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# Use of visualisation software to support understanding of chemical equilibrium: the importance of appropriate teaching strategies

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# Use of visualisation software to support understanding of chemical equilibrium: The importance of appropriate teaching strategies

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This paper describes the results of a study in which a group of science pre-service teachers used computer-based visualisation software resources to develop teaching strategies and lessons that would support the development of students' conceptual understanding of chemical equilibrium. They used SMV: CHEM, VisChem and chemistry software packaged with textbooks. The goal was to assist science/chemistry teachers to design lessons that would overcome known difficulties in developing students' understanding. Four teaching strategies of one teaching team are described in detail to illustrate the multifaceted nature of the way in which the software resources were used in lessons. Such a process of software deconstruction and resource integration in lesson plans has implications for all teachers of chemistry.

Keywords: visualisation software, conceptual understanding, chemical equilibrium, teaching strategies

## Introduction

Conceptual knowledge of chemical equilibrium is considered fundamental to the understanding of many other areas of chemistry such as acid-base behaviour, solubility, oxidation, and reduction reactions. Reviews of NSW HSC examination reports (Weerawardhana, 2006) revealed that students have difficulties in solving conceptual questions about chemical equilibrium. These difficulties could be categorised into two types of lower performance: language difficulties interpreting the problem statement, and expressing (representing) their understanding; and inadequate factual, conceptual and procedural knowledge. Review of literature (Weerawardhana, 2006) has identified three major possibilities, which are likely to cause senior high school chemistry students' difficulties in learning chemistry/chemical equilibrium. These three are: the nature of chemistry itself, the methods of teaching chemistry, and the students' methods of learning chemistry.

Conceptual questions in chemistry require higher-order thinking skills or higher-order cognitive skills (HOCS) to invoke student's deeper understanding of chemical ideas (Huddle, 1998; Nurrenbern & Robinson, 1998; Zoller, Lubezky, Nakhleh, Tessier, & Dori, 1995). Many conceptual questions involve three forms of representations - macroscopic, sub-microscopic, and symbolic - to be used with chemical information (Nurrenbern & Robinson, 1998). Zoller et al. (1995), Zoller (2001), Zoller, Dori, and Lubezky, (2002) strongly suggest that traditional methods and instructional strategies of teaching chemistry are not adequate to attain conceptual learning and use of HOCS. According to Anderson et al. (2001), HOCS involve procedural and conditional (metacognitive) knowledge. The development of students' understanding from a procedural (knowing how) to a conditional level (knowing why) could be aided by linking chemical concepts at the macroscopic level with the symbolic and sub-microscopic levels of representation (Treagust, Chittleborough & Mamiala, 2003). In other words, HOCS make use of 'representational competencies' or the ability to comprehend inter-relationships among macroscopic, sub-microscopic, and symbolic representations and the ability to represent chemistry concepts in multiple ways (Kozma & Russell, 1997). The use of multiple representations in combination can support a more complete understanding of chemistry concepts (Burke, Greenbowe, & Windschitl, 1998; Sanger & Greenbowe, 2000) because students are able to formulate mental images (mental models) of an object or process at sub-microscopic level that is not physically perceived (Wiebe, 1993).

## Theoretical background

In order to use and apply scientific understanding in a meaningful way students require better organised and deeper knowledge of basic concepts of science rather than having broader but superficial factual knowledge. Roth (1990) states that:

> Rich understandings of particular concepts and of the variety of relationships among them are also important cognitive tools, which are needed in order to create new meaningful conceptualisations. …meaningful conceptual understanding in science goes far beyond knowing facts and labels. Rather, conceptual knowledge becomes meaningful only when it can be used to explain or explore new situations (p.141).

Knowledge of chemistry is often communicated by using sub-microscopic representations such as molecular and structural formulae, stoichiometric reactions, ball-and–stick models, and bond-angles. Most sub-microscopic chemical representations are real, but too small to be observed. Therefore, much of the information about them is based on extrapolations of macroscopic representations - for example, sub-microscopic representations such as structural formulae, or the arrangement of atoms in molecules.

