Using a context-based approach to undergraduate chemistry teaching – a case study for introductory physical chemistry

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Abstract: This paper describes the rationale for using a context-based approach to the teaching of undergraduate physical chemistry, together with an overview of a case study, which has been developed to teach aspects of thermodynamics, kinetics and electrochemistry usually associated with the early stages of undergraduate chemistry courses. The context is that of the next generation of energy for an emerging city (Los Verdes) located in the south-west region of the USA. Working in groups, students use an array of physical chemistry principles to examine the combustion of fossil fuels and hydrogen, the use of hydrogen in fuel cells, solar power, and energy from a geothermal source. Students gain experience in working with both familiar and novel types of problem solving. [*Chem. Educ. Res. Pract.*, 2005, **6** (3), 166-179]

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Introduction

Employers, educators and funding bodies continue to emphasise the importance of the development of a wide range of subject-specific and transferable skills during university courses. This view has been reinforced in the UK by the QAA Subject Benchmarking activity and the Programme Specification Template in which subject specific skills, cognitive and transferable skills are very prominent.[1, 2] Within the new system of quality assurance, UK chemistry departments will need to demonstrate that students have developed and been assessed in a range of these skills. Such skills include, for example, working with novel problems and planning strategies for their solution, interpretation of chemical information and presentation of scientific arguments, as well as the usual range of transferable skills such as communication, group work, information retrieval and time management. Although some traditional methods of teaching and learning chemistry do not enable students to gain many of these skills or, at least, do not provide academics with evidence that they have done so, various strategies have been developed for addressing these issues. Some of these teaching and learning styles involve discipline-related activities (Bailey, 1997), while others are discipline independent (Wyeth, 1997). Problem-based case studies have a long history in many subject areas and their value within chemistry has long been recognised (Garratt and

[1] http://www.qaa.ac.uk/academicinfrastructure/benchmark/honours/chemistry.asp
[2] http://www.qaa.ac.uk/academicinfrastructure/programSpec/progspec0600.pdf

Mattinson, 1987; Pontin et al., 1993). More recent examples within the main sub-disciplines of chemistry e.g. organic (Bennett and Cornely, 2001), inorganic (Breslin and Sanuodo-Wilhelmy, 2001) and physical (Holman and Pilling, 2004) chemistry, and subjects allied to chemistry such as biochemistry (Cornely, 1998) and environmental science (Breslin and Sanuodo-Wilhelmy, 2001; Cheng, 1995) have also been described. Problem-based approaches in laboratory work are also gaining in popularity (McGarvey, 2004; Jervis et al., 2005; Tsaparlis and Gorezi, 2005).

An increasing number of students entering into higher education to study chemistry do so having studied in a context-related way in schools and colleges, and a review of such an approach has illustrated its popularity for students studying chemistry in the UK (Holman and Pilling, 2004; Burton et al., 1995). The employment of more 'real-life' examples has also been identified as a recommendation for the teaching of chemistry following a review of the science curriculum in schools in the UK.[3] This context-based approach is not necessarily continued into first year courses although there are materials readily available for use in later stages of programmes. Such materials tend to focus on applied areas of chemistry, such as industrial, pharmaceutical, forensic, and environmental chemistry. This is not surprising, given the linear degree structure traditionally adopted by the majority of university chemistry courses, with core chemistry being taught early in the programme and applications appearing later. Our own experience (Belt & Phipps, 1998; Belt et al., 1999, 2002; Summerfield et al., 2003) in producing case studies for analytical chemistry revealed that not only could the problem-based approach deliver curriculum content, but it also succeeded in engaging, enthusing and motivating undergraduates in chemistry. Therefore, we decided to produce a series of problem solving case studies, which focussed on core areas of organic, inorganic and physical chemistry usually encountered during the early stages of undergraduate chemistry courses. One of these case studies, which is concerned primarily with fundamental aspects of physical chemistry, is described here.

