they can apply physical chemistry to ‘real life’, but they never specifically say what concepts they can apply or to what aspect of ‘real life’ the concept can be applied.

On Survey 2 and Survey 3, after the students had some experience with the physical chemistry laboratory course and any other physical chemistry courses in which they were enrolled during the semester, the students were asked what connections they could see between physical chemistry and their lives or the world around them. For this question on Survey 2, the most common answer was included in the coding scheme as “generic connection”. Many students (15 students, 25.9%) responded with what seemed to be a very ambiguous, uninformative general statement, such as:

> *It seems like PChem is used in every aspect of everyday life (Student 307).*

Some of these vague responses were very elaborate, but still did not explain what connections the student saw.

> *Physical chemistry has taken my satisfaction and amazement of this universe to a new level (Student 429).*

Other students responded with very specific situations and topics such as refrigeration (3 students, 5.2%), engines, fluorescence, medicine, meteorology, nanotechnology, and phase changes (1 student each, 1.7%). None of these students provided any details, but because of the specific nature of their responses, it would seem as though they had been exposed to these applications in other situations. A large number of students (19 students, 32.8%) stated that they saw no connection between physical chemistry and their lives.

On Survey 3, there were still a large number of students (15 students, 25.9%) who responded with a generic physical chemistry connection. A much larger group of students mentioned a connection between physical chemistry and the medical field (15 students, 25.9%). This increase was most likely due to the use of the DVD the week previous to the survey, where the module specifically showed the use of Surface Enhanced Raman in a medical setting. Eleven students (19.0%) still said they saw no connection. The increase in the number of students who see a connection between physical chemistry and the world around them supports the use of an approach, such as the one facilitated by this DVD, which makes explicit connections between physical chemistry theory and its research and ‘real world’ applications. The fact that students made connections to topics that were explicitly described in the DVD suggests that this tool is effective for this purpose.

Physical Chemistry as a career or field of study

The responses to the 5-point Likert-scale questions asking “*would you pursue a career in physical chemistry?*” and “*would you take additional courses in physical chemistry beyond those required?*” were tallied and a paired samples t-test was conducted to examine if there was a significant difference between the answers from Survey 1 and Survey 3. Both the physical chemistry career question (n=58, t=-3.446, p=0.001) and physical chemistry course question (n=58, t=-6.343, p<0.001) showed a significant change in the distribution. For both questions, the results were consistently weighted toward ‘definitely not’, with a shift occurring toward the positive end of the scale in Survey 3. These results can be seen in Tables 5 and 6. Overall, from Survey 1 to Survey 3, there is a decrease in the number of ‘definitely not’ responses. On the physical chemistry course question, there is an increase in the number of ‘maybe’ and ‘likely’ responses. These shifts are statistically significant, indicating that students had a less negative attitude toward physical chemistry by the end of the semester. Furthermore, the shift was not statistically significant until after the students viewed the DVD, indicating that this multimedia tool may have had an impact on student attitudes toward the course.

Table 5. Results for question "*would you pursue a career in physical chemistry?*"

	Survey 1	Survey 2	Survey 3
Definitely not	20	19	15
Unlikely	26	26	29
Maybe	12	9	11
Likely	0	4	3
Definitely	0	0	0

Table 6. Results for question "*would you take additional courses in physical chemistry beyond those required?*"

	Survey 1	Survey 2	Survey 3
Definitely not	30	20	19
Unlikely	16	23	17
Maybe	10	9	17
Likely	1	6	4
Definitely	1	0	1

The most common explanation for the large number of 'definitely not' responses was that the students had no interest in physical chemistry.

Definitely not. Subject matter does not interest me at all (Student 674).

Another common reason that appeared was that these students did not want a career based in research and laboratory bench work.

Definitely not. It's interesting, but I don't want to spend my life locked in a lab with a chalkboard assembling a laser or a math proof (Student 527).

Students also had plans for other careers in which they had more interest, even if physical chemistry held their interest.

Unlikely. I have other plans lined up, and while PChem is interesting, I do not know that I would make a life of it (Student 953).

The students who showed interest in pursuing a career in physical chemistry (those who responded as 'maybe' or 'likely') explained their choice mainly in terms of their interest in the topic.

Maybe. I have so far found it [physical chemistry] very interesting, prior to this course the answer would have been definitely not (Student 906).

Some students also described their interest in physical chemistry in terms of the value of the field itself.

Likely. It's [physical chemistry] a good blend of theory and practice, yet seems fundamental to the rest of chemistry (Student 685).

The students who showed some interest in taking additional physical chemistry courses (those who responded as 'maybe', 'likely', or 'definitely') explained their position primarily in terms of the course content capturing their interest.

Maybe. PChem is very interesting to me (Student 355).
Likely. I like the discussions and the new topics that I haven't heard of before (Student 116).
Definitely. It's a very exciting topic and field (Student 685).

Questions about the usefulness of the PCIP DVD

On Survey 3, students were asked to list the aspect or aspects of the DVD that were the most useful for their learning. The response given by the largest number of students to this question (15 students, 25.8%) was that the video component of the DVD was the most useful. Eleven students (19.0%) stated that the animations were the most useful.

> *Several of the diagrams/charts/visual aids proved quite useful to enabling better understanding of the concepts (Student 914).*

Ten students (17.2%) said the script was the most useful. One student who felt the script was useful said,

> *The end [was the most useful] where you can navigate through each different chapter and look at what they talked about in words [the script]. I learned a lot better by reading what they said (Student 766).*

Since reading the script is much like reading a textbook, it was surprising that such a large proportion of students found it more useful than the video, which includes animations and visual examples. Mayer (2002) suggested that the combination of visual and audio should help create the most useful multimedia learning situation, but these students did not take advantage of this multimedia learning, choosing instead to use the more traditional, written materials.

Six students (10.3%) said the navigational abilities of repetition and control over the flow of information were the most useful. Having both video and script allowed the students to control the format through which they could obtain information, enabling them to interact with the information to best suit their learning styles. A student described why this was his preference:

> *The ability to go back and see things a couple of times to make sure I understood the material (Student 719).*

Five students (8.62%) said the use of the script and the video together was the most useful.

Aspects of the DVD perceived not to be useful

Students were also asked to state which aspect or aspects of the DVD they did not find useful. Rather than identify a section or component of the DVD, the students instead said the scientists on the video (14 students, 24.1%) and their monotone voices (6 students, 10.3%) were not useful for their learning. The scientists in the videos had been reading a teleprompter. This tended to make their dialog seem non-conversational. One student's response was characteristic of all responses:

> *Staring at the monotonous emotionless boring speakers talk during the video (Student 363).*

Eleven students (19.0%) said that all parts of the DVD were useful for them. This shows that this group of students was open to the use of the DVD as a learning tool, even though a number of students (17 students, 29.3%) said that while it provided them with new information, it was not a good substitute for a hands-on laboratory activity. Rather than identifying certain aspects as not useful, many students gave suggestions as to what they would prefer, such as:

> *I felt disorganized going through it. I would have rather seen all Ch 1 (movies, theory, figures, etc) then move on. I know I could have done this, but I wanted to simply click next and have that occur (Student 251).*

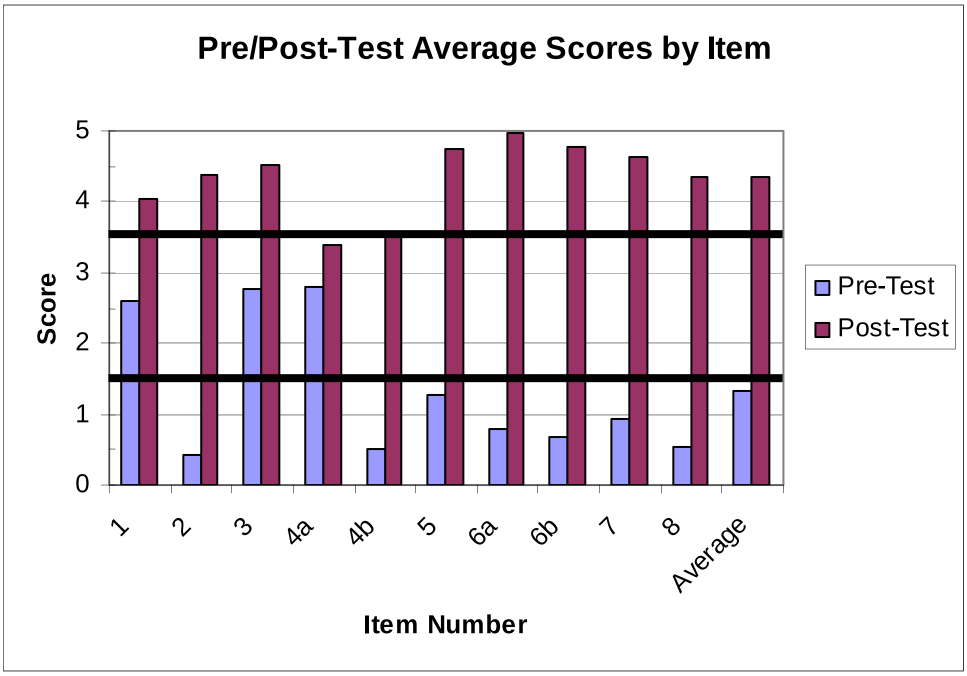
This student's quote is interesting, in that s/he did not want the level of navigational freedom that our interface provided, which contradicts much of the research in multimedia design. While providing flexibility in navigation allows the material to be used in different ways by different students in order to suit their learning needs, certain individual students may desire a prescribed order for viewing the material.

Learning gains data

Students' responses on both the pre- and post-test forms were scored on the 0-5 point scale described earlier. Even though each form had twelve questions, only the first ten were scored (1-8 in Table 3). Two questions were not scored because they could be answered in a much broader manner and still be considered correct; there was no single correct answer. The scores for the remaining questions were tallied for all participants (N=58). The overall pre-test average was 1.3, and the overall post-test average was 4.3. Each question had a positive gain average, and the average gain for all questions was 3.0.

The numerical range can be described in three broad ranges, in order to simplify interpretation and illuminate patterns within the data. These ranges are shown with horizontal lines in Figure 4, such that the general level of understanding increases from the bottom to the top. The figure shows that every question except 4a shows a major change in the level of understanding, and there is an overall trend in the student responses toward the 'understanding' level on the post-test.

Figure 4. Graph of pre- and post-test average scores for each question and overall. Regions separated by the thick horizontal lines denote a rough demarcation from lower levels of understanding (bottom) to higher levels of understanding.



Statistical analysis

In order to determine if any of the gains on these questions were statistically significant, the Wilcoxon Matched-Pairs Signed Ranks Test was performed on the data. The Wilcoxon test is designed as a nonparametric alternative to a repeated measures t-test. The data presented here is considered nonparametric because the 0-5 values do not represent an even interval scale. For example, a score of 4 on this scale does not mean the response is twice as correct as a response scored as a 2. Instead of comparing means, scores are converted to ranks and compared at two different times (Pallant, 2001). All Z-scores are greater in magnitude than 1.96 standard deviations and all p-values are below 0.05. This means that the gain for every item is statistically significant.

Question analysis

For some questions, this shift to the 'understanding' level is more dramatic than for others. Questions 5-8 all show a major shift in category from a majority of the responses being categorized as 'no understanding' to 'understanding'. The answers to all the question numbers 5-8 were rather explicitly stated in the DVD material about the application of SERS to brain trauma analysis. Thus, these represent rote memorization learning. Questions 1 and 2 focus on the theory behind Raman and SERS, respectively. Since the students had performed a Raman experiment during the two weeks prior, many responses to question 1 were in the 'partial understanding' category, showing that the students remembered some of what they had learned previously about Raman spectroscopy. Question 2 shows a dramatic shift, showing that the students have learned about the process of signal enhancement in SERS, which is not something they were exposed to as part of their conventional Raman experiment. Questions 4a and 4b do not show as much of a shift in responses. These two questions (4a and 4b) required the most synthesis of any of the questions. The information about the sensitivities of different instruments necessary to answer these questions was distributed throughout several chapters of the DVD, and students had to find all the information, compare the sensitivities, and rank the instruments. This was obviously difficult for the students, as shown by the much smaller shift in response categories as compared to the other questions

Conclusions

Overall, the DVD can be considered to have been an effective multimedia tool for teaching concepts and research applications of physical chemistry, especially those that are not usually included in the curriculum. Students showed positive learning gains for the information contained in the DVD module. Because there was no other method of instruction provided between the pre and post tests, the learning gains are attributable to the use of the DVD and, to some degree, to the short amount of time that elapsed between the two tests. Because the learning gains described here were measured very soon after the students viewed the DVD, the information was still fresh in their minds. It will be necessary to perform a longitudinal learning study to find out how much of the information they will retain.