In chemistry, most concepts can be understood at the macroscopic, sub-microscopic, and symbolic levels. Johnstone (1993) places these three levels at the vertices of a triangle and emphasises that “every student studying chemistry for whatever purpose needs to operate within the triangle” (p. 703). The same view is presented by Bowen and Bunce (1997), who emphasise conceptual understanding in problem solving as the ability to represent and translate chemical problems using three forms of representations: macroscopic, sub-microscopic (particulate), and symbolic. Students’ skills in translating among representations are often limited since their understanding (schema) is confined to surface features of a particular and familiar representational form; for example, different forms of a macroscopic representation such as colour, density and appearance (physical properties). Kozma and Russell (1997) stress that the development of representational competencies is important for students since “these skills can help students extend an understanding built on the surface features of a single representational form to one that is connected to other representational forms and includes underlying principles and concepts” (p. 964). Mahaffy (2004) adds another important aspect of understanding chemistry i.e. *human influence*. Understanding chemistry depends on the diverse influences of the society and living environment that shape the teaching and learning of chemistry.

> …Fundamental changes in the contours of chemistry as defined by new interfaces and research areas; changes in our understanding of how students learn, and how that applies to chemistry education; the wide-spread implementation of computer and information technologies to visualize complex scientific phenomena; and external forces, such as global concerns about energy and water resources and the environment, and the level of chemical literacy and public understanding of science (Mahaffy, 2004, p. 229).

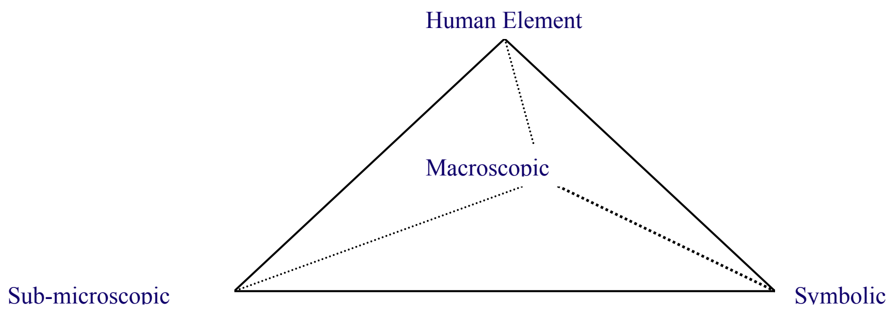


**Figure 1: Tetrahedral chemistry education (Mahaffy, 2004, p. 231)**

As a consequence of these influences the need for new dimensions of learning chemistry have emerged and these extend ‘three-fold representations’ of chemistry (Johnstone, 1993) to ‘tetrahedral chemistry education' (Mahaffy, 2004) with the addition of the 'human element'. The tetrahedron model (see Figure 1) weaves conceptual knowledge of chemistry with its applications. Hence ***Conceptual understanding of chemistry*** involves conceptual knowledge, the ability to translate between and among different representations (representational competencies), and their use and application to explore new situations, and understand human influences and environmental events.

## The study

The participants of the study were a group of eight pre-service science teachers, who engaged in two workshops, designed lessons then implemented them with 65 year eleven chemistry students from two schools. The first pre-service teacher workshop refreshed their knowledge of the topic of chemical equilibrium and allowed them time to use the software SMV: CHEM and VisChem. The second workshop challenged them to rearrange software interface elements to incorporate them into classroom teaching strategies that they would implement with the 65 year eleven students in the two local schools.

The pre-service teachers collaborated to design and implement their teaching strategies. They worked as small teams (Team A, B, and C) and were encouraged to use various combinations of resources from application software (including other software packaged with chemistry textbooks) with hands-on activities and chemical demonstrations.

Classroom observations, students' attitudes towards lessons, pre-service teachers' reflections and interviews were conducted to identify the impact of these teaching strategies on the professional development of the pre-service teachers.

**Table 1: Pre-service teachers' use of different resources**

| Teams | Team A (2 members) | Team B (2 members) | Team C (3 members) |
|---|---|---|---|
| Application software | Word only | Word, PowerPoint, and Excel | Word, PowerPoint, and Excel |
| Physical analogies as demonstrations | Water boiling in a covered beaker illustrates the dynamic reactions of evaporation and condensation.<br><br>Tennis balls used to show equal rates of dynamic reversibility.<br><br>Two containers are joined with a plastic tube. When water is added to one container the level in both stabilises; used to explain Le Chatelier's principle.<br><br>Seesaw analogy. | A glass 2/3 filled with water.<br><br>Students act as water molecules and desks are arranged as a beaker to represent evaporation of water in an open and sealed beaker (simulation). | Preparation of soda water.<br><br>Catching of golf balls (simulation).<br><br>Sand put in and out of a big container at equal rates to show the steady state of the system (simulation).<br><br>Escalator analogy. |
| Hands-on activities | $Fe^{3+}$ / $CNS^-$ experiment to illustrate Le Chatelier's principle. | Group activity with computer – Dynamic equilibrium task. | Group activity with computer experiment and animation. |
| Resources from SMV: CHEM | | Animations, Dynamic graphs, Video segments. | Animation video segments and dynamic graphs. |
| Resources from VisChem | Water boiling animation. | | |
| Resources from other chemistry software | Dynamic (animated) graphs to illustrate the results of $Fe^{3+}$ / $CNS^-$ experiment from software in textbooks. | Some diagrams and pictures from clip arts or websites | |