Case studies in physical chemistry

A review of the chemical education literature indicates that many teachers of physical chemistry believe that their students find this sub-discipline of chemistry to be 'hard' (Sözbilir, 2004), although we remain unconvinced that this perception is any truer for physical chemistry than for any other chemical sub-discipline. What is clearer is that this perception has prompted some researchers to investigate the reasons *why* students find physical chemistry difficult (Nicoll & Francisco, 2001; Hahn & Polik, 2004). A number of factors appear to contribute to this perception. Perhaps surprisingly, these are not simply limited to students' abilities in mathematics, despite physical chemistry having such a high mathematical component. Factors such as motivation, logical thinking and prior knowledge are also important. In any case, there exist a substantial number of examples in the literature where teachers of physical chemistry have attempted to alleviate this perceived problem using a diverse array of teaching methods, and these are reviewed elsewhere (Hamilton, 2003).

It is clear that teaching chemistry within an applied context is gaining in popularity and Zielinksi and Schwenz have identified the importance of context-rich teaching materials in the teaching of physical chemistry in the 21st century (Zielinski and Schwenz, 2001). Emerging out of the success of the Salters chemistry course used in pre-university chemistry teaching in the UK (Burton et al., 1995), Holman and Pilling have adopted a contextualised approach to the teaching of thermodynamics for university students, concluding that such a method seems to be successful in enhancing students' interest in, and understanding of, thermodynamics,

[3] http://www.planet-science.com/sciteach/review/Findings.pdf

though they expressed some doubts over how successful it is in developing students' abilities in problem-solving (Holman and Pilling, 2004). In the US, high school students taking a context-based course (ChemCom) outperformed those students studying more traditional courses. This success was attributed, at least in part, to higher levels of interest and motivation amongst the students, together with their perception of the relevance of the topics (Sutman and Bruce, 1992; Gutwill-Wise, 2001). However, there can be an apparent mismatch between the teaching styles that school students experience (and their prior knowledge) with expectations of tutors in universities, and this has been identified as a possible cause of students' difficulties in understanding thermodynamics (Carson and Watson, 1999).

Having considered these points, our rationale for producing some context-based teaching material for physical chemistry appears justified. That apart, when we first set about designing a case study for physical chemistry teaching, it was also our aim to produce a resource that would complement other teaching activities, rather than substitute for them, especially as it is also clear that different students respond to contrasting learning environments, often at different times. In addition, we chose to concentrate on selected topics of physical chemistry with an emphasis on revisiting these themes rather than attempting to cover an entire syllabus. By taking this approach, we believed that the case study would enable students to reinforce their knowledge and understanding of topics, make links between different areas of chemistry, and to integrate theory with applications. The case study has been designed to use as an entire package, but individual activities can be used with appropriate introduction and background information. This feature enhances its flexibility. Finally, in selecting a context, we decided that students would be motivated by a 'domestic energy' related theme, since it is topical (and will continue to be so in the foreseeable future), relevant to all students, and encompasses both economic and environmental considerations. From a tutor's perspective, it has the additional appeal that various physical chemistry principles can be investigated within this theme.

Capital City

The chemistry covered in the *Capital City* case study is concerned with, but not exclusively, introductory thermodynamics and kinetics, the latter having been identified as a particularly key topic for 21st century physical chemistry teaching (Zielinski and Schwenz, 2001). The case study uses the context of identifying fuel sources for an emerging city (Los Verdes, located in the south-west USA) by evaluating and interpreting a range of physical chemistry data. These fuels include both traditional energy sources (e.g. fossil fuels) and renewable energy sources (e.g. fuel cells, solar cells). In terms of scientific skills, students need to manipulate 'core' thermodynamic and kinetic equations and evaluate the outcomes of these. As the case study evolves, students need to make estimations and approximations where traditional approaches are inappropriate. In order to complete the case study, students need to develop and use a range of other skills such as effective group work, communication, organisation, problem solving and critical thinking.

Overview

The case study is delivered over 8 1-2 hour sessions and all the paper-based material required for each session is provided by the tutor (see **Case Study Layout - Editorial considerations**). In Plymouth, the case study is compulsory for all the students and is timetabled towards the end of the first year of the degree programmes in order that it complements and builds upon the relevant background lecture courses, particularly in thermodynamics, kinetics and electrochemistry, which are delivered earlier in the year. The format of the study consists of a 3-way liaison between the head of a city council department (unseen), a project manager of a power consultancy company (the tutor) and a project advisory team (the entire student cohort). This advisory team is subdivided into smaller groups (3-5 students) and these retain their membership for each session. Each sub-group works on a common theme during each session, although in some cases, the datasets with which they are working are different. Having begun the case study with a general discussion of potential energy sources (Session 1), the groups accumulate a portfolio of data and analyses for various fuels in the subsequent sessions (Sessions 2-7), re-visit the overall project aim in the final session (Session 8), and deliver a short oral presentation and/or report, the content of which is informed by the outcomes of the previous sessions. A summary of the sessions in terms of their principal themes and tasks is shown in Table 1. A tutor guide has also been produced which gives outline time plans for the sessions, model or suggested solutions to the individual tasks, topics for discussion and blank templates where needed.