The number of students identifying specific applications of physical chemistry also increased. This cannot be completely attributed to the DVD, because students experienced other instruction between the surveys that asked them about applications. The same is true for shifts in students' interest in the field of physical chemistry. However, the interview data indicate that the DVD contributed to these positive shifts. Also, students stated that they felt the DVD was useful for their learning. Of the students who said the DVD was not completely useful for their learning, the overwhelming reason given was that the speaking style of the scientists interviewed in the video was monotonous. In newer modules, this issue has been addressed, and a much more conversational tone is used by the speakers, as well as much shorter time on camera ('talking head') interspersed with video, graphics and animations to help explain concepts.

The DVD in its current form does show promise as a tool for including new topics in the physical chemistry curriculum, as recommended by Zielinski and Schwenz (2004). It is a tool that is designed to be a supplement to a course, which allows for the inclusion of techniques, experiments or demonstrations that are not possible or feasible to be performed by students in the classroom or undergraduate lab. A good example of this is magnetic resonance imaging, which is carried out in specialized facilities with very expensive equipment, but which can be shown to students easily with the DVD module that covers NMR and MRI. The DVD was designed to serve as a supplement to the lecture and laboratory course, and this study demonstrates that it can be a useful tool when used in that way. Additional studies are planned that will examine the effects of using other modules on the DVD and will attempt to distinguish the effect of learning with the DVD from that of other educational interventions.

Acknowledgement

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Appendix

Figure A1. Main menu of the PCIP DVD.

The DVD can be used either in a computer that has a DVD player, or in a set-top DVD player connected to a television monitor. If used in a computer, the DVD will launch automatically using the NetBlender player. This is a file that is resident on the DVD and does not require any software to be loaded onto the computer. The player is designed to incorporate both HTML content and DVD video into the same interface. The opening screen is a graphical menu of the available modules, as well as links to the help pages and animations index (discussed below). Selecting and item from the main menu brings the user to the module menu, as show in Figure A2.

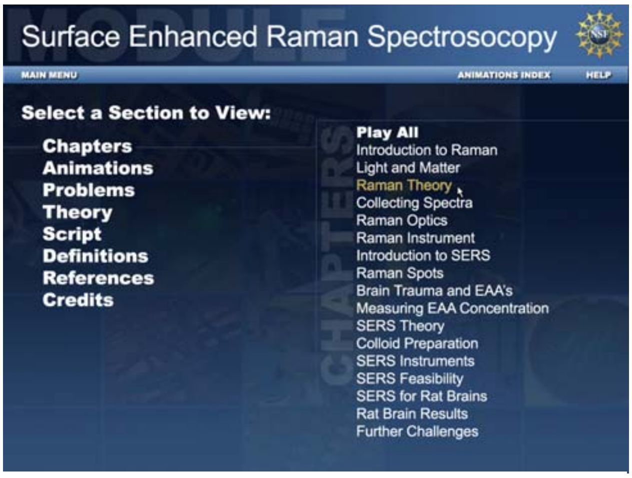

Figure A2. A typical module menu.

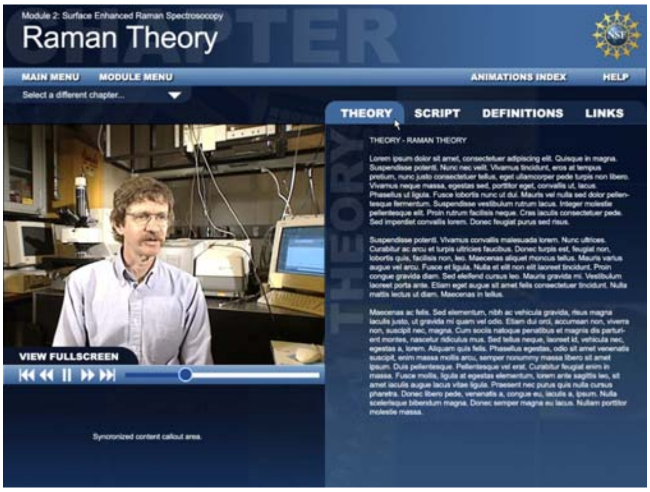

Figure A3. Chapter window with tabbed view.

Each module contains five main components, which are accessible through the module menu: video chapters, animations, problems, theory and script. When the 'chapters' link is selected, the screen gives a list of the chapters for that module on the right side of the screen (see Figure A2). Each chapter will open with a 'tabbed' view that shows the DVD video in a small window, along with the theory, script, definitions and links available as tabs next to it (Figure A3). The video can also be viewed full screen, and has all of the capabilities of standard DVD video with respect to resolution, flexibility in sizing, and random access to different time points in the program.

Animations that are associated with each module are integrated into the video content itself. However, these animations can also be accessed individually from the module menu or from the animations index link on the main menu. The animations index allows animations to be played '*à la carte*' either for students to review them or for demonstration purposes in the classroom.

The theory section of each module includes information about each section of the DVD module. These are linked to the curriculum materials that students will be learning in the classroom. The problems section of each module includes problems for students to work on that are related to the material in each module. The problems progress from fundamental concept problems up to data analysis problems that utilize the actual data collected by the scientists in the module. For example, for the AFM module, students are asked to calculate the force that will be felt by an AFM tip. In a later problem, they are provided with AFM images of an arsenic covered surface at different temperatures and asked to analyze the size distribution of the arsenic islands.

In addition to the main content continued in the chapters, the disc also contains a list of references, definitions and production credits for each module. The video component of this disc is a standard DVD video that can be accessed through any standard DVD player on a computer or on a television set-top player. If accessed in this way, only the video components will be available, along with a searchable menu. None of the ancillary information (script, theory, definitions, etc.) will be available when viewed in a standard DVD player.

List of modules

1. Atomic Force Microscopy to Examine Growth of Germanium Layers on Silicon. This video features the work of Prof. Stephen R. Leone, who was at the University of Colorado of Boulder at the time the video was created and is currently at UC-Berkeley.
2. Surface Enhanced Raman Spectroscopy to Examine Amino Acids in the Cerebral Spinal Fluid after Brain Trauma. This video features the work of Gerard Coté at Texas A&M University.
3. Kinetics of Photolithographic Polymers. This video features the work of Frances Houle and William Hinsberg at the IBM-Almaden Research Laboratories.
4. NMR and MRI applications. This module features the work of Jack Roberts at the California Institute of Technology and William Bradley at the University of California, San Diego.
5. Hydrogen Fuel Cells and Solid Acid Electrolyte Research. This module features the work of Sossina Haile at the California Institute of Technology.
6. Bose-Einstein Condensation. This module features the work of Eric Cornell at the University of Colorado at Boulder.
7. Spectroscopy of Vitamin B_{12} Cofactors. This module features the work of Thomas Brunold at the University of Wisconsin – Madison.
8. Thermodynamics of DNA and RNA single molecules using optical tweezers. This module features the work of Carlos Bustamante at the University of California, Berkeley.

Educational research

Combination of Phenomenography with Knowledge Space Theory to study students' thinking patterns in describing an atom[†]

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Abstract: This study compares Hungarian 7th to 11th graders' and American 9th to 11th graders' thinking patterns in describing an atom. A new evaluation method, the combination of phenomenography and knowledge space theory was used to explore students' reasoning and to follow the change in students' cognitive structures. According to the phenomenographic analysis of the responses, three main categories, 'units of matter', 'constituents of atoms' and 'model of atoms', were identified. Connections between these categories were determined by adapting Knowledge Space Theory to the hierarchy of categories. Results showed that during the instruction, the initial uniform model for representation of students' knowledge structure became more diffuse but at the end of the instruction the organisation of the categories in students' minds could be represented again by a single model. In the initial model, the 'units of matter' category was independent of the 'constituents of atoms' and 'model of atoms' categories, and the 'model of atoms' category was built on the category 'constituents of atoms'. Significant change in connections among categories could be detected only in the case of Hungarian students. In the reasoning of Hungarian 11th graders, the hierarchy between 'constituents of atoms' and 'model of atoms' was reversed. [*Chem. Educ. Res. Pract.*, 2007, **8** (3), 327-336.]

Keywords: phenomenography, knowledge space theory, students' thinking patterns, atom

Introduction

The atomic hypothesis is a primary concept of scientific knowledge. When we teach about atoms, we give the key to unlock many of the doors of the sciences. However, there is a lack of agreement about when students should be introduced to the concepts of an atom and molecule. There is a view (AAAS, 2001; Taber, 2002) that says the ideas should be left until near the end of the secondary school, because only a few students can comprehend the idea of atomic and molecular particles. Research in science education during the last twenty years has shown students' difficulties and misconceptions about the atom concept (see for example: Lee at al. 1993; Harrison and Treagust, 1996; Taber, 2002; Cokelez and Dumon, 2005), as well as the problems and possibilities of teaching the atom concept (see for example: Tsaparlis, 1997; Toomey at al. 2001; Nelson, 2002; 2003; Tsaparlis and Papaphotis, 2002).

Unal and Zollman (1999) investigated students' ideas about an atom using phenomenography as research method. They did not attempt to develop a catalogue of students' misconceptions of atoms. Instead, they were interested in learning how students describe atoms when they are presented with an open-ended question. Responses were evaluated not as 'right' or 'wrong' but with identifying categories using an iterative process.

[†] This paper is based on work presented at the 8th ECRICE Conference, Budapest, 31 Aug - 1 Sep 2006

Students' descriptions fell into six categories; three of these ('Units of matter', 'Constituents of atoms' and 'Model of atoms') were used to classify students' reasoning levels in a hierarchical system suggested by the authors. Their research showed that in describing the atom, most of the students fall into a low hierarchical level of reasoning categories. The majority of the students did not include an atomic model in their descriptions of an atom. The authors established that students did not seem to retain what they have learned from previous courses or years.

This paper (Unal and Zollman, 1999) initiated our present work on studying students' thinking patterns in describing an atom. In addition to evaluating data of our survey among Hungarian students, data in the Unal and Zollman's paper were subjected to a secondary analysis. Thus, we could compare the characteristic thinking patterns and their changes between Hungarian and American students. Furthermore, we tried to use a new evaluation method, combination of phenomenography with knowledge space theory to explore students' reasoning about an atom.

Phenomenography

Phenomenography is an area of research which focuses on identifying and describing the qualitatively different ways in which people understand phenomena in the world around them (Marton, 1981, 1986). The major premise of phenomenography is that although individuals will have different experiences and conceptualisations of a phenomenon in a given context, the number of qualitatively different conceptualisations is limited. These different conceptualisations are the focus of a phenomenographic study rather than each individual learner's conceptualisations. One major assumption of phenomenography is that individuals can accurately express their experiences and conceptualisations.

Once the data for a group of individuals has been collected, it is then organised and reviewed several times in order to identify the limited number of ways a phenomenon has been experienced and conceptualised. There are three main principles for this identification process: (1) categories should be extracted from the student's responses; (2) categories should not be mutually exclusive or inclusive, but distinguishable; (3) responses must be explicit to be capable of being categorised. These categories of description are the main outcome of the research. The categories often are presented in increasing levels of understanding.

Phenomenography is different from other qualitative approaches (e.g. field research, grounded theory, etc.) in its major premise, the assumption (cited above) and the principles for categorisation.

Knowledge Space Theory

Knowledge Space Theory (KST) was developed by Doignon and Falmagne (1999), and its application to science concepts have been previously demonstrated by Taagepera et al. (1997, 2000, 2002), Arasasingham et al. (2004, 2005), and Tóth and Kiss (2006). In this theory, the organisation of knowledge in students' cognitive structure is described by a well-graded knowledge structure. Although KST was originally developed for modelling the hierarchical organisation of knowledge needed to answer a set of problems in science and mathematics, the formalism of this theory can be extended to any hierarchically organised input data. In the study reported here we combined phenomenography with KST.

For this analysis, responses were scored in a binary fashion, according to whether they contained the given category (1) or not (0). As we construct three-item groups from the categories, theoretically we can have 8 (2^3) possible response states, from the null state [0] where none of the above categories were used to the final state [Q] where all the categories appeared in the student's description. A set of response states for a student group gives the *response structure*. Starting from this response structure, one can recognise a subset of response states (so called *knowledge structure*) fitted to the original response structure at least at the p = 0.05 level of significance. There are several methods to find the knowledge structure from the response structure. These methods have two common features: *(i)* lucky-guess and careless-error parameters (most often 0.1) are estimated for each item; *(ii)* the knowledge structure has to be well graded (e.g. each knowledge state must have a predecessor state and a successor state except the null state and the final state). Based on the knowledge structure we can determine the most probable hierarchy of the categories (represented by the so-called *Hasse diagram*) by a systematic trial and error process to minimise the χ^2 value. (The χ^2 value was calculated on the basis of the difference between the predicted and the real populations on the knowledge states in the assumed knowledge structure.) For the calculations, a Visual Basic computer program (Potter) was used. Details of the KST analysis will be presented in the Results and discussion section.