## Results

Pre-service teachers drew on a range of resources and methods to design their lessons, including graphics from related web sites or resources in any software they found relevant. Table 1 presents what software, physical analogies, hands-on resources and electronic resources (from software or elsewhere) the three teams of pre-service teachers incorporated in their lesson designs.

Each team took slightly different approaches to the topic of chemical equilibrium. Team A covered reversible reactions and Le Chatelier's principle and Team B covered the dynamic nature of chemical equilibrium and the effects of temperature and pressure on equilibrium systems. Team C covered phase equilibrium, properties of equilibrium and dynamic nature of chemical equilibrium.

Teaching strategies of three lessons are presented in Table 2. Most teaching strategies used the same sequence of instruction, same presentation methods and resources. Four teaching strategies in lesson one (highlighted in Table 2) were chosen to illustrate how pre-service teachers of Team A used different resources to integrate them into their lesson plan (see Figures 2 and 3). First two strategies linked hands-on demonstrations and students' group simulations to VisChem animations, and the 3rd and 4th strategies coupled experimental observations and analogies with dynamic graphs to explain Le Chatelier's principle.

**Table 2: Teaching strategies of three lessons**

| Lesson | Part | Teaching strategy |
|---|---|---|
| 1 | 1 | 1. Experimental observation linked to an animated model. |
| | | 2. Actions of animated model coupled with a students' simulation activity. |
| | 2 | 3. Experimental observation linked to dynamic graph. |
| | | 4. Experimental observations and dynamic graphs coupled with two analogies. |
| 2 | 1 | 5. The use of familiar examples to explain reversibility of reactions. |
| | | 6. Symbolic equations were linked to molecular-level animations. |
| | | 7. The use of videos of experiments, synchronous animation, and synchronous graph. |
| | | 8. Molecular-level animation linked to a simulation (students' activity). |
| | 2 | 9. Video first and then video with animation. |
| | | 10. Changes in video linked with the changes in dynamic graphs. |
| | | 11. Different connections were made among different representations. |
| | 3 | 12. Experimental video first and then combined with molecular-level animation. |
| 3 | 1 | 13. Use of single representations first and then followed combined representations. |
| | | 14. Temporal changes of animation and dynamic graph linked to an experimental demonstration. |
| | | 15. Simultaneous use of synchronous actions of video, animated molecular model and dynamic graph. |
| | 2 | 16. Analogies linked to simulations (students' activities). |
| | 3 | 17. Mapping similarities and temporal changes of three similar systems: video and animation, and video, animation and symbolic representations progressively. |
| | | 18. Observations from video of experiment mapped with the changes of animation |

### Example 1: Part 1 of lesson 1 (Team A)

*Organization of instruction*
1 Experimental observations were illustrated using an animated model.
2 Changes in the animated model were explained with students' simulation activity.

*Strategy 1*
Students in small groups were asked to observe the similarities of both the animation and experimental demonstration at the same time. The experiment demonstrated how steam goes up and condensed water droplets flow down along the walls of the beaker.

*Strategy 2*
Students simulated the evaporation and condensation process using tennis balls as water molecules. Rolling of the same number of tennis balls along the floor in both forward and backward directions at the

same speed and same time represented the constancy of product's and reactant's concentrations (but not equal) in an equilibrium system at any time. This also represented the equal rates of both forward and reverse reactions at equilibrium of $H_2O_{(g)} \Leftrightarrow H_2O_{(l)}$.