Individual sessions

Session 1: *New energies – new futures: the Capital City project*

In the first session, students are introduced to the case study in terms of their roles, the overall aims and the assessment. Having also discussed the philosophy behind the study and overviewed the scientific and transferable skills that will be developed, the groups are given the first e-mail correspondence from the project manager (the tutor), which describes the expectations for the session. Accompanying this e-mail is a letter from the Head of the Department of Energetic Affairs (DEA) at the Los Verdes City Council who is responsible for the overall energy project, inviting the project manager and his/her team to provide some early feedback on potential energy sources. An extract from a previous 'initial needs' study is also included in the correspondence. After discussing these documents, the students produce a short summary outlining their suggestions for future power generation. At this early stage of the case study and, with the absence of more detailed information, the students need to rely principally on their prior knowledge and engage in group discussions. There is no single 'correct' solution to the first session, but each group is briefed to make a single proposal that is 'Economical, Environmental and Eye-catching'. As such, the first session acts as a suitable 'ice-breaker' and can give an early indication to the tutor of students' prior knowledge of energy production and possibly of physical chemistry (Carson and Watson, 1999).

Session 2: *Steam power plant using fossils fuels*

At the beginning of the second session, the groups are informed that their initial proposals have been considered by the DEA, along with those provided by competitors. The outcome of these deliberations reveals that a total of six named energy sources should be investigated in more detail. These are presented to the group by the project manager together with a brief rationale for why some alternatives have been rejected (e.g. negative public opinion for nuclear power, limited water supply for hydroelectric). By doing this, all the group's suggestions are acknowledged, but the tutor is able to keep the subsequent investigations within his/her control.

Table 1. Summary of the *Capital City* case study

Session	Title	Tasks / Activities	Problem-solving
1	*New energies – New futures: The Capital City project*	Discussion of potential energy sources based on prior knowledge. Propose a solution which is 'Economical, Environmental and Eye-catching'	Evaluation of prior knowledge within a group. Working within a restricted timescale (all sessions)
2	*Steam power plant using fossils fuels*	Use of the Carnot cycle and determination of the cost efficiencies of fossil fuel combustion. To consider the potential environmental impact of fossil fuel combustion	Carnot cycle and Gibbs free energy calculations. Conversion of thermodynamic terms to costs. (Homework: Quantitative determination of CO_2, NO and SO_2 from combustion)
3	*Air pollution from fossil fuel burning in steam power plants*	Determination of production of the greenhouse gas NO due to combustion of fossil fuels and direct oxidation of nitrogen at high temperatures. Evaluation of the total contributions of CO_2, NO and SO_2	Influence of temperature on equilibrium constants. Making estimations from graphical data and applying approximations to determine equilibrium constants
4	*H_2 production by steam reforming of methane (SRM)*	Assessment of the generation of hydrogen by the Steam Reforming of methane (SRM) and subsequent combustion	Determination of rate parameters for a catalytic process. Calculation of optimal conditions for a series of catalysts and temperatures according to specified criteria
5	*Fuel cells*	Assessment of the use of hydrogen in fuel cells by calculation of energy efficiencies from two contrasting methods	Calculation of thermodynamic data from electrochemical measurements. Identification and quantification of errors. Conversion of thermodynamic terms to cost efficiencies
6	*Solar power*	Determination of the efficiencies of two types of solar energy conversion and up-scaling to a power plant	Interpretation of graphical data. Using estimations and approximations to solve numerical problems. Interconversion of units and manipulation of unfamiliar parameters
7	*Geothermal power*	Investigation of the potential to use pressurised steam from a natural source as an energy source	Carnot cycle (re-visited). Interpreaetion of unfamiliar graphical data and numerical manipulations
8	*Final recommendations*	Synthesis of previous findings and presentation of final recommendations	Interpretation of a large dataset including both quantitative and qualitative data