The aim of the study

We used KST to explore the connections among the categories obtained from the phenomenographic analysis of students' responses and to answer the following research questions:

1. What is the characteristic hierarchy of the categories regarding the concept of the atom?
2. Is there any change in students' thinking patterns during their instruction?
3. Is there any difference and similarity between the Hungarian and American students' ideas about an atom?

Research methodology

Instruments and subjects

Students were asked - among other items – to describe an atom on a paper-and-pencil questionnaire: 'Describe the following concepts: atom, molecule, ion etc.'

Data were collected at the end of the school year of 2002/2003. A random sample of 724 out of 2954 Hungarian secondary school students (grades 7 to 11, age 13 to 17) from 17 schools participated in the test. (7th graders: 171, 8th graders: 165, 9th graders: 136, 10th graders: 135 and 11th graders: 117.) The 7th graders have 1 or 2, 8th to 10th graders have 2 chemistry lessons per week, respectively. Just a few students have chemistry lessons in the 11th grade. It is noted that in Hungary the concepts of atoms and molecules are introduced in the 7th grade. Hungarian chemistry textbooks give various definitions of an atom in grade 7: (1) an atom could not be divided up; (2) the atom could not be divided by chemical methods; (3) constituents (protons, neutrons, electrons) of an atom; (4) simple models (Rutherford, Bohr) of an atom. In the 9th grade, chemistry textbooks (and lessons) deal with the basic quantum mechanical description of an atom. Later each book completes the description of the atom but does not give new definitions.

Data about the American students were obtained from the paper of Unal and Zollman (1999). In their survey a total of 239 high school students were asked to describe an atom at the end of the Spring Semester of the 1995/96 academic year. Most of the students in all grade levels were taking or had taken a physical science course at the time of the survey. The majority of the 11th and 12th graders were taking a chemistry course. In our research the data of the students in grades 9-12 (9th graders: 69, 10th graders: 51, 11th graders: 88 and 12th graders: 29) were used.

Results and discussion

Categorisation of the students' responses

Similarly to the Unal and Zollman (1999) results, students' responses were divided into six categories: (0) No response; (1) I don't know; (2) Units of matter; (3) Constituents of atoms; (4) Model of atoms; (5) Other. Among these categories *'Units of matter'*, *'Constituents of atoms'* and *'Model of atoms'* were used for further analysis.

Response was marked with 'Units of matter' (*U*) if the student defined the atom as a constituent (or the smallest particle) of matter. For example, 'An atom is the smallest particle/unit of matter.' 'An atom can not be divided chemically.'

The 'Constituents of atoms' (*C*) category includes students' responses containing the name of the constituents of an atom. For example, 'An atom contains electrons, protons and neutrons.' 'The atom is a neutral particle involving electrons, protons and neutrons.'

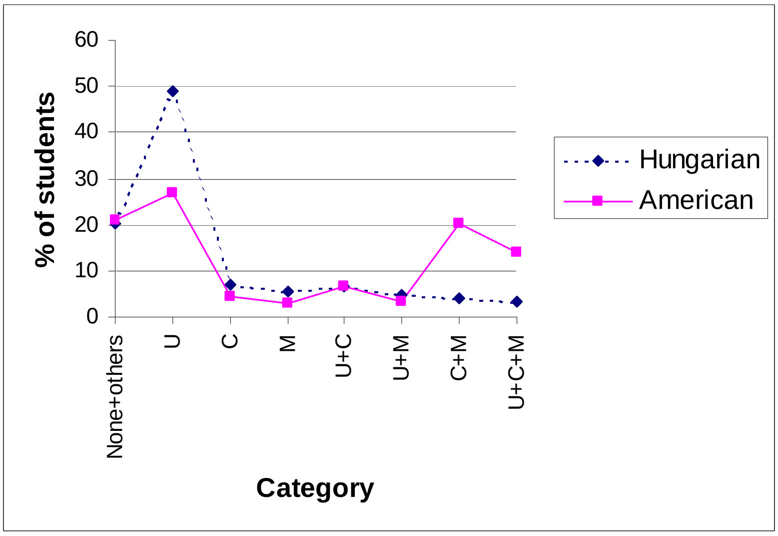
When the student described any atomic models his or her response was listed into the category 'Model of atoms' (*M*). For example, 'An atom consists of a nucleus and an electron cloud around it.' 'In an atom electrons circle around the nucleus.' Note, that in spite of the fact that chemistry textbooks for 9th graders discuss the basic principles of the quantum mechanical models, practically none of the students used these terms (e. g. atomic orbital, electron density, quantum numbers etc.) in describing an atom.

All possible combinations of the above three categories (U, C, M, U+C, U+M, C+M, U+C+M) were detected in the students' responses.

Frequency and distribution of the students in the categories and their combinations

Figure 1 shows the students' distribution in each category and combination of categories. Both similarity and significant difference can be seen in distribution of Hungarian and American students. The similarity is that the proportion of the students is the same in the category 'None + Others', is the highest in category 'Units of matter', and is low in categories 'Constituents of atoms', 'Model of atoms', 'Units of matter + Constituents of atoms' and 'Units of matter + Model of atoms'. However, the percentage of American students is much higher in categories 'Constituents of atoms + Models of atoms' and 'Units of matter + Constituents of atoms + Model of atoms' than the percentage of Hungarian students. These general features of the distribution curves do not change significantly through the grade levels (Table 1).

Figure 1. Comparison of Hungarian and American students' distribution in each category or combination of categories



The differences between the Hungarian and American students in the distribution of categories can be explained by the different instructions regarding the atomic concept. As mentioned earlier, Hungarian students learn about the atom in chemistry courses, while the American students who participated in the Unal and Zollman's survey learned the atomic concept mainly in physical science courses. "*…most of the students in all grade levels were taking or had taken a physical science course at the time of our survey. The majority of 11th and 12th graders were taking chemistry. Almost half of the 12th graders and a few 11th graders had taken or were enrolled in the high school physics course*" (Unal and Zollman, 1999, p. 6). Physicists emphasise the constituents and the models of the atom rather than the indivisibility, and the smallest particle as well as the units of matter characters of the atom.

Table 1. Students' distribution in each category or combination of categories.

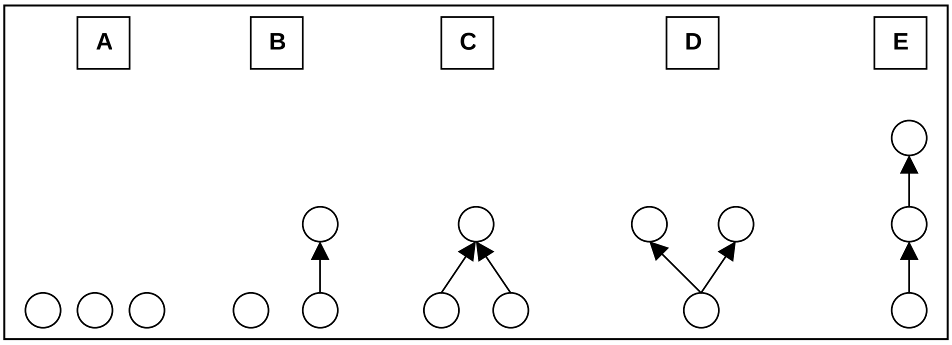
	Hungarian students					American students			
Grade level	7th	8th	9th	10th	11th	9th	10th	11th	12th
None + others	22%	25%	18%	16%	20%	20%	25%	18%	24%
U	48%	49%	49%	47%	52%	12%	33%	36%	24%
C	8%	7%	2%	12%	4%	6%	4%	4%	7%
M	6%	8%	7%	1%	3%	3%	6%	2%	0%
U + C	6%	4%	10%	8%	5%	9%	2%	10%	0%
U + M	1%	3%	4%	8%	10%	4%	2%	4%	3%
C + M	5%	3%	5%	4%	3%	26%	16%	16%	28%
U + C + M	4%	1%	5%	4%	3%	20%	12%	10%	14%

U: Units of matter; C: Constituents of atoms; M: Model of atoms.

Hierarchy of the categories

Unal and Zollman (1999) in their paper suggest the following hierarchical structure of the categories: 'Units of matter' → 'Constituents of atoms' → 'Units of matter + Constituents of atoms' → 'Model of atoms' → 'Units of matter + Model of atoms' → 'Constituents of atoms + Model of atoms' → 'Units of matter + Constituents of atoms + Model of atoms'. This is a so-called expert's hierarchy. However, we are interested in the hierarchy of the categories which is characteristic of the students' group at different grade levels. Theoretically there are 19 possible connections between three categories (Figure 2) from the totally separate state (A) to the strictly hierarchical order (E). Among these hierarchical schemas we tried to find the one(s) fitted best to the input data (response structure of the students' group) using KST analysis as follows.

Figure 2. Theoretically possible schemas for connection between three categories (Number of variations in schemes: A = 1; B = 6; C = 3; D = 3; E = 6).



Using KST for determining the connection between the categories

As an example, let us consider the case of Hungarian 7th graders. Table 2 contains the response states of the Hungarian 7th graders in binary fashion, which is the first input file for the calculations. The second one contains the knowledge states derived from one of the connection schemas we assumed as a model for describing the organisation of the categories in students' cognitive structure. For example, Figure 3 shows one possible hierarchy of categories with the knowledge structure and knowledge states.

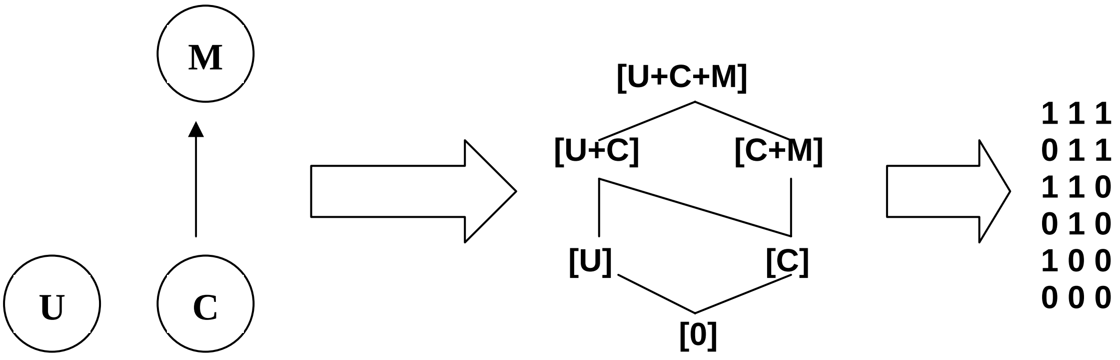
We used Hasse diagrams for presentation of this hierarchy. How should these be read? Hierarchy in Figure 3 means, for example, that the knowledge (category) 'Models of the atom' is built on the knowledge (category) 'The constituents of the atom", but both the categories 'Models' and 'Constituents' are separated from the knowledge (category) 'Unit of matter'. It means that one does not need to know that an atom is a small unit of matter before describing the constituents and the models of an atom, but one does need to know the constituents of an atom before describing the models of an atom. From this Hasse diagram we can deduce the assumed knowledge structure as it is shown by the Figure 3.

The second input file also contains the estimated probabilities of lucky-guess and careless error. In KST analysis we used 0.1 (10%) value for each parameter.

Table 2. A set of response states of Hungarian 7th graders.

Units of matter	Constituents of atoms	Model of atoms	Number of students
0	0	0	38
1	0	0	81
0	1	0	14
0	0	1	11
1	1	0	11
1	0	1	2
0	1	1	8
1	1	1	6

Figure 3. Deriving knowledge states and knowledge structure from the hierarchy of categories.



In the output file (Figure 4) we can see the two input files ('Response states' and 'Knowledge states') and the knowledge states in the assumed knowledge structure, the calculated probabilities of these knowledge states ('Prob'), the predicted populations ('Pred Pop'), the original populations ('Pop') and the χ^2 value ('Chi Sq') for each knowledge state, and finally the total χ^2 ('ChiSqT'). This total χ^2 together with the degree of freedom characterise the degree to which the assumed knowledge structure fits to the original response structure. The degree of freedom (d. f.) can be calculated as follows: d. f. = the number of knowledge states in the knowledge structure + the number of estimated parameters (lucky-guess and careless error) – 1. The numbers appearing on the first column in the output file are the codes of the knowledge states in decimal system. The last column in the input file (‘Response states’) shows the real population. Because of the similar form of the other input file (‘Knowledge states’) we used zeros for creating this last column.

Figure 4. A typical output of KST analysis using Potter’s software.

```
Response states:
    0   000      38
    4   100      81
    2   010      14
    1   001      11
    6   110      11
    5   101       2
    3   011       8
    7   111       6

Knowledge states:
    0   000       0
    4   100       0
    2   010       0
    6   110       0
    3   011       0
    7   111       0
n=8   m=6   Population =171

Knol.st.         Prob    Pred Pop     Pop      Chi Sq
    0   000    0.24609   42.08157      38    0.39588
    4   100    0.42811   73.20646      81    0.82970
    2   010    0.10595   18.11735      14    0.93571
    6   110    0.11226   19.19698      11    3.50006
    3   011    0.05992   10.24616       8    0.49240
    7   111    0.04767    8.15148       6    0.56786
ChisqT(6)= 6.722
```

Hungarian students’ knowledge structure

Figure 5. The best models for representation of Hungarian students’ knowledge structure.

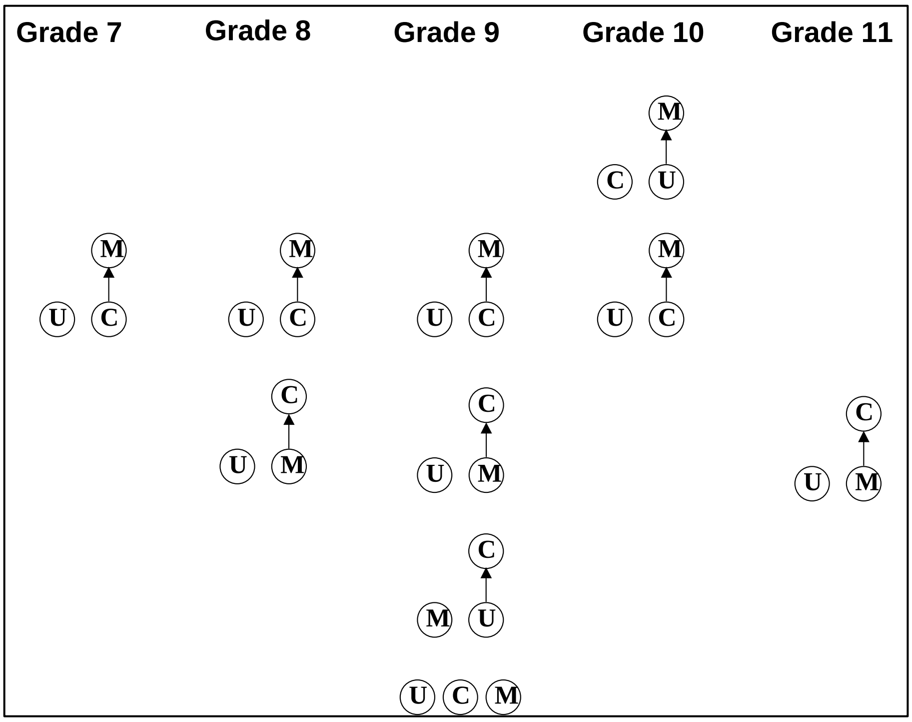
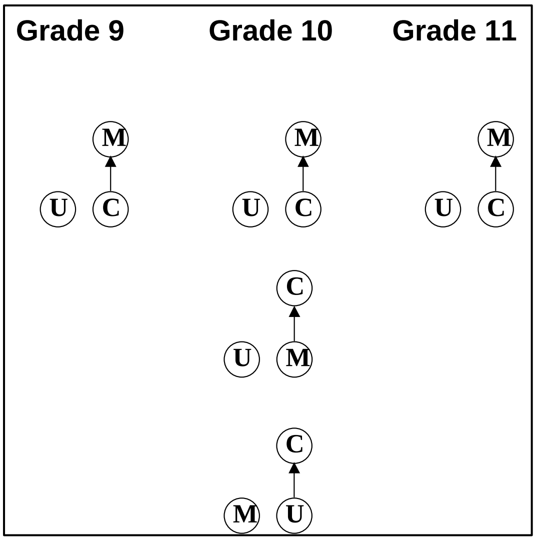


Figure 5 summarises the results of the KST analysis in the case of Hungarian students. It can be seen that there are some significant changes in the best models through the grade levels. The number of the best models for organisation of knowledge is varied with the grade levels. Only one model was found in the case of 7th and 11th graders, but in contrast, the organisation of knowledge could be described with two equivalent models in the case of 8th and 10th graders, and in addition we found four models in the case of 9th graders. These suggest that from the viewpoint of knowledge structure students' groups are uniform at the beginning of the chemical studies (in grade 7). Moving forward in their instruction students' knowledge structure becomes more complex, and in grade 9, where students study the models of an atom in detail, this organisation of knowledge is the most complex one. In grades 10 and 11 a unification process is taking place, and at the end of their chemistry studies (in the 11th grade) the knowledge structure of the students again becomes uniform. Figure 5 also shows that there is a change in the knowledge organisation from 7th to 11th grades. In the early chemistry courses the category 'model of atoms' is built on the category 'constituents of atoms', and the category 'units of matter' is independent of the other two categories. After changes in connections between the categories, at the end of their chemistry studies in students' mind the category 'units of matter' remains independent of the categories 'constituents of atoms' and 'model of atoms', but the connection between the two latter categories is reversed. In contrast to the knowledge structure of the 7th graders, the category 'model of atoms' becomes fundamental in the knowledge structure of the 11th graders.

American students' knowledge structure

We found similar trends in changes in the number of the best models in the case of American 9th to 11th graders (Figure 6). The results of the KST analysis of 12th graders were omitted because of the small number of the students (N = 29) in this group. In contrast to the patterns with the Hungarian students, KST analysis could not show any lasting change in the knowledge structure between the 9th and 11th graders. Similarly to the Hungarian 7th graders in the characteristic model the category 'units of matter' is independent of the other two categories, and the category 'model of atoms' is built on the category 'constituents of atoms'. This is a typical shape of the process of conceptual change. The initial model is a simple one but during the instruction this model becomes more complex and finally 'crystallises' the new model.

Figure 6. The best models for representation of American students' knowledge structure.



Conclusions and implications for teaching

Using phenomenography combined with knowledge space theory we could study the main categories of students' descriptions about an atom and the characteristic hierarchies between these categories. Our results can be summarised as follows.

1. Both the Hungarian and American students' responses to describe an atom fell readily into six categories: 'No response'; 'I don't know'; 'Units of matter'; 'Constituents of atoms'; 'Model of atoms'; and 'Other'. From these categories 'Units of matter', 'Constituents of atoms' and 'Model of atoms' were used for further analysis.
2. We established that the percentage of American students is much higher in categories 'Constituents of atoms + Models of atoms' and 'Units of matter + Constituents of atoms + Model of atoms' than that of the Hungarian students', and this general feature of the distribution does not change significantly through the grade levels. The differences between the Hungarian and American students in the distribution of categories can be explained by the different instruction regarding the atomic concept: Hungarian students learned the atomic concept in chemistry courses, while the American students learned it mainly in physical science courses.
3. Using knowledge space theory (KST) we could find the best models among the theoretically possible schemas for representation of connection between the three categories. Results show that during the instruction the initial uniform knowledge structure of the students becomes more diffuse, the number of the best models increases but at the end of the instruction the organisation of the categories in students' mind can be represented again by one model.
4. In the initial model 'Units of matter' category is independent from the 'Constituents of atoms' and 'Model of atoms' categories, and there is only one connection between the latter two categories: the category of 'Model of atoms' is built on the category of 'Constituents of atoms'. (This is a very acceptable model of describing an atom: one does not need to know that an atom is a small unit of matter before describing the constituents and the models of an atom.) Although the connection between the categories changes with the instruction, the initial model remains the same in the case of American students. In contrast, in the characteristic model of the Hungarian 11th graders the hierarchy between the categories of 'Constituents of atoms' and 'Model of atoms' reverses, and the 'Constituents of atoms' category is built on the 'Model of atoms' category.
5. These results show that even though the instruction brings about significant changes in students' knowledge structure, the final model is the same or very similar to the initial model in hierarchy between categories used by the students when describing an atom.
6. Our work demonstrates that combination of phenomenography and knowledge space theory is a powerful method for exploring students' thinking patterns.

The small effect of the instruction on the initial thinking patterns of the students regarding the description of an atom shows that teachers and textbooks authors should pay much more attention to the description of the atom. It is not enough to give a definition of the atom at the beginning of the instruction and to complete the description without giving newer and newer definitions. Our results of the survey among Hungarian students show that most of them like to use definitions. Because their 7th grade chemistry textbooks define the atom in as the unit of matter, Hungarian students use this definition even at the end of their instruction, in the 11th grade, too. There could be considerable benefit gained from teachers revisiting some of the fundamental concepts in subsequent years, perhaps by offering more sophisticated definitions, to bring their students' understanding of these into line with what they had learned in their later studies.

Acknowledgments

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Practice

Using home-laboratory kits to teach general chemistry

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Abstract: University-level chemistry courses that contain a substantial laboratory component have always been a challenge to deliver effectively through distance education. One potential solution is to enable students to carry out real experiments in the home environment. This not only raises issues of logistics and safety, but also the fundamental question of whether an equivalent learning experience could be achieved with home laboratories. Athabasca University, Canada's Open University, has been successfully running chemistry courses for almost three decades. The migration from traditional supervised laboratories to home-study experiments over a fifteen year period in a general chemistry course is described. The study examines both student experience using the home-study laboratory kits, and their actual performance. Student grades in the course essentially remain the same as supervised laboratories are replaced by home-study laboratories, while at the same time offering the student increased access and flexibility. Furthermore, bringing experiments into a home environment contextualizes learning for the student and raises the possibility of incorporating the home-study laboratory experience, in whole or in part, into traditional general chemistry course offered on campus. [*Chem. Educ. Res. Pract.*, 2007, **8** (3), 337-346.]

Keywords: general chemistry, laboratory, home-study, home-laboratory kits, distance education, educational freedom, contextualized learning

Background

While laboratory work is at the heart of many good chemistry courses, it is also one of the most difficult components to deliver effectively at a distance. In developing laboratory components for distance education one invariably faces the larger question of why we, as chemical educators, actually require laboratory work. What are we trying to achieve? Is it a right of passage for chemistry students? Is it a historical tour of chemistry past? For a distance educator it would certainly be easier to deliver only the content and theory without requiring the practical work. It would also seem that, given the choice, chemistry students might choose to avoid the laboratory experience. Byers observed that many students, essentially motivated by marks, are uncomfortable doing practical work, and view it as yet another form of assessment (Byers, 2002).The rationale for having practical work in chemistry, the role of the teaching laboratory and its changing nature has been discussed and will continue to be discussed at great length within the chemical education community (Kember, 1982; Lagowski, 1989; Bennett and O'Neale, 1998). The design of any laboratory component, including home-study experiments, is often done to meet a variety of aims. The most general aim is the reinforcement of course concepts through illustration and making it real for the student. This is followed by the development of techniques and skills in the student that are either cognitive or practical in nature. It could include skills such as physical manipulations, observations, problem solving, data handling, interpretation of results, time management, and dealing with errors to name just a few. Finally, many teachers cite the laboratory environment as an opportunity or vehicle to inspire students and make chemistry impressive enough to remember. The approach described by those who have designed and used home-study laboratories will certainly be familiar to educators creating equivalent on-campus experiments (Rudd, 1994; Ross and Scanlon, 1995; Boschmann, 2003; Casanova et al., 2006).

Although chemistry home-study laboratories have many of the aims, concerns, and approaches in common with traditional laboratories, there are notable differences. The first and most obvious is that they offer the learner autonomy in space and time. Educators such as Moore and Paulsen argue that a high level of freedom and individual choice is crucial in distance education (Moore, 1983; Paulsen, 1993). Distance learners perceive themselves as self-directing individuals who are seeking control of their own learning outcomes. The assumption is that they are highly motivated, so course design incorporating a high degree of student freedom is desirable. While home-study laboratories achieve this aim, it should be remembered that students enjoying the freedom of carrying out experiments individually are also isolated from their peers. Apart from the feeling of loneliness and seclusion, the lack of student-student interaction does raise the question of whether this laboratory learning experience is being adversely affected.

This leads to the second notable difference. Of the three common types of interaction involving students described in the literature (student-student; student-teacher; student-content), the home-study laboratories possess a strong student-content component. There is some student-teacher interaction with tutor e-mail and phone communication, but no real student-student interaction. Anderson recently proposed an equivalency theorem, which suggests that one form of interaction can be effectively substituted for another (Anderson, 2003). In essence, so long as there is at least one mode of interaction present in the three legs of this interaction tripod, deep and meaningful formal learning is supported.

The third notable difference that should be considered is the context of the home-study laboratory itself. We recognize that not only what we teach but how we teach is affected by our chemistry environment and culture. Our teaching and learning approach is different from other disciplines—even other disciplines in science. The importance of chemical philosophy in chemical education has been well identified and discussed in the literature (Scerri, 2001; Erduran et al., 2007). The teaching laboratory experience is certainly an important vehicle in conveying how chemists think and operate. The home-study laboratory kits will also do this, but it differs from the residential laboratory in that it further contextualizes learning for the student. The experiments are brought right into the home and chemistry is no longer something that is done only in the laboratory.

This work examines student experience and performance over sixteen years as we have incrementally replaced traditional supervised experiments with home-study experiments.

Methodology

This study is focussed on the laboratory component of the course *Chemical Principles I* (CHEM 217), which represents the first half year of general university chemistry. The intent was to determine whether CHEM 217 students could attain an equivalent learning experience with home-study experiments compared with supervised laboratory work. Athabasca University chemistry course delivery of CHEM 217 including the course development team, course materials, importance of the laboratory component, and the role of the telephone tutor, has been previously presented in detail (Kennepohl and Last, 1998). The important features to remember with delivery of chemistry courses at Athabasca University are:

1. There is continuous, year-round enrollment.

2. Except for some supervised laboratory sessions (found only in older versions of CHEM 217), the course is self-paced.
3. Although there are online components and resources, the courses are mainly print-based materials that wrap around (integrate with) commercially available textbooks.
4. Students receive tutor support by telephone and e-mail.
5. Telephone tutors mark assignments and laboratory reports giving detailed feedback.
6. The course has mostly visiting students from other universities or students wishing to attain pre-requisites for professional programs (e.g. medicine, dentistry, pharmacy). Only 6% are program students with Athabasca University.

Originally, the CHEM 217 laboratory component was only offered as paced face-to-face instruction in supervised laboratories on campus or at regional centres. Several years ago a kitchen chemistry component and then a home-study kit was introduced so that students could complete half of the experiments at home. Students in the current version of CHEM 217 can complete the course by doing the laboratory component completely at home with a home-study laboratory kit ordered from the university. At the end of their CHEM 217 course the students working entirely at home were surveyed and asked about their laboratory experience and their background. The performance of students in the laboratory component, assignments, and examinations was also tracked over several years through all the different versions of the course. A simple t-test was employed to determine if there were significant differences in performance of groups of students as more home-study laboratories were introduced.

Kit development

We originally became involved with home-study laboratories through the incorporation of kitchen chemistry experiments into the regular laboratory component of the course. To overcome some of the students' diffidence in coming out to the first face-to-face laboratory session, we made their first experiment one that could be done at home using simple household equipment and chemicals. The idea was to engage students with laboratory work early enough in the course to encourage attendance at supervised sessions. The results of this pilot were reported elsewhere (Kennepohl, 2000). We then developed a series of four home-study experiments that were much more sophisticated than the kitchen chemistry experiments. Students would now carry out the kitchen chemistry as well as home-study experiments using the kit. They would then attend another 16 hours of face-to-face laboratories. Detailed descriptions of these experiments, as well as the equipment and chemicals used, can be found elsewhere (Kennepohl, 1996). Students felt that unlike the kitchen chemistry experiments, these new home-study experiments were of university quality.

In an effort to engage students further in the laboratory component of CHEM 217 we increased flexibility and access for the students by developing a home-study kit that would allow all laboratory work to be done independently at home. A major concern during the development of these home-study kits was providing portability and safety, while still achieving university-level quality in the experiments. What that quality actually means and how it is perceived is certainly debatable. In the end, a vital part of achieving that quality meant the incorporation of appropriate quantitative experiments, which in turn often comes down to providing the student with a suitable laboratory balance. It was a challenge to find a balance that was inexpensive, precise (± 0.01 g), and robust enough to be shipped in the home-study kit. However, the balance was seen to be an important component of the kit and certainly differentiates this kit from others that contain primarily qualitative experiments.

We converted all the face-to-face experiments and added them to the existing home-study kit. These included mass and volume measurement, use of a simple spectrophotometer, acid-base titrations, determining the universal gas constant, and determining the stoichiometry of a reaction. In each experiment the home-laboratory kit provided the students with the necessary chemicals and equipment (http://science.pc.athabascau.ca/chem217.nsf/experiments2?OpenPage) . We also developed an instructional CD to accompany the kit, which showed video clips of good safety practices, experimental set up, and techniques required to carry out the experiments.

Laboratory' program

- In the first experiment the students learn how to calibrate and use a general pan balance. They learn the technique of weighing by difference and determine the density of water. They also calibrate a volumetric pipette using mass and density.
- In the second experiment students determine the amount of acetylsalicylic acid in a commercial ASA tablet using spectrophotometry. The tablet is hydrolyzed with NaOH, the acetylsalicylic acid is complexed with iron(III) chloride, and then analyzed in a simple spectrophotometer. The resulting absorption is compared to absorptions of standard acetylsalicylic acid solutions.
- In the third experiment students again determine the amount of acetylsalicylic acid in a commercial ASA tablet but using acid-base chemistry. The tablet is hydrolyzed with a known amount of NaOH and the excess NaOH left over after the reaction is titrated with HCl standard. The calculated amount of acetylsalicylic acid present is compared with the value obtained spectrophotometrically in the previous experiment.
- The aim of the fourth experiment is to determine the universal gas constant (R). Nitrogen gas is chemically generated and trapped over water. Assuming the ideal gas law, the student calculates R and compares the value obtained with the literature value.
- Finally, the last experiment illustrates how the determination of the stoichiometry of a reaction can be determined empirically using a redox titration. Iodine produced in the reaction is titrated with sodium thiosulphate and calculations can then be done to determine the ratio of iodate to iodine in the overall reaction. This is the last experiment in the course and differs from the other experiments, because no experimental procedure is given to the student. After reading the theory and background information on the reactions, students are given the objective of experimentally finding the stoichiometry of a reaction. They must develop their own written procedure and have it approved by their tutor before proceeding.

Each kit costs approximately $800 CAN ($ 680 US, euro 500, £350 GB) and contains the essential chemicals and equipment for all the experiments. However, students are expected to provide some common household ingredients and equipment such as a stove top or tap water. The kit dimensions are 41×46×47 cm and it weighs 5.4 kg. Once registered in the chemistry course, a student can order a home-laboratory kit online to use for a period of two months. The kit is shipped cost-free to the student and the university also covers the return shipping costs. There is no kit deposit required, but grades are withheld until the kits are returned. The non-return rate of kits is relatively low (1.0%). Once a kit is returned, staff check it over to replace consumables and any damaged items before sending it out to the next student.

Results

The survey data of students taking the full home-study laboratories were compared with previous students taking half the laboratories at home and those only doing one kitchen chemistry experiment at home (Table 1). Examining student profiles, the average age of the students (30 years) was slightly higher, but essentially the same (29 and 28 years) as in previous surveys. The number of students with absolutely no post-secondary experience (7%)

was also slightly higher, but essentially the same (5 and 6%). However, the average time since a student has done a laboratory course (4.7 years) was slightly lower than the other groups (5.7 and 6.3 years). There were two major differences observed in the profile of students who did the laboratories entirely at home. First, the proportion of female students (65%) had grown significantly from earlier surveys (41 and 48%). Secondly, there were substantially fewer students with completed university degrees (39%) or college diplomas (22%) than those who had university degrees (50 and 48%) or college diplomas (45 and 45%) in former survey groups. The increase in the number of female students parallels the trend seen at other Canadian universities and has been generally attributed to a strong economy and employment opportunities decreasing male participation in post-secondary education. We cannot interpret the observation of the decrease in proportion of previous degrees or diplomas held by students.

Table 1: Summary of CHEM 217 student surveys of the Home-Study Experiments.

	Full Home Lab	Half Home Lab†	Kitchen Chemistry†
Female	65%	41%	48%
Male	35%	59%	52%
Average Age	30 years	28 years	29 years
University degree	39%	50%	48%
College diploma	22%	45%	45%
No post-secondary experience	7%	5%	6%
Average time since last chemistry laboratory experience	6.7 years	Not available	Not available
Average time since last science laboratory experience	4.7 years	5.7 years	6.3 years
University quality achieved	83%	85%	No (anecdotal)
Want home-study option for other science labs	78%	83%	85%
Instructions easy to follow*	3.9	4.5	4.3
Easy to obtain all equipment*	4.5	4.1	4.0
Experiments interesting*	4.2	4.0	3.1
Course material reinforced*	4.1	4.0	3.0
Number of responses	182	218	59

* Students were asked to rate on a five-point Likert scale.
† Previously reported data (Kennepohl 2000)

Many of the qualitative ratings compared between the full and half home-study laboratory students on the home-study laboratory kit were very similar (Table 1). Students felt that university quality was achieved (83 versus 85%), that the experiments were interesting (4.2 versus 4.0), and that course material was reinforced (4.1 versus 4.0). The ease of finding equipment was rated higher for the full kit (4.5 versus 4.1), but there were lower scores for ease of experiment instructions (3.9 versus 4.5) and desire to want more home-study laboratories (78 versus 83%). We feel the difference in the last two categories is small and might be a reflection of the increased sophistication of added experiments. Still, there is an overall positive student satisfaction.

There was an opportunity in the student survey to comment freely on the laboratories. The most common remarks were about the flexibility offered by the home-study kits, as well as the positive response to the accompanying instructional CD. Several students also commented that they would involve their family in carrying out the experiments at home and seemed quite enthusiastic about doing so. This was an unexpected result, and although anecdotal information, it underscores the importance of viewing these laboratories in the context of the home environment.

Of more interest is the actual student performance. Student performance in CHEM 217 with respect to assignments, examinations, and laboratory component is summarized in Table 2. The data corresponds to students who completed the course from January 1990 to July 2006. The course version (numbered 1 through 6) represents major course revisions to the theory part of the course. We see that the composite final grade has stayed in the 75-80% range over the last fifteen years. Students tend to score highest on their assignments and laboratory components, with assignments usually being slightly higher. As a group they score lower on the examinations, where the final examination is always lower than the midterm examination. We see this same general pattern in other chemistry courses at the university.

As we change course version (1 through 6) there are some slight variations in final grade. Versions 1 through 4 represent change in edition of the same text book. Versions 5 and 6 are two editions of a different text book. The overall pattern seems to start with a composite grade of approximately 76%, then moves to about 80% (Versions 2-4), and finally drops back again at the end to 76% (Versions 5 and 6). Superimposed on the particular course versions are changes to the laboratory component of the course which occurs part way through Version 4 (introduction of 50% home-study laboratories) and part way through Version 5 (introduction of 100% home-study laboratories). These two transition points represent change to only the laboratory portion of the course and are of most interest to this study.

Within Version 4 the average grade values for each component of the course appear slightly greater in the group having 50% home-study laboratories. However, a simple t-test confirms that the values are statistically the same within each course component (p values > 0.05 ranging 0.16-0.79). Within Version 5 the transition to 100% home-study show more substantial grade increases in each course component. Indeed t-test confirms that (with the exception of the assignment component, p value = 0.054) the values are statistically different (p values < 0.05 ranging 0.004-0.026).

Table 2: CHEM 217 Student Performance (1990 to 2006).

Course version	1	2	3	4		5		6
Home-study laboratory component	None				Half		Full	
Number of students	52	49	19	15	124	222	60	194
Assignments (%)†	85.8	85.7	80.5	84.0	86.5	85.2	87.5	88.9
Midterm exam (%)†	74.7	80.6	84.4	78.0	83.6	71.4	75.3	74.4
Final exam (%)†	68.2	76.0	75.5	73.9	74.9	67.5	71.9	68.8
Laboratories (%)†	78.8	81.6	80.7	80.4	82.5	83.5	87.5	87.8
Composite (%)*†	75.8	80.1	79.6	78.4	80.4	74.7	77.7	76.6

† Percent values truncated to one decimal place.

* Composite grade is a weighted average equal to 20% assignments plus 20% midterm exam plus 20% lab plus 40% final exam from original values.

Discussion

The concept of freedom and individual choice for distance learners is an important driver for success. Yet designing genuinely independent and self-paced chemistry courses for the individual learner is challenging, especially when a laboratory component is required. There have been numerous approaches to address this, including using regional laboratory sites, concentrating laboratory sessions, offering flexible hours (weekends and evenings), as well as employing computer simulations and remote laboratories. The home-study laboratory kit offers another approach to attaining access, flexibility and freedom for the distance learner. The student surveys certainly support this view from the students' perspective. However, it is more than opinion. Many students come to CHEM 217 and other distance courses, because the more traditional routes to access an equivalent course are just not readily available to them.

Although one can argue that increased student freedom and individual choice may motivate learning or just plain make it possible to access the opportunity to learn in the first place, it does not necessarily follow that learning equivalent to the traditional face-to-face can be achieved. The potential concern with the home-study laboratory is that there is no student-student interaction and there is no physical presence of a laboratory instructor. The course tutor is available remotely via telephone or e-mail, and so the student-instructor interaction is certainly less than one would find in a traditional teaching laboratory. It is a potential concern because epistemological assumptions are such that a high value is placed on the role of human interaction in education and learning. Indeed, human interaction can and does lead to both formal and informal learning. However, we know that other forms of interaction can also lead to learning.

The main interface in the home-study laboratory is the student-content interaction followed by limited student-instructor interaction. In this regard, one vital feature of the kit that cannot be over emphasized is the accompanying instructional CD containing indexed video clips. Although all the safety instructions and information to carry out the experiments are available in the printed laboratory manual, the CD is an effective medium to emphasize safety and demonstrate experimental techniques. It provides a closer connection between the student and the content by reinforcing the text in the laboratory manual, making the experiments less daunting, giving the students more confidence in carrying out the experiments, and hopefully, also inspiring them to start the experiments in the first place. In addition, the use of video clips of actual laboratory instructors talking to the students provides a type of simulated human interaction, albeit one-way. Effectively, some aspects of the student interaction with the instructor migrate to interaction with the content. The comment section on the student survey did reveal the existence of another type of interaction. In some cases students would involve their families in carrying out experiments at home. This suggests that students working at home might also make use of student-family (or student-room mate) interactions in their learning process, in addition to the types of interactions already discussed. However, it is unlikely that the family or room mate interactions would focus directly on the course material to the same degree as interactions with an instructor or with fellow students. It is unclear to what degree family or room mate interactions occur or what their exact role is in the learning process. Presumably that interaction may serve more to support, encourage, and contextualize rather than offer access to content and experience. This area would need further study.

Even though grades slightly increase with the home-study students, both the survey and the course performance statistics indicate that the CHEM 217 home-study laboratory mode is essentially equivalent to our earlier supervised laboratories. Some other studies comparing student performance between home-study and on-campus laboratories in general chemistry demonstrate that home-study students perform better (Boschmann, 2003; Casanova et al., 2006). The stronger performance by distance students has been attributed to student maturity in at least one study (Boschmann, 2003). It should be noted that the distance students in all these studies (including this work) tend, as a group, to be more mature, possess more experience, and have more commitments outside of their studies at university. The increased degree of these additional commitments such as family or job would certainly explain the pursuit of the access and flexibility distance learning would offer. This in itself is not a new observation, but it does underline the fact that these more mature students will have a greater tendency to self select for distance education than the typical 18-19 year old coming straight from high school. In contrast to our study, the studies carried out at dual mode institutions allow for that self selection. That comparison of non-equivalent groups raises the question whether the learning method or the make up of group itself is driving the difference in performance (Casanova et al., 2006). In this study there is not as great a difference in the student profile between those that that have done fully supervised laboratories or either the half or full home-study laboratories. Presumably any differences between the groups would more likely be due to the environment of the course itself rather than the background of the group.

The learning experience between home-study and the supervised laboratories is not identical, but undoubtedly equivalent. This is consistent with Anderson's equivalency theorem and shows that this mix works well in this particular case (Anderson, 2003). The learning experience in the home-study laboratory is different, but is it merely a substitute for supervised laboratories when students cannot attend? One notable benefit the home-study laboratory does have is the potential to contextualize learning for the student. General chemistry deals with a lot of abstract ideas and symbol manipulation, which can be barrier to a learner new to world of chemistry. The laboratory component offers an opportunity to make some of those concepts real for the student. However, the laboratory environment with its specialized equipment, procedures and particular hazards can possess its own barriers to effective learning. Some students are downright intimidated when working in a formal laboratory environment. Over fifteen years ago in our investigation of the low participation rate in CHEM 217 supervised laboratories, our students reported a lack of confidence and reluctance in attending initial sessions. This was not surprising as our students tended to be older and had on average not been in a laboratory for about six years (see Table 1). This prompted our development of the kitchen chemistry experiments, which eventually lead to a full home-study laboratory. Bringing those experiments into a home situation allows the student to work in more familiar surroundings. In some cases the experiment itself may make use of techniques and equipment found in the home. For example, instead of demonstrating boiling point elevation by using a beaker of water and Bunsen burner, a cooking pot of water and stovetop is used. The idea of contextualizing the laboratory in this manner is that intimidation is reduced; it affords the opportunity to use what students know already, and should result in more effective learning. In addition, the strong underlying message given to the student is that chemistry exists outside the laboratory.

At this point it may be worthwhile asking if there is any application of our home-study laboratory experience for the more traditional general chemistry course on campus. The trend in recent years has been the exploration of blended learning in which on-line and multimedia resources supplement face-to-face teaching. Institutions delivering supervised laboratory sessions are also under increasing financial and regulatory pressures to minimize the practical aspect of their chemistry courses. Many are turning to virtual laboratories to either replace or supplement current laboratories (Kennepohl, 2001). Computer simulations can offer some learning opportunities that real laboratories alone cannot, but conversely, they cannot replace the real experience in all cases. It is the innovative combination of the virtual and real laboratories that seems to offer the potential for effective and meaningful learning. In a similar fashion, a home-study laboratory (whether used in whole or in part) would not only address institutional challenges, but offer an extra dimension of learning for residential chemistry students who might respond well to and benefit from some independence and exploring chemistry outside the traditional laboratory.

Conclusions

We feel that a strong laboratory component is vital to our general chemistry course and have designed a home-study laboratory for our students studying at a distance. Our conclusions are summarized as follows:

1. The home-study kits developed are safe, portable, easy to use, and inexpensive to maintain.
2. The independence and freedom that a home-study laboratory offers is vital to success of our students taking the course at a distance.
3. Student survey results and actual student performance indicate that the home-study laboratory experience is equivalent to that found in supervised on-campus laboratories.
4. Bringing experiments into the home contextualizes the learning, and demonstrates that chemistry can be done outside a formal laboratory environment.
5. There is potential application for home-study laboratories at residential institutions.

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Providing solutions through problem-based learning for the undergraduate 1st year chemistry laboratory

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Abstract: A PBL laboratory-based module for first year undergraduate chemistry has been developed and successfully implemented. Its aim was to develop the students' practical and transferable skills, as well as their content knowledge and scientific understanding, and also to address the concern expressed in the literature over the effectiveness of the traditional laboratory courses to achieve these aims. The PBL module also encouraged students to prepare for their laboratory session in an active and collaborative manner through pre-lab exercises. By combining elements of group work, discussion, hands-on activities and alternative assessment methods, the students were provided with an environment conducive to meaningful, deep learning. We describe how the PBL module was developed by adapting the experience for the students rather than changing the experiments. Specific examples from analytical, physical and organic chemistry are given with a focus on the pre-laboratory exercises, associated group work, and the assessment methods, as well as on the actual practical work. [*Chem. Educ. Res. Pract.*, 2007, **8** (3), 347-361.]

Keywords: Problem-based learning, laboratory work, general chemistry, pre-labs, group work, alternative assessment

Introduction

Problem-based learning (PBL), a teaching and learning method founded in the medical sciences and first introduced in 1969, is becoming increasingly popular in other academic disciplines such as education, psychology and business (Coombs and Elden, 2004), and also in science, for example Belt et al., 2002. This paper describes the development of a problem-based learning approach for a traditional chemistry laboratory module by looking at the traditional laboratory format to see why there might be a need to change and PBL will then be discussed to see how this might provide the solution. Finally, the development of the module will be described in detail.

Traditional labs

Laboratory classes typically involve students performing teacher-structured laboratory exercises or experiments. Each step of a procedure is carefully prescribed and students are expected to follow the procedures exactly. Usually, little is left to the students' own thought or ingenuity. This type of laboratory activity is often referred to as a 'recipe lab' (Domin, 1999). This requires little student engagement with the content, and as Johnstone et al. (1994) commented, "*students can be successful in their laboratory class even with little understanding of what they are actually doing*". However, the student may have little choice but to adopt this passive approach while they grapple with new techniques and equipment, especially when the preparation for the lab has involved no more than reading the laboratory manual. Johnstone (1997) reported that the laboratory is a place for information overload, which results in students having little ‘brain space’ to process information and therefore they blindly follow the instructions and seldom interpret the observations or the results made during the experiment.

At this stage, it is important to highlight the expense of running laboratory sessions in university. Firstly, specialised laboratory space is costly to build, equip and maintain. Secondly, it requires technical and academic staffing, as well as postgraduate demonstrators. Laboratory work is also time-consuming, and finally, there is ongoing expense of consumable chemicals and apparatus (Bennett and O’Neale, 1998). The question is raised as to whether the students are deriving maximum benefit from these laboratory sessions, and if the typical recipe lab format can be justified in the context of such expense.

In recipe labs the activity is predetermined, with demonstrators, technicians, and staff all clearly knowing what is expected to happen. Therefore, errors can be clearly identified by the teaching staff and rectified for the students before they continue with the laboratory work, with the result that students get little experience of problem-solving in the laboratory. Additionally, all the students are generally carrying out the same experiment and this can lead to students only being concerned with getting the same result as their laboratory neighbour. However, recipe labs have the great advantage that they allow the inexperienced student to take the same attitude to laboratory work as is taken by the professional scientist: the recipe allows the student to devote all his or her attention to the technique and not to worry at all about theory (Garratt, 1997). They get direct opportunities to develop manipulative and technical skills. This maximises the quantity of practical experience gained by students, and the quality of the results they can potentially obtain. Conversely, the students are not concerned with matching their learning in the laboratory to previous experience or as Johnstone (1997) put it “*consolidating their learning by asking themselves what is going on in their own heads*”, unlike the researchers and professional scientists who are doing the laboratory work for a particular purpose, which has meaning for them. The other problem with recipe type labs is that the actual practical aspect of any experiment represents only a small part of the whole process of experimental science (Garratt, 1997), while in recipe labs the practical aspect is all that is covered.

Hunter et al. (2000) suggested that the recipe lab “*omits the stages of planning and design*” and it encourages ‘data processing’ rather than ‘data interpretation’. Garratt (2002) developed this further by commenting on the various steps a research scientist would take before actually getting to the practical aspect of the experiment as follows:

- What questions are we trying to answer?
- What observations would provide an answer to the questions?
- How can we best create conditions for making the desired observations?
- How will we process and evaluate the observations?
- What will we do next?

These are all aspects of a practical problem that students have no association with, as the laboratory instructor and technician make these decisions long before the student gets to grips with the experiment.

It is clear that recipe labs have their advantages, and with modifications, could be much more effective in teaching and learning science. Incorporating student ownership, relating experiments to previous experiences, and getting students to use higher order cognitive skills would provide authentic investigative processes (Johnstone and Al-Shuaili, 2002). Laboratory sessions should provide students with the opportunity to hypothesise, explain, criticise, analyse, and evaluate evidence and arguments. Bailey (2001) highlighted the importance of transferable or general skill development in a UK context, with reports from both science graduates and employers in chemical industry suggesting that an emphasis on transferable skills at the third level is highly desirable.

With this as a motivation for enhancing the experience for our undergraduate chemists, our traditional first year laboratory course, a typical recipe-type laboratory module with written laboratory reports as the assessment, was analysed, adapted, and a PBL module developed.

Problem-based learning

PBL sees a shift in educational focus from a teacher-centred approach to teaching and learning to a student-centred one, where students construct meaning for themselves by relating new concepts and ideas to previous knowledge. It is an alternative approach to teaching and learning, which encourages active involvement of the learner (Tan, 2004). As a learner-centred method that challenges the learner to take a progressively increasing responsibility for his or her own learning PBL is therefore consistent with the constructivist theory (Coombs and Elden, 2004). Furthermore, it also draws from another aspect of constructivism, which is to do with learning through social interaction, which recognises the impact of others' ideas on the way learners make sense of things (Harlen, 2006).

The aim of PBL is to develop self-directed, reflective, lifelong learners who can integrate knowledge, think critically and work collaboratively with others (MacKinnon 1999), thus enhancing the chances of students emerging from University with some of the skills that are highly desirable in the work place. Furthermore, by using unstructured real-life problems rather than the content as the focus, students are given opportunities to really learn how to learn (Tan 2004).

White (2002) stated that PBL provides an alternative to traditional education:

> *"In principle, PBL reverses traditional education by putting the problem first and using it to motivate learning. By using real-world problems, PBL enables students to see the relevance that they often miss in other contexts. The promise of PBL was that students would learn better, understand what they learned, and remember longer by working cooperatively in groups."*

In PBL, the problem, as the focus of the learning, is typically an ill-structured, complex one, with no clear 'right answer'. This provokes extended collaboration among groups, leading to conceptual learning. Students automatically have to activate their prior knowledge in order to start thinking about the problem confronting them, and build it into new knowledge, which is the basis of constructivism. This has been shown to enhance learning (Norman and Schmidt, 1993 cited in Exley and Dennick, 2004). This is in stark contrast to traditional labs which use tasks with clear procedures and right answers, which is associated with limited exchange of information among students, leading to simple explanations and routine learning (Wilkerson 1996). Similarly, Belt et al. (2002) suggested that problems act as the context and driving force for learning, and that the acquisition of new knowledge is done through these contexts. PBL differs to the familiar case-based or problem-solving approaches since in PBL the problems are encountered before all the relevant knowledge has been acquired (Albanese and Mitchell, 1993).

However, there are a number of implementation issues that must be addressed. Woods (1997) listed the main issues with implementation of a PBL approach into a traditional chemical engineering lecture course as follows:

1. Preparing the students with the required skills
2. Students must be willing to take charge of their own learning and to cope positively with the attitudinal shifts that occur when they experience change
3. Empowering the students to be their own facilitators
4. Selecting and preparing teachers to operate in PBL courses (called the facilitators)

5. Student attendance and participation
6. Choosing and formulating the problem, preparing resources
7. Creating the student groups

With respect to point 4, in general the facilitator is not there to provide answers to students' questions but to guide the groups in their discussions. This can be a difficult activity to engage in, and PBL facilitators require training and continuing support to ensure that their role helps the group to function optimally (Exley and Dennick 2004). Additionally, facilitators must be willing to take risks as they give up their sense of 'control' that one is familiar with in a lecture setting (Woods, 1997). Furthermore, Albanese and Mitchell (1993) questioned whether the facilitator should be an expert in the discipline or not.

The purest form of PBL has just PBL tutorials and independent learning where problems can last for weeks or even semesters. However, this approach can require faculty level change and typically more time/staffing/training/resources, and there are often concerns of a trade-off between content and depth (Albanese and Mitchell, 1993). This pure form of PBL was not considered suitable within the constraints of resources and staffing in this study and the varied student backgrounds in terms of content knowledge and process skills on entering undergraduate level 1. Therefore the 'pure' PBL approach was adapted as discussed below. The authors however will use the PBL acronym throughout to describe their approach. Factors that were considered in the development of the PBL module by the authors of this work included:

- The problems developed were based on existing experiments
- The problems were designed to ensure that students covered a pre-defined area of knowledge, and to help students learn a set of important concepts, ideas, skills and techniques
- The form that the problems usually took were descriptive statements
- The students worked either in groups or individually
- The students took part in a pre-lab, where the students' initial answers to the problems were discussed with the lab instructor who provided further context and/or chemistry help, and who pointed out potential pitfalls and blind alleys before proceeding to the lab work

Theoretical background

The development of skills, both general and technical, chemical concepts, knowledge and understanding were the core aims of the PBL module, and these were to be achieved through an alternative teaching and learning environment combining pre-labs, group work, discussion, practical work and alternative assessment.

Skills

The first stage in the development of the PB laboratory was to reflect on the desired learning outcomes in terms of skills and scientific method that should be developed from laboratory work. Garratt (1997) and Bennett and O'Neale (1998) describe the range of skills that should be developed through laboratory work (Table 1). Laboratory work should also provide the experience of designing an experiment, consolidating subject knowledge with practical experience, and the process of science (Garratt 1997).

Table 1. Skills to be developed through practical work.

Garratt (1997)	Bennett and O'Neale (1998)
Technical skill	Manipulation
Confidence in lab work	Lab know-how
Observational skills	Observation
Awareness of safety	Experiment design
Recording skill	Data collection
Data manipulation	Processing and analysis of data
Data interpretation	Interpretation of observations
Presentation skills	Problem-solving
Report writing	Team work
Oral communication	Communication and presentation

There are obvious similarities between the ranges of skills promoted by these authors. Skills, such as technical and observation skills, confidence in practical work, and data collecting are integral parts of most laboratory sessions; however, what of skills such as data interpretation, problem-solving, team-work and communication of findings? On reviewing the traditional module, it was apparent that many of these elements were missing. Therefore, it was integral to the PBL module that students would have the opportunity to develop and use all these skills.

Having identified skills that were to be central to the PBL module, each of the traditional experiments was analysed to identify the main focus of each experiment in terms of chemical concepts, and techniques.

Chemical concepts and techniques

The three areas of analytical, physical and organic chemistry that were covered in the traditional module were studied to assess their suitability to develop students' understanding of the fundamentals of these disciplines. Also, the possibility of setting the experiments in relevant contexts was examined. A selection of these experiments was chosen for use in the PBL module which covered fundamental concepts and techniques, such as acid/base theory, titrations, mole calculations, rates of reactions, gas laws, Beer-Lambert Law, recrystallisation, and organic synthesis.

Teaching and learning environment

Having determined the skills, concepts and techniques, the next phase involved designing the teaching and learning environment to include pre-lab work, group work, discussion and alternative assessment.

Pre-lab

The use of pre-lab session before the laboratory to 'prepare the mind of the learner' is not a new one. Johnstone (1997) described the elements of an effective pre-lab exercise as including:

- Revision of theory
- Reacquaintance with skills
- Planning the experiment to some extent
- Discussion with peers

When combined with elements of ownership and relevance for the students, the pre-lab can be very effective at preparing the mind of the learner (Johnstone 1997). Also, if students have had direct input into the laboratory experience, for example deciding the procedure or techniques to be used, and have an inherent interest in the experiments due to its relation to everyday life, for example, they will have a greater motivation and personal interest in actually doing the experiment.

Johnstone et al. (1998) reported on the use of pre-labs in physics: "*The aim of the pre-labs was to prepare students to take an intelligent interest in the experiment by knowing where they were going, why they were going there and how they were going to get there*". Also, Sirhan et al. (1999) commented on pre-lectures in chemistry being "*a useful tool in enabling students to make more sense of lectures, the effort being particularly important for students whose background in chemistry is less than adequate*". Allen et al. (1996) described how problems in PBL can be introduced with mini lectures, similar to the form of pre-lab session used in this research.

Group work

Through small-group co-operative learning, individuals can pursue their own learning needs within the context of the group, referring to others for support, feedback, and validation. Much learning occurs from interactions between group members, provided it is appropriately structured to allow discussion and consideration of different points of view (McManus and Gettinger, 1996) Group work both in and out of the lab is an integral part of this PBL module.

Discussion

Discussion can be defined in a broad sense as a wide range of informal situations where talk between people occurs. More specifically, it refers to a particular form of a group interaction where members join together to address a question of common concern, exchanging different points of view in an attempt to reach a better understanding of the issue (Bahar, 2003). Again, discussion both before the lab class and during the pre-lab session is encouraged in this PBL module. Nicol and Boyle (2003) have shown that students discussing concept questions in small groups not only enhanced their conceptual understanding, but it also proved to be a powerful motivating force. It was also reported that students showed a preference for thinking about the problem prior to the discussion; two reasons were offered for this. First, the requirement to make an individual response meant that they were forced to think about the problem, and to formulate their own reason for their selected answer, prior to the group discussion. Second, having constructed their own answer, students felt they benefited more from the subsequent peer discussion. They would be more likely to engage in dialogue and to provide reasons for, and defend their ideas and they would be more likely to be able to identify gaps in their thinking.

During the pre-lab session (no more than half an hour of the 3 hour lab time) discussion was initiated by the facilitator based on the pre lab task, from then on the students exchange ideas, explain and elaborate on their views, question and respond to each other and jointly derive a solution. The goal was to get students to think critically and creatively, and questions should be posed to promote these demands (Bahar, 2003).

Assessment

Savin-Baden (2004) reported that assessment currently seems to be one of the most controversial issues in PBL. She went on to discuss how "*many of the concerns about assessment in higher education seems to relate to the unintended side-effects that undermine staff intentions to encourage students to learn effectively*". Her study reported that students had three main issues with assessment in PBL:

- Unrewarded learning
- Disabling assessment mechanisms

- Impact of assessment on group work

Though PBL does allow for more alternative and varied assessment tools, including oral and poster presentations, written reports, and peer assessment among others, the issue of unrewarded learning and undervalued learning in groups is a difficult one to solve. Overton (2001) reported on a variety of assessment tools which have been used in case studies:

> "*Assessment tools which have been successfully used include oral presentations to other scientists, oral presentations to a lay audience, written reports, summaries of data collected, peer assessment of group participation, and individual reflection on skills development.*"

Many advocates of PBL promote the use of oral presentations in various disciplines (Allen and Tanner, 2003; Cooper et al., 2003; McGarvey, 2004; Polanco et al., 2004; and Serpil Acar, 2004) and McGarvey (2004) and Wimpfheimer (2004) both reported the use of poster presentations in chemistry. Wimpfheimer (2004) described the benefits of posters, including the fact that it encourages creativity and it provides another platform for assessment, reaching students who perhaps have been overlooked in the traditional assessment formats. Also posters, because of their limited size, stress the importance of clear and concise information and can encourage collaborative work in a way than written lab reports cannot. Finally, he reported a positive attitude toward posters both by students and instructors.

Furthermore, the written report is still encouraged and has its advantages, including the fact that it draws together the method and results and enables students to report, analyse and draw conclusions in a concise and informative style. Therefore, written reports are an integral part of the PBL module, however, the emphasis is on the conclusions that the students have to draw from their results, and how these related to the original problem they were given.

Development of the module

Skills profile of the students

To identify what skills students felt that they were confident using, and which skills the students had little opportunity to develop, students who were to take the PBL laboratory module were asked to complete a skills survey, adapted from the Royal Society of Chemistry's Undergraduate Skills Record (Royal Society of Chemistry, 2006), at the beginning of their first year. Tables 2 and 3 summarise the skills that students felt most and least confident in. It is worth noting the limitations of this skills survey, as some students have limited practical experience when they start their university course and therefore limited understanding of the statements. Furthermore, approximately 43% of these students had previously studied chemistry at school, and within that group 22% took part in practical work less than once a month in school. Despite this, it was a useful tool to identify the strengths and weaknesses of students' perceptions of their own skills.

Table 2: Skills students feel most confident in.

Work in groups
Interact with people to obtain the necessary information and assistance
Maintain awareness of specific hazards relating to chemicals
Measure and observe chemical events and changes
Maintain an interest in general science issues

Table 3: Skills students feel least confident in.

Plan and present an oral presentation
Analyse and evaluate experimental data
Interpret chemical information
Select appropriate techniques and procedure
Understand errors
Use internet and other resources to gain information

This information was used to develop the PBL module by focusing on tasks/problems that would develop these skills further and build students' confidence in using these skills. This could be achieved, for example, by incorporating oral presentations into the lab assessment, and getting students involved with the design of experiments by researching appropriate techniques and procedures using the internet and other resources. Also, the importance of errors and evaluating the experimental data was a key focus of their write-ups and their oral presentations.

Keeping it real!

Having identified important skills, concepts and techniques within the traditional experiments that were deemed important to the module, the next stage was to make the experiments appear relevant to the students. This meant finding a context to which the students could relate. For example, they were asked to apply the results of an iron tablet analysis to an anaemia case, where a female aged 20yrs is suffering from anaemia, and who needs to know how many tablets to take per day to keep her iron levels up, taking into account the amount of iron in the tablet that is actually available to the body. This also means having to do some reading around the subject. Other examples included environmental contexts, industrial analysis and food analysis. By brainstorming and simple internet searches, it is usually possible to devise relevant and interesting contexts that may engage the students.

Session outline

This PBL approach was designed for a year 1 undergraduate general chemistry laboratory module, which runs over 2 semesters. The laboratory session lasted for three hours, the same as the traditional lab sessions, inclusive of the pre-lab discussion and/or oral/poster presentations, which were delivered during the lab time. In some cases the problems were run over two laboratory sessions, however, the majority of the problems were completed within one session. The students were given the task a week before the lab, and were expected to have some written evidence of having tried to solve the problem before starting the pre lab discussion. This included looking up resources to support the theory, and practical elements of solving the problem, as well as technical information such as a possible procedures and/or chemicals/apparatus needed. During the pre-lab discussion the students were encouraged either in their groups or individually to offer their ideas on the problem and how they might solve it. Before going into the lab, any safety or technical information was described clearly to the students by the demonstrator. Once in the lab, students set about solving the problem, again either in groups or individually. On completion of the problem, the students submitted a written report and in some cases gave oral or poster presentations to conclude their laboratory session. Throughout the duration of the PBL module, the resources needed were either the same as in the traditional lab or other basic glassware/chemicals which were readily available in the lab. Furthermore, the PBL module was no more labour intensive than the traditional lab with one demonstrator assigned per sixteen students.

The PBL module

Elements of pre-lab work, discussion, group work and hands-on science were combined with alternative assessment in the development of the PBL module, as outlined above, to provide an environment in the laboratory, which supported student learning and skill development. It was decided that the problems would primarily focus on concepts, skills development or understanding. Table 4 gives two examples for each of the ‘concept driven’, ‘skills development’ and ‘understanding’ problems.

Table 4: Examples of ‘concept driven’, ‘skills development’ and ‘understanding’ problems

Title	Description	Main aims
Concept driven problems		
M&M’s	The problem was to use sweets such as M&M’s to demonstrate simple mole concepts	To introduce students to the concepts of moles and molarity
Apples and Oranges	The challenge was to investigate whether apples or oranges were acidic or not, and to determine their acidity.	To introduce acid-base chemistry, indicator theory, and titration as a quantitative method
Skills development problems		
Clock reactions	The challenge was to find a series of reactions to change colour in time with a piece of music	To provide students with an opportunity to develop technical, observation and data manipulation skills
Hard-boiled or scrambled	The problem was to cook an egg without using a combustion-based source of heat	To provide students with an opportunity for group work and problem solving
Understanding problems		
Old Wives’ Tale	The task was to determine if baking soda was effective at relieving indigestion, and to compare its effectiveness to that of a commercially available antacid tablet.	To provide students with an opportunity to apply their previous knowledge of titrations to a real situation
Gas behaviour	The challenge is to design a set of experiments to support the gas laws	To provide students with an opportunity to devise their own experimental procedures

Furthermore, the problems are sequenced in such an order so that there is progressive development of key concepts and techniques. This is to maximise the potential for cognitive gain and development of process skills. For example, in the first week the students engage with a simple problem to support development of group working skills and problem-solving in a non-chemistry environment and with some simple practical tasks to develop their understanding of moles and molarity. Following on from this, they do a problem based on acids and bases and ways of testing for/measuring these. In the third week, the students do the Case of the Unlabelled Bottles problem (see below) which further builds on these concepts and techniques. The titration technique is only introduced when they have encountered some simple, less accurate ways of determining concentrations and therefore, have more of an appreciation for its use in quantitative analysis. Additionally, every effort is made to reinforce learning by putting things in other contexts to challenge the students to transfer their skills, knowledge and understanding.

Concept driven problems

These problems were used to help students understand the major concepts of the first year programme, including moles and molarity, acid/base theory, use of indicators, the Beer-Lambert Law, polarity and purification. In the traditional labs, these concepts were only explained by a small introductory paragraph in the manual. However, students mostly ignore this information and even if the students attempt to read and understand it, according to Byers

(2001), effective thinking is inhibited because of information overload in the students working memory, leaving no room for information processing and hence understanding.

The concept driven problems aimed to give students a real opportunity to engage with the concepts both prior to the laboratory exercise through the pre-lab and discussion session and during the laboratory through relevant hands-on student driven investigative experiments.

Skills development problems

This group of problems aimed to develop the skill-base of the students, both in terms of their transferable skills and their technical skills. Transferable or general skills developed include group working and communication skills and problem-solving within a chemistry domain, whereas the technical skills developed include improving accuracy and precision in:

- Making up solutions
- Selection of appropriate apparatus
- Carrying out titrations

Understanding problems

Throughout the duration of the PBL module, there was an emphasis on group work, communication, problem-solving and researching skills. These were mostly developed through the pre-lab exercise and discussion. Through the pre-lab exercise the students were expected to go and actively research their problem using books and websites, and to solve the problem through collaboration with their peers in small groups. As well as developing the general skills mentioned, the aim of the pre-lab exercise was also to provide a platform for enhanced understanding by the students. The benefit of working in small groups has been discussed, with special focus on the enhancement of student learning and understanding through positive interactions with their peers. Suffice to say, that pre-labs are seen as integral in furthering students understanding and experience of the laboratory (Carnduff and Reid, 2003).

However, other methods can be used to enhance student learning in the laboratory, such as getting students to present their results in oral or poster presentations or to carry out real investigative experiments. Oral and poster presentation encourage them to ensure they understand fully what they have done, and hence can back up their argument. Also, investigative laboratories, where students have ownership over the design and implementation of the experiment, and the experiments have unknown outcomes, can give rise to real understanding. This set of experiments used the problem, pre-lab, discussion, experiment, and subsequent report to enhance students' understanding of their experimental results and hence of the experiment and its concepts.

Sample problems

Problem 1. The Case of the Unlabelled Bottles

This was adapted from an exploratory lab at Brigham Young University (Exploratory Lab, 2006). The PBL experiment asks students to label five solutions correctly, given five names and concentrations. The students are not given any other solutions, only indicators. Secondly, having identified the bottles, the students must accurately determine the concentration of one solution by titration. They must decide what other solution to use in the titration and what indicator. The solutions were acids and bases of varying concentrations, namely:

Acetic Acid	0.05M
Hydrochloric Acid	0.05M
Hydrochloric Acid	0.075M

- Sodium Carbonate 0.01M
- Sodium Hydroxide 0.025M

This problem aimed to further the students' understanding of acids and bases, indicators and quantitative measurement. From the preceding week's experiments, they should be able to distinguish easily between the acids and bases, but the next level was to determine different strengths of acids and bases so as to distinguish between, for example, the sodium carbonate and the sodium hydroxide, and then also to distinguish between different concentrations of the same solutions, i.e. the 0.05M and 0.075M hydrochloric acid solutions. They could use a variety of techniques, from indicator theory to 'small-scale' titrations to solve this. Given the added challenge of using as little of the solution as possible, meant that they were discouraged from using the typical standard titration equipment, and instead encouraged to try well plates and small beakers to carry out small-scale titrations. This encouraged the students to think 'outside the box', thus developing a better appreciation of alternative methods, and adapting their previous knowledge of titrations to a new context.

This was instead of the traditional prescribed lab where students weigh out a primary standard (Na_2CO_3) and carry out a standardisation against HCl.

Problem 2. Gas behaviour

In this PBL experiment, the students are given a variety of equipment and consumables to design a series of experiments to support the Ideal Gas Law, mainly using a gas chamber (syringe) and pressure and temperature sensors connected to dataloggers. The students were unfamiliar with the datalogging equipment; therefore it was necessary to give them some guidance and support at the beginning of the lab session. However, once they became familiar with the equipment they became more confident in their ability to design experiments and hence obtain acceptable results.

The very nature of this experiment required them to understand what each of the gas laws meant, and how they fitted into the Ideal Gas Law. To set up the experiments they needed to take into account what they wanted to measure, what had to be kept constant, how they were going to do it, and from there, develop a fair test. If for example they wanted to measure the effect of pressure on volume, then all the other variables needed to be kept constant i.e. the amount of gas, n, and the temperature, T. They then needed to generate data and manipulate it, to show the correct relationship between the two variables. Because there are no set procedures, the students really had to think about the experiments, and they were involved with all steps of the development, and hence involved in investigative experiments. Since some students were familiar with the laws and knew the expected outcome, having studied them for Leaving Certificate Chemistry or Physics, it was a surprise to them that designing effective experiments to prove the gas laws was not necessarily an easy task.

Problem 3. StateLab vs. LabAnalysis

StateLab vs. LabAnalysis is another excellent example of a PBL experiment carried out by students in their first semester. It builds on the previous week's skills, concepts and techniques, including problem solving, group work, acid base theory, titrations and mole calculations. It is also an experiment which requires group work both during the lab session and before and after. Students are given a number of 'vinegar' samples taken from an alleged 'suspect' batch delivered to a local supermarket. Then, representing either the StateLab (on behalf of the consumer) or LabAnalysis (on behalf of the shop owner), they have to carry out an analysis of these samples to determine if the vinegar is suitable for resale. They must do their analysis over two lab sessions by two different methods and compare their results. The task concludes with an oral debate, where the groups 'defend' their results and make recommendations. The groups are encouraged to find potential mistakes (such as using a graduated cylinder to measure an accurate volume for a standard) and gaps in the other groups' arguments.

Discussion

As this is an adapted form of PBL, some of the issues with PBL and its implementation, as discussed earlier, didn't arise here. For example, there was no sacrificing of the quantity of content and/or practical work for quality. Before PBL, in the traditional course students carried out 10 prescribed titration-based experiments in the first semester and 6 out of 9 physical chemistry experiments and 5 organic experiments in the second semester. In planning for the change-over the whole traditional module was reviewed to select the key skills, concepts and techniques to be covered. The PBL approach ensured that the students still get experience with all the key instrumentation and techniques, and cover similar chemistry concepts and, in fact, in most cases the actual experimental method employed in solving the problems is very similar to the procedure followed in the traditional laboratory.

Safety implications which can arise from students undertaking a PBL approach in the laboratory are also minimised by this adapted PBL approach. Though the students were encouraged to provide solutions to the problems, the actual laboratory procedures that the students had access to had already been limited by the PBL staff and were set out by the technical staff. Therefore, any safety implications were already identified and discussed with the students during the pre-lab sessions. Additionally, this meant that there were few extra resource or technical support issues.

Another issue with implementation of PBL is equipping the students with the skills to be successful in this alternative approach, especially in a context where the majority of their other courses and modules are taught in a traditional way, and where their previous experience most likely involved a minimum of 13 years of traditional schooling. The lack of experience with cooperative group working, taking responsibility for their own learning, searching for relevant information, communicating, etc. can place unwanted stress and worry on the students. Furthermore, there is an issue with prior knowledge, in that students need a certain amount of knowledge to be able to engage successfully with the problems. This is definitely an issue, especially considering the varied background of the students, where some have completed chemistry courses in second-level schools and others have not. The evaluation of this alternative approach showed that only 60% of the students indicated a preference for the PBL approach over a traditional approach after taking it for one semester, whereas 83% indicated a preference for the PBL approach by the end of the 2nd semester. This suggests that the students were better able to cope with these demands of both content and process, having gained more experience of it over the course of the year both within the PBL course and from the lecture-based chemistry module that runs concurrently with the laboratory module. There is further evidence to support this from the same evaluation, which specifically investigated the students' likes and dislikes of the PBL approach, where at the end of semester 1 some students reported a feeling a sense of frustration with the new approach. This was less prevalent by the end of 2nd semester.

Key issues, identified by Savin-Baden (2004) in her research on assessment in PBL, were unrewarded learning, disabling assessment mechanisms and impact of assessment on group work, and this is something that students in this study identified in some of their evaluations. They felt that the assessment mode, which was largely through their written lab reports, often did not reflect their level of engagement with the problem. However, where group work was assessed, the students' did not report any negative experiences about this.

On a general note, the students rated the pre-lab elements and the group work as the most beneficial aspects of the approach. With regard to the pre-lab element one student commented: "*Gave me as a student who hasn't done chemistry before an opportunity to get to grips with what I was doing before I went in*". Furthermore, the students were very positive about the whole experience and one reason given by a student for enjoying the PBL labs was that it "*Gave the chance to learn why we were doing an experiment and research background to it. This allowed a proper understanding of the procedure rather than just following the manual*". However, there were elements the students disliked, such as having to do more work outside of the designated laboratory time than the traditional students, and some did not like oral presentations. On a personal note, the principal investigator enjoyed facilitating these PBL-laboratory sessions more than the traditional ones, and was pleased to see at first hand the higher motivation and excitement for learning that a PBL approach can invoke in the students.

Conclusions

The PBL module aimed to develop students' practical and transferable, life-long learning skills as well as their scientific content knowledge and understanding in an environment where there is concern over the effectiveness of the traditional laboratory courses at undergraduate level. The PBL module also encouraged students to prepare for their laboratory session in an active and collaborative manner through the pre-lab element of the module, thus ensuring they were well prepared, thereby maximising the benefits of time spent in the laboratory. Furthermore, elements of group work, discussion, hands-on activities and alternative assessment methods, including oral and poster presentations, were combined to immerse students in an environment conducive to meaningful, deep learning.

The full PBL module has now been trialled over two years on 2 subsets of year 1 undergraduate students, and most recently (2005-2006) it was run without the presence of the principal investigator (O. K.) as a fully developed module in its own right. Following these developments, the traditional module has been redesigned for the whole 1st year cohort, encompassing many of the aspects of the PBL module (Lovatt et al., 2007).

In conclusion, both the PBL and traditional students cover all the same techniques and the same chemistry concepts within the same time frame and using similar resources. The PBL approach, however, provides more scope for skills development, and understanding of concepts and of the experimental process. The students get experience of the whole scientific process in a relevant and stimulating format. Furthermore, they seem to enjoy the experience.

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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,
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