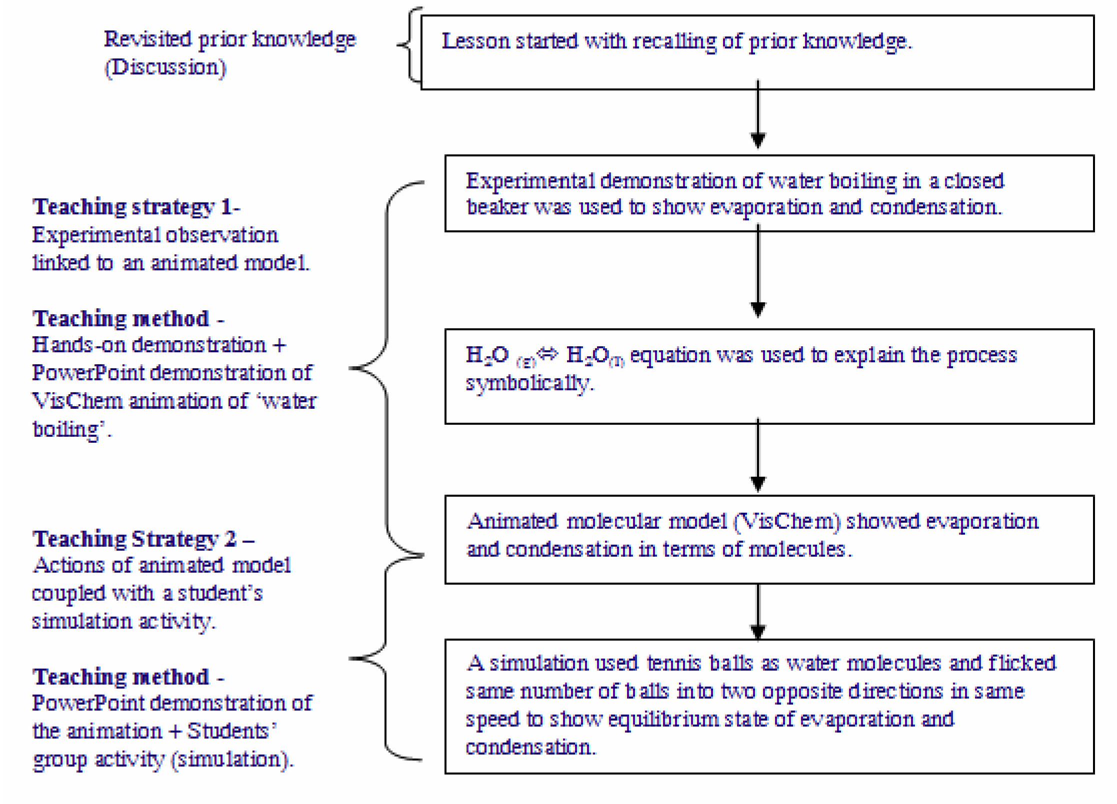


**Figure 2: Example one**

*Summary of Team-A pre-service teachers' comments (from interviews and their reflections)*
Recalling of students' prior knowledge and experience is important to connect new information into existing knowledge. Experimental demonstration, animation and simulation may help students to map different attributes such as surface similarities, temporal changes, and relations of the same process otherwise many aspects related to the sub-microscopic level cannot be perceived. If these students were presented only with the experimental demonstration with teacher's explanation (like traditional chemistry teaching) or only the animated molecular model with accompanying narration, or only the simulation, it would not make sense. Even though the molecules of the animated molecular model do not represent every feature such as exact shape, actual size, accurate bond angles, etc. of real water molecules, students may develop mental models that contain many of the attributes in relation to the physical equilibrium of water (evaporation and condensation process). The simulation activity, which involved students' actions, could further strengthen the mental models, which were already developed by the first strategy.
An increase in the number of representations may increase the understanding of different aspects or attributes of the same concept. For this purpose the presentation format of instructions and the use of different teaching methods (teaching strategies) appear to be crucial. For example, teaching methods such as students' simulation activities could increase student engagement and motivation. These strategies may provide students with more opportunity to construct their mental models of the equilibrium process.

### Example 2: Part 2 of lesson 1 (Team A)

*Organization of instructions*

1. Experimental observations were illustrated using dynamic graphs.
2. Experimental observations and features of the dynamic graphs were illustrated using analogies.

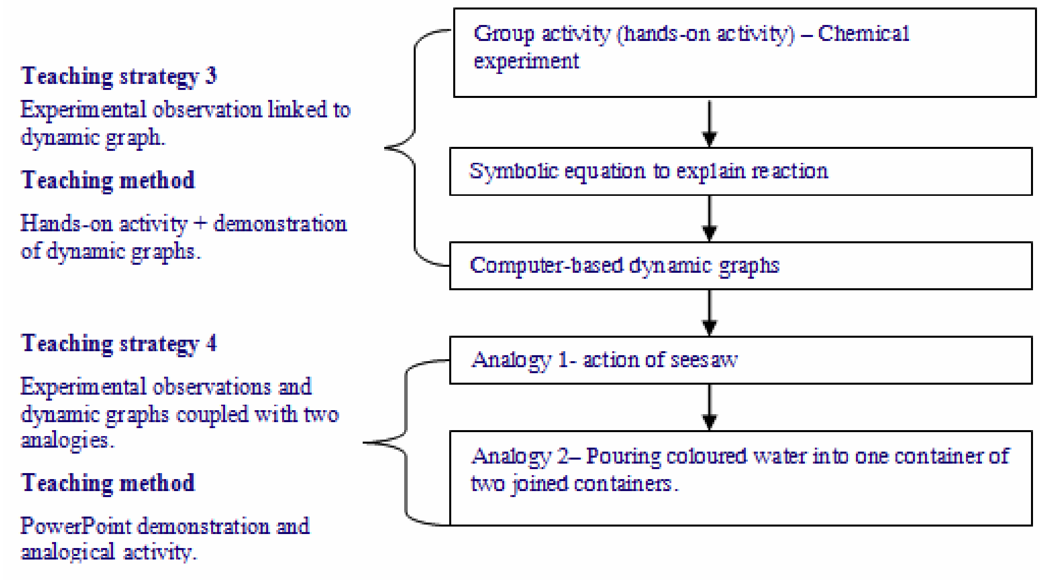


**Figure 3: Example two**

*Strategy 3*
After explaining the physical equilibrium (part 1 of lesson 1), the pre-service teachers (Team A) applied the knowledge of physical equilibrium to describe reversible reaction of chemical equilibrium and Le Chatelier's principle.
They used visible changes of the following reaction:
$Fe^{3+}$ (yellowish) + 3 $CNS^-$ (colourless) ⇔ Fe $(CNS)_3$ (deep red)
The students were in small groups (3-4 students) when completing the experiment. When $CNS^-$ or $Fe^{3+}$ is added to the system the red colour increased. The colour changes of the reaction mixture indicated respective changes in concentrations of reactants and products. Le Chatelier's principle was first explained using experimental observations and then the reaction equation, followed by the dynamic graphs from a CD-ROM packaged in a chemistry textbook.

*Strategy 4*
The pre-service teachers combined the experimental observations and the actions of dynamic graphs with two analogies to explain Le Chatelier's principle. The first analogy was the seesaw.

*Summary of Team-A pre-service teachers' comments (from interviews and their reflections)*
Since the reaction is very fast, students had difficulty in observing fast colour changes. Pausing the dynamic column graphs at three-second intervals that could show the fast reaction in slow motion. This helped students to see that fast reaction and the colour changes slowly. The changes in heights of three coloured columns indicate the respective concentration changes of two reactants and product.

The seesaw analogy can explain some aspects of Le Chatelier's principle, i.e., when reactants concentrations are changed the equilibrium is disturbed. During the second analogy, students added water into one container of two joined containers to show the same water levels after some time. This was explained as the system coming to a new equilibrium after adding coloured water (reactants) and its colour changed due to new concentrations of reactants and products. However, although these two analogies could show two or three different attributes of the real reaction system, all aspects related to Le Chatelier's principle could not be explained.

## Discussion

As illustrated in the pre-service teacher reflections on the lessons they conducted with year 11 students, the combination of workshops, collaborative lesson design and team implementation helped to develop pre-service teacher awareness of the complexity of helping students to develop conceptual understanding of a core chemistry concepts. Pre-service teachers indicated the need for recall of prior knowledge, connection with student experience, the value of multiple representations, and the ability for minor defects in any individual representation (such as an animation or analogy) to be diminished as the number of representations or teaching strategies is increased. Multimedia resources could allow students to pause, replay and relate different representations and emphasise the dynamic nature of chemical equilibrium.

This increased awareness among pre-service teachers of the complexity of the topic, coupled with willingness to design multiple strategies to support student learning, could translate into a range of benefits for students. The year 11 students in this study valued the pre-service teachers' use of multiple representations (animations, video, and dynamic graphs) combined in various ways with analogies, physical simulation activities, and hands-on experiments. Although detailed data was not collected on student learning outcomes as a result of these brief lessons, the motivational benefits of the range of strategies was readily apparent.

Physical analogies linked to computer-based representations appear to play a motivational role in meaningful learning as they provide concrete references. Students reported that they felt they could understand 'chemical equilibrium' and therefore wanted to learn more. Analogies made highly interactive animated molecular models interesting to students. An analogy may relate new information or targeted molecular level information to students' real world experience. For this reason analogies can potentially promote conceptual change by helping students to overcome existing misconceptions or alternative conceptions of the dynamic nature of chemical equilibrium. Ideally analogies could help students recognise errors in conceptions they currently hold, reject those conceptions, and adopt new conceptions that are accepted by the scientific community.

Several strategies in one lesson could use many multiple representations in a flexible way that makes it easier to present different aspects of concepts. The sequence of strategies and the order of multiple representations complement information previously presented and reduce misinterpretations. For example, the first teaching strategy used experimental observations and an animated molecular model, which are two external representations that differ in the information each expresses, so that each representation denotes different aspects of the targeted internal representations (mental models) of reversible reactions in the physical equilibrium process. Empirical observations showed evaporation and condensation as a physical process, and the animated molecular model reduced possible misinterpretations of the physical process in terms of molecules. Symbolic representation combined the information from both empirical and sub-microscopic representations and communicated that knowledge. Empirical observations or animation alone would be insufficient to carry all the information about the physical equilibrium process or would be too complicated for students to interpret if it did so.

The second strategy used a simulation that supported and strengthened the targeted mental representations in the animated molecular model. Familiar or concrete simulation activity simply provided the same information in a different way, limiting misinterpretation of the animated model and therefore perhaps making internal mapping of similarities easier. Further, active engagement of students in simulation activity could increase attention and motivation. Since some information was common to the animation and simulation the simulation is partially redundant. This partial redundancy of information makes possible new interpretations about reversible reactions. Further, by distributing information over partially redundant representations, multi-representational learning environments can use less complicated representations. Since the knowledge about reversible reactions in terms of molecules was used, the third teaching strategy was complemented by the first two strategies.

In the fourth strategy some aspects of the experimental observations and the dynamic graph and the analogy were similar, therefore the analogy was partially redundant, but it limited misinterpretations of the dynamic graph and strengthened the targeted mental representations by facilitating comprehension.

By combining representations, students were no longer limited by the strengths and weaknesses of one particular representation. Therefore analogies combined with multimedia representations can play an important role in promoting meaningful learning by: organising information or viewing information from a new perspective; giving structure to information being learned by drawing attention to significant features of the target domain or to particular differences between the multiple representations and target domains; and visualising abstract concepts, or unobservable phenomena.

## Conclusion

The pre-service teachers worked in small peer groups with the workshop facilitators, shared their understanding and had opportunities to obtain expert guidance. They were able to incorporate different representations (macroscopic, sub-microscopic, and symbolic) into teaching strategies with different combinations of other analogies and simulation activities to engage students in learning about chemical equilibrium.

Researchers report that most chemistry teachers rely on textbook information, but these pre-service teachers did not rely on textbooks – instead they used new teaching approaches and materials. They used computer-based technologies to couple software resources with physical analogies in teaching strategies that lead to a motivational learning environment and may have contributed to meaningful learning (conceptual understanding). Further data collection from students over an extended time period would be required to verify the extent of the development of their conceptual understanding. The planning of analogies and simulations was done in advance and the teachers provided rich explanations. They applied a variety of examples (multiple representations) that appeared to motivate students.

Pre-service teachers' knowledge construction was an iterative and collaborative process. By working in groups they developed accurate communication, shared meanings of words, negotiation skills, respect for others' ideas, and meanings of common words used in chemistry. They collaborated to design experimental set-ups and helped each other to understand how to use unfamiliar materials and apparatus.

We believe that the process of workshops, shared experimental design and classroom implementation allowed the pre-service teachers to more fully develop their conceptual understanding of chemical equilibrium. This form of professional development also helped them to be more aware of student learning difficulties in this area and to use the software resources in ways that targeted the specific needs of their students. Our interview transcripts from pre-service teachers and students indicates that this was an efficient and effective use of rich media elements in the software that targeted the specific learning needs of students. The process benefited pre-service teachers by allowing them to customise the media to suit their approach to teaching as well as to take into account the learning needs of their students.

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