The first potential power source to be investigated in more detail is fossil fuel combustion. Each group receives a briefing paper on 'Steam Power Plants', which describes the principles of their operation together with some relevant thermodynamic relationships. Individual groups are allocated a different fossil fuel type (further e-mail) ranging from coal of various grades to oil and gas. The objective for each group is to determine the efficiency of each fuel expressed as the cost per unit power output ($\$ MWh^{-1}$). In order to do this, the groups need to perform thermodynamic calculations (e.g. free energy calculations) and combine these with power plant operational parameters such as fuel consumption rates and fuel costs (see Appendix 1 for briefing paper, e-mail correspondence and fuel data for one group). As such, this session involves the students performing the types of calculations that they are likely to have some familiarity with, even if the exact procedure is new. This type of problem solving was perceived by the authors as being an important feature of the early stages of the case study to promote the students' confidence. At the end of the session, the results of the individual group calculations are collated by the tutor, compared with model answers and feedback is given. The session concludes with a further e-mail to each group that acknowledges their economic considerations and raises the potential environmental significance of fossil fuel burning (*viz*. the production of CO_2, NO and SO_2 as atmospheric pollutants). In order to investigate these impacts more rigorously in the subsequent session, the groups are asked to calculate quantities of CO_2, NO and SO_2 emissions for their respective fuels, and present these data at the beginning of Session 3 (note: this is the only formal 'homework' for the entire case study).

Session 3: *Air pollution from fossil fuel burning in steam power plants*

Once the atmospheric gas calculations from Session 2 (homework) have been collated and summarised, the groups receive a further e-mail stating that the project team may not be aware that NO production can also take place due to direct reaction between N_2 and O_2 in air, particularly at elevated temperatures (e.g. in combustion chambers). The groups are advised that this is in need of further investigation if the true environmental significance of fossil fuel combustion is to be evaluated, and they are given some further thermodynamic data, along with a briefing paper on greenhouse gases. In order to complete this task, students need to combine thermodynamic terms (determination of a free energy of reaction and subsequent determination of an equilibrium constant, K) and evaluate the effect of temperature on K for a reaction. Whilst the former type of calculation may well be familiar, the second has been designed so as to require the students to make estimations from graphical data and, in turn, make assumptions about variations in atmospheric partial pressures of gases. In this particular case, since the equilibrium constant for the formation of NO from N_2 and O_2 is always small, even at high temperature (K = 6.3 x 10^{-3} at 2700 K; the highest combustion temperature encountered by any group), a reasonable assumption to be made is that the N_2 (*ca*. 0.78 atm) and O_2 (*ca*. 0.21atm) partial pressures are essentially constant. As such, reasonable NO concentrations can be determined from a simple consideration of the dependence of K on T (graphical data supplied). This type of 'one-step' estimation/assumption for a quantitative calculation enables the students to observe the outcome quickly, which is particularly useful for students who have little experience with this type of problem solving.

This session ends with a tutor-led discussion (optional) on the potential significance of NO and SO_2 generation in terms of the production of acid rain (further chemistry is involved before HNO_3 and H_2SO_4 are generated as shown via a handout/overhead transparency).

Session 4: *H_2 production by steam reforming of methane (SRM)*

Having spent two sessions considering the combustion of fossil fuels, students turn their attention to the utilisation of hydrogen as a fuel in Sessions 4 and 5. In Session 4, the groups are given a briefing paper that describes the Steam Reforming of Methane (SRM, the catalytic production of hydrogen from methane and water) as a source of hydrogen, because hydrogen itself is not readily available directly from natural resources. Since the thermodynamic parameters for hydrogen combustion are known and there would be little benefit to the students in terms of further calculations of this type, we decided to introduce some kinetics into this part of the case study. It also occurred to us that the majority of kinetics-based calculations that most students perform during the early stages of physical chemistry courses relate to the determination of orders of reaction (which are nearly always integer values), rate constants (k) and activation energies (E_a). The types of calculation that appeared to us to be less common, but valuable for students to perform, included the determination of rates of change of reactants or products (this is somewhat surprising, given that this is the basis of chemical kinetics!) and the temperatures at which such processes should be carried out in order for a rate of reaction to be optimised or for some other specific criteria to be met. The production of hydrogen via the SRM process for combustion purposes provided an opportunity to achieve both of these.

In the first part of the session, and as a means of re-familiarising the groups with the terms usually associated with chemical kinetics, the groups need to realise that orders of reaction cannot be predicted from the reaction stoichiometry but have to be determined experimentally. Having then been given some experimental data (concentrations of reactants versus time), the groups identify up to 3 methods for determining the order of reaction (with respect to [H_2O]; the groups are advised that the rate of reaction is linear with respect to [CH_4]), perform one of these calculations, and evaluate the results. Since each group works with the results obtained from a different catalytic system, the orders of reaction with respect to water are different, and they turn out to have non-integral values. In the next step, the groups are informed that in order to be considered further, the catalytic processes must operate as efficiently as possible in terms of (a) costs and (b) a production rate of hydrogen such that subsequent combustion will be competitive with fossil fuels encountered previously (Sessions 1-2). In order to address the production rate criterion, rate constants are determined at different temperatures using the activation energies provided. Since all terms in the rate equation are now known, the rates of reaction, expressed in terms of rates of formation of hydrogen, can be determined as a function of temperature. However, the overall solution to the task is not simply to carry out the SRM reaction at the highest temperature (as might be predicted *a priori*) since the operational costs increase with temperature. The groups need to determine the optimal trade-off between H_2 production rate and increasing costs.

Collation of the results from each group reveals the identity of the most cost efficient catalyst for further consideration and one of the catalysts that is incapable of satisfying both criteria. However, since the groups are allocated different catalytic systems at random, it is not appropriate to identify individual groups as ‘winners’ or ‘losers’.

Session 5*: Fuel cells*

In this session, the groups evaluate the potential use of hydrogen in fuel cells as an alternative to combustion. The groups receive data from the DEA in the form of a FAX document, which summarises certain fuel cell data provided by two rival companies working in ‘alternative technologies’. However, as the accompanying e-mail describes, the data is both incomplete and questionable in terms of its accuracy. It is, therefore, up to the team to complete the data by performing some electrochemical calculations, determine any discrepancies that are present and identify the cause of these if appropriate. Having done this, and discussed whether either of the providers are sufficiently reputable, the preferred alternative is decided upon and the electrochemical efficiency is converted into a cost efficiency, which permits comparison with the other fuels considered thus far.

Session 6: *Solar power*

The student groups consider the use of solar power in Session 6. Although most students will have some familiarity with the basic principles of solar power, it is unlikely that many (if any) will have performed any calculations associated with it. Therefore, at the beginning of the session, the students discuss their perceived pros and cons of using solar-derived energy. The groups are then given a briefing paper describing two types of solar energy technology, solar cells and a solar plant. The latter operates on a collector/converter principle used to drive a turbine encountered previously in combustion plants. They are also given some graphical data, which includes efficiencies of collectors/converters, solar irradiance information such as a photon response curve for a semiconductor, a typical irradiation spectrum for the Los Verdes region and temporal irradiance curves (daily/monthly).

The main task for this session is to determine the scale of operation needed for each solar power method in order for them to be at least equivalent in power generation compared with more conventional fuel sources, and then determine the respective costs (see Appendix 2 for the solar energy briefing paper, e-mail correspondence and solar data information). What may appear on first inspection to be an ‘impossible’ problem, becomes achievable once simplified into a series of more recognisable tasks. Thus, having roughly converted the energies for a Si response curve (expressed in eV) into a wavelength equivalent (nm), the response curve can be mapped directly onto the solar spectrum in order to estimate the fraction of the irradiance that can be utilised (simplifying the solar spectrum by averaging intensities over larger wavelength ranges further simplifies this approach, Appendix 2). This efficiency can then be combined with an estimate of the average daily and monthly irradiance intensity (taken from further graphical data) to yield the overall harnessing of a solar cell for an extended period. There are, of course, alternatives to tackling this problem and the students are encouraged to consider how the task could be tackled more rigorously. However, what is important is that students recognise that meaningful solutions to physical chemistry problems can sometimes be achieved by taking approximations and/or estimations of data, and without the need of equations or prescribed methods. This is one of the desired outcomes from this session. By combining the power output from an individual cell with the associated costs and the power requirements for the city of Los Verdes given in the first session, a direct comparison between this technology and more conventional sources can be made to conclude the session.

Session 7: *Geothermal power*

The final type of power to be considered by the team is that derived from geothermal energy since the Los Verdes region of the USA is considered to be a suitable location to exploit such technology. Due to the complexities of geothermal energy use, this session focuses on one aspect (*viz*. heat transfer from pressurised steam), which, despite the oversimplification, provides a further opportunity for students to engage in unfamiliar problem solving. The groups need to familiarise themselves with new terminology (the technology is probably new to them too) and proceed through a series of thermodynamics calculations to determine the optimum combination of well depth and wellhead pressure to maximise on power output. Collectively, the groups consider a series of permutations and use the optimum conditions to determine the economic parameters, thereby enabling a direct comparison with the other energy sources investigated. The task involves critical analysis of the accompanying briefing paper (an extract from a review article written previously by the project leader) together with interpretation of graphical data as per Session 6. Having completed the calculations, the session concludes with a discussion on how geothermal resources may be utilised further, including integration with other energy sources.

Session 8: *Final recommendations*

In the final session, the groups re-visit the original aims of the case study. They are given some additional information relating to how the DEA currently predict the future developments of various energy sources ('insider information' provided as a private e-mail from a DEA employee/friend of the project manager). Together with this information, the groups need to synthesise their results from the previous sessions and present their recommendations within the time restrictions of a 1-hour workshop. The session concludes with a discussion of the entire case study, including a reflection on students' learning.

Managing the case study including assessment

To date, the *Capital City* case study has been piloted with groups of *ca*. 30 students studying for degrees in Analytical Chemistry and Applied Chemistry at the University of Plymouth, so the observations described here are primarily those of the main tutor (STB). Evidence from our previous work using case studies as teaching material has shown that a key to the success of such an approach is to ensure that the students are 'on-board' with the teaching approach and the expectations of the tutor from the outset (Belt & Phipps, 1998; Belt et al., 1999, 2002; Summerfield et al., 2003). While this may seem obvious, we feel it is of particular importance for this style of teaching for a number of reasons. Firstly, the case study is taught over a number of sessions (and in our case, a number of weeks), so for this reason alone, it is important to establish a *modus operandi* early on. Secondly, the context-based approach will probably be different from that used in other areas of the course which are taught in parallel (this is certainly the case in Plymouth), even though some students will have encountered the teaching of chemistry in context pre-university. Thirdly, most of the sessions have more than one component, with at least one of these having a discussion or calculation that does not necessarily have a 'correct' or unique solution. This too, may be unfamiliar to many students, particularly with disciplines like thermodynamics and kinetics, which have such a significant mathematical base. As a result of this third point, it was decided not to assess the students summatively, but to give rapid formative feedback during the sessions. By doing so, it was predicted that students would engage more positively with the philosophy of the case study approach, without concerning themselves with levels of reward normally associated with 'correct' answers, particularly with the types of tasks that demand making estimations and assumptions.

It is probably also the case that for most undergraduate degree courses in chemistry, evaluation of students' learning focuses on subject related knowledge and understanding during the first year, with formal assessment of other key skills such as critical thinking and communication occurring later on, once students have gained further experience in these (e.g. via project work). In addition, since some of these so-called key or transferable skills rely more heavily on subjective testing, it is probably more effective, from an encouragement point-of-view, to avoid formal summative assessment of these skills too early in undergraduate courses. Of course, there can be the risk that a lack of formal assessment results in poor attendance, so students are required to attend and contribute to all of the sessions in order to complete the module. In addition, the open-ended nature of several of the tasks with incomplete or poorly defined solutions means that the tutor potentially runs the risk of losing some control over managing the sessions, or even of suffering loss of credibility with the students, features that have been identified by others (Hinde and Kovac, 2001; Bailey and Garratt, 2002). With all of these points in mind, the tutor conducting the piloting in Plymouth (STB) dedicated a significant time period in the first session (*ca*. 30 minutes) to explain the case study philosophy, including his role as tutor and his expectations of the students.

Subsequent sessions concluded with a feedback period during which the results of the groups' conclusions were collated and discussed. This provided an opportunity for students to raise issues and for the tutor to review the session in general terms, to give credit for correct and/or partially correct solutions (Bailey and Garratt, 2002) and to provide model solutions (if necessary) such that groups were 're-aligned' before the beginning of the next session.

Observations

Tutor observations

On the basis of feedback obtained from end-of-session discussions, it is clear that the students welcome the opportunity to work within a real-life context even though the topic itself may appear far removed from their normal day-to-day experiences. The first session is mainly concerned with small group discussions, so each student is able to make a positive contribution and to familiarise themselves with group members. Similarly, the groups seem more comfortable with the calculations associated with the early sessions once they recognise how the tasks can be broken down into more recognisable thermodynamical calculations. As expected, once the tasks require the students to make approximations and estimations, or demand mapping of an unfamiliar scenario onto a familiar algorithm of calculations, more guidance from the tutor is required. However, in most cases, it is the **recognition** that such methods are needed or acceptable rather than the **performing** of them *per se*, that would appear to be important to the students' progress with the tasks. As such, one benefit of the case study approach is that its session-by-session continuity means that most groups find themselves rediscovering novel approaches to problem solving and using them with increased confidence as the case study progresses, which is a clear demonstration of transferable skills development.

Student feedback

In terms of student evaluation of the case study, feedback questionnaires were used at the end of the final session in addition to end-of-session discussions with the tutor. Students were asked to identify their perceptions of ease/difficulty in carrying out the tasks, to describe their individual contributions, and discuss how they might approach such problems differently in the future. They were also asked to classify the tasks using their own terms (physical chemistry, maths, environmental chemistry, problem solving, industrial, etc.) and to describe whether they had needed to use prior knowledge and/or learn something new in order to complete the tasks. A selection of questions and responses are given in Table 2. Consistent with the tutor's observations, the majority of students welcomed the opportunity to 'put theory into practice' by studying physical chemistry in an applied context and to work as part of a group. When it comes to students' perceptions of difficulty, probably the most significant point is that the majority of the students found the calculations to be difficult until they recognised a familiar method that they could apply. At this point, many of the determinations then became relatively straightforward. This is in-line with Bodner's description of the transition between problem-solving and performing exercises (Bodner, 2003).

Table 2. Selected feedback from chemistry students having completed the *Capital City* case study

Q: Which part(s) of the session did you find easy / difficult?

Easy	**Difficult**
Calculations that I already knew how to do.	New calculations that I had to get my head around.
	Getting confused with units.
Most of the calculations up until the last cost per MWh were not too difficult and well within my capability.	Minor errors made last session (MWh) difficult.
Most parts were within my capability.	Talking at group discussions.
The first session when we had to think about energy sources was easy.	Some demanding calculations, discussion helped solve these.
First session – advantages/disadvantages of different fuels	Calculations (x2)
First task in first session (discussion)	Some of the calculations, not enough time (x2)
Discussion at start to think about positives and negatives of different fuels	Calculations, units made things difficult. When sorted out, it was straightforward.
Methane / coal powered plant.	Identifying the information needed was hard.
The harder tasks were easier when longer time period was given made it easier to work out what to do.	Working out how to arrive at the answers. Maths was simple but difficult to know which values to use.
	Calculations and working out how to approach the tasks.
	Manipulating information and equations.
	Estimating power use for solar power plant.
	Shorter time period made it more difficult.
	Knowing where to start was a problem.
	Session 6 was very difficult (x2)
	Understanding what is being asked for amidst all the information.
	Most of the sessions were fairly difficult. However, after discussion / feedback sessions the answers were a lot easier to understand.
	Deciphering each task to know which bits of information to use was difficult, but once this was done it was OK.
	Session 6 (Solar Power) was very difficult – would never have got to the end answer. Most was challenging, but rewarding.
	Most of it.
	Found energy cell sessions quite complex.
	Ensuring units are correct was difficult. Perhaps a little more guidance in that area (importance of units) would be useful.

Q: Would you approach the task(s) differently in the future? If so, what would the differences be?

Yes	NO
9	17

Yes – Units would be monitored much more carefully
Being able to think for myself, equipped me with the knowledge to know what principles are applied.
Be more confident in trying my ideas.
I would be more confident in my original thought processes.
Look at units, more time thinking.
Read up before, learn equations.
Spend more time organising the tasks and working through them.
Background reading.
More delegation.

Q: To what extent did you need to use prior knowledge / learn something new?

Other lectures had equations that needed to be used, but this put in practice what I had learnt.
Prior knowledge of thermodynamics, but we learned how to use knowledge in real life situations.
All was prior knowledge, but learnt how to apply it to real life. (x 7)
Helpful to see how theory is used
Gained more experience on practical application of theory.
Prior knowledge not needed (x 3)
Formulas would have been nice.
Learnt new things in every session (x 5)
Mostly new (x 2)
A lot of prior knowledge of algebra was needed.
Prior knowledge: physical chemistry, maths. Learned lots of new ways of working things out.
Learnt a bit about solar power.
Prior knowledge included Partial pressures, Carnot cycle, renewable energy.
Used prior knowledge and learnt something In all tasks

On a less positive note, several students said that they would have benefited from more time or clearer guidance and help from the tutor. However, they thought that the feedback/discussion sessions helped in their understanding, and a number of students concluded that the case study had given them increased confidence in problem solving and taught them the need for working in a more organised way.

Case study layout – editorial considerations

In addition to the scientific content required for each session, we also decided that students (and tutors) would benefit from consistency and quality in format, and that the context-based philosophy would be supported via the use of ‘familiar’ and ‘external’ documentation. Each session has some (hard copy) e-mail correspondence together with additional information, which takes the form of extracts from technical reports, published articles, FAX documents and datasheets (see Appendices 1 and 2). As such, consistency in delivery is maintained across each session and all the necessary information is available for the tasks to be completed in-class. We believed that this consistency in the formatting of the documentation would also help students in their cross-referencing of material towards the later stages of the case study, when it was hoped that the data from each session would be synthesised. In summary, students work with each of the following for each session:

- A cover page for each session with a relevant graphic and description of the session aims
- An e-mail communication giving feedback from the previous session
- Background paper(s) to provide relevant numerical data, equations, graphs
- A further e-mail setting tasks and guidance for the current session (the individual tasks are further highlighted by the use of 'Post-It' type notes)
- Blank tables and other materials (as decided by the tutor)

The tutor's notes have been written with the intention of being as comprehensive and navigable as possible. These comprise the following for each session:

- A cover page, similar to that received by the students, with further elaboration of the key aims
- An outline of the session including a suggested time plan
- Model or suggested solutions to the tasks showing both questions and answers (answers are presented in shaded boxes for ease of navigation)
- Additional material that might be useful (e.g. completed tables)
- Overhead transparency templates

Conclusions

At the outset of this project, it was our intention to produce a case study that would enable chemistry students to develop their understanding of various aspects of physical chemistry during the early stages of their undergraduate degree course. Students would perceive the relevance of the context-based approach and this would lead to greater motivation. We decided to limit the number of topics in order that they would be revisited and this would reinforce learning. We also believed that the evolving storyline of the case study would provide an opportunity for students to work with different problem types, from the familiar to the novel. Further, it was hoped that students would recognise the differences between these problem types and that they would particularly benefit from working with unfamiliar problem-solving scenarios.

The early piloting of the *Capital City* case study indicates that we have made some progress in achieving our aims. Our evaluation suggests that students welcome studying chemistry within an applied context and that this can lead to the development of their subject knowledge and their perception of its relevance. Some students expressed increased confidence in approaching problem solving in the future.

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References

Bailey P.D., (1997), Coaxing chemists to communicate, *University Chemistry Education*, **1**, 31-36.

Bailey P.D. and Garratt J., (2002), Chemical education: theory and practice, *University Chemistry Education*, **6**, 39-57.

Belt S.T. and Phipps L.E., (1998), Using case studies to develop key skills in chemists: a preliminary account, *University Chemistry Education*, **2**, 16-20.

Belt S.T., Clarke M.J. and Phipps L.E., (1999), Exercises for chemists involving time management, judgement and initiative, *University Chemistry Education*, **3**, 52-58.

Belt S.T., Evans E.H., McCreedy T., Overton T.L. and Summerfield S., (2002), A problem based learning approach to analytical and applied chemistry, *University Chemistry Education*, **6**, 65-72.

Bennett N. and Cornely K., (2001), Thalidomide makes a comeback: a case discussion exercise that integrates biochemistry and organic chemistry, *Journal of Chemical Education*, **78**, 759-761.
Bodner G., (2003), Problem solