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

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

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

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

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

History and brief description of the experiment

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

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

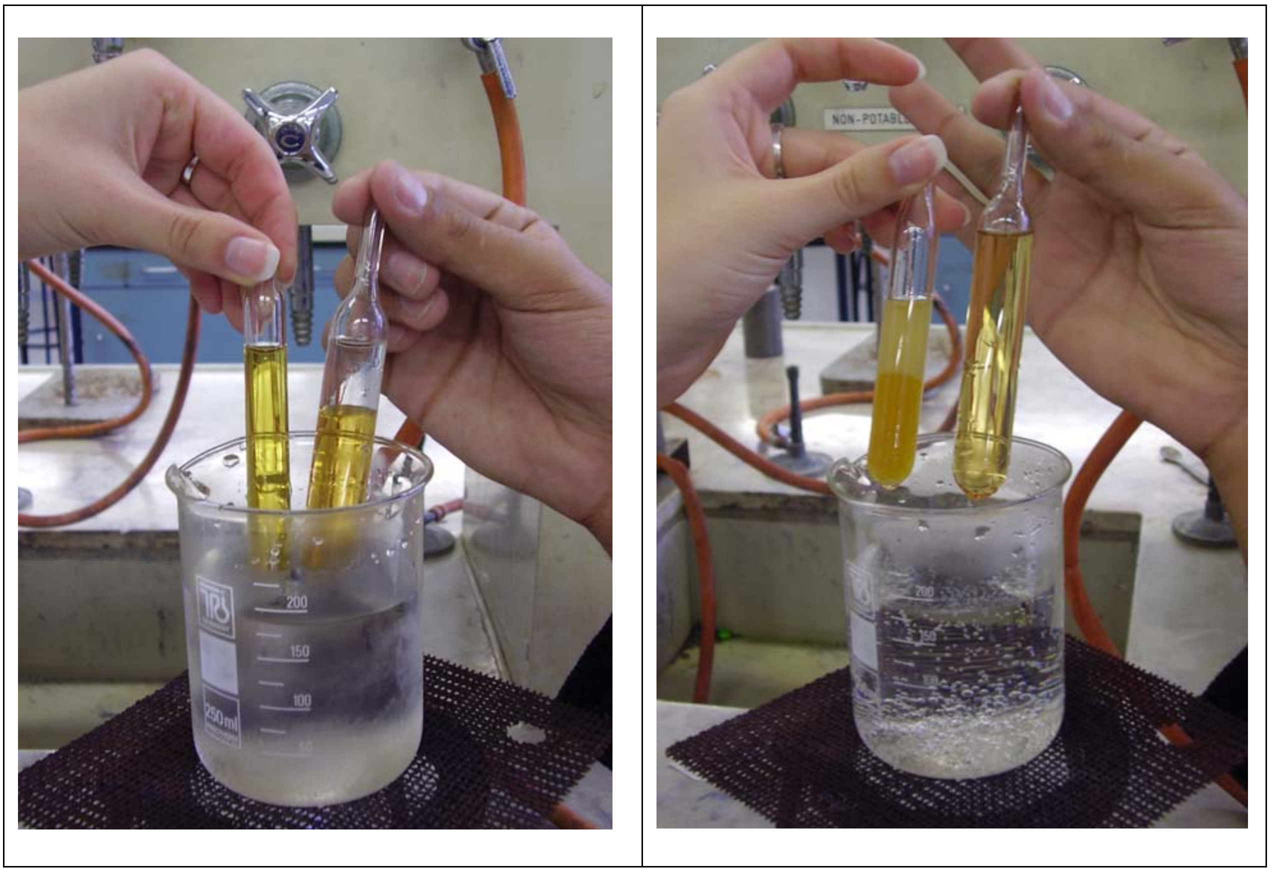
Experiment 1A (Thermodynamics of rubber bands, Part 1): Students place a rubber band against their lips and rapidly extend it so that the length is at least doubled. They then let the rubber band relax quickly, while still holding it against their lips. Students are asked whether they felt a temperature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

Experiment 2A (Thermodynamics of rubber bands, Part 2): The students suspend a 1 kg block from a retort stand using 3-4 rubber bands. They then gently warm the rubber bands with a heat gun and watch whether the bands expand or shrink. Counter-intuitively, the rubber bands shrink when they are heated, as shown in the short video clip (http://www.rsc.org/Education/CERP/issues/2007_2/index.asp), which is available with the on-line article or the ACELL website. Students are provided with a generic description of polymers and some background material about entropy. The pair must explain their interpretation on both a macroscopic and microscopic level.

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

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

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



Experiment 5A (Drinking Duck): The students must explain the thermodynamics principles behind how the famous 'drinking duck' works (see Figure 2, a short video clip at http://www.rsc.org/Education/CERP/issues/2007_2/index.asp, and Lorenz (2006) for an in-depth analysis). The duck takes a drink from the bowl, then sways like a pendulum, slowly stopping, then tips over and drinks again. We use ethanol in the bowl rather than water to speed the duck up, especially on humid Sydney summer days! This is a good test of whether the students have developed a deep understanding of enthalpy, entropy, heat, temperature, and pressure.

Figure 2. Photo of drinking duck in action.

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

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

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

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

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

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

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

Educational Objectives

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

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

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

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

2.1 Theoretical and Conceptual Knowledge

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

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

2.2 Scientific and Practical Skills

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

2.3 Thinking Skill and Generic Attributes

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

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

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

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

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

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

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

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

Student learning experience

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

Method

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

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

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

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

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

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

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

Student feedback results and discussion

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

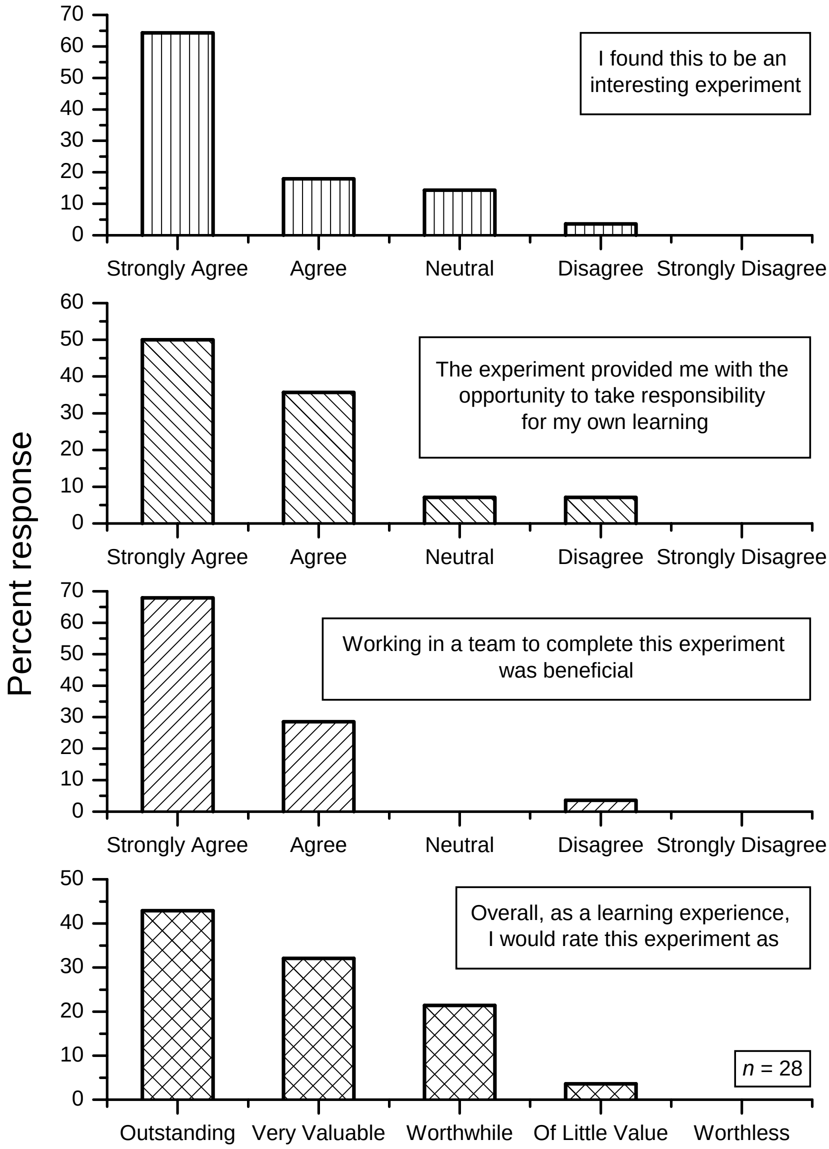
Table 3: Summary of categories used in content analysis of the ASLE open-response items.

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Summary and conclusions

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

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

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

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

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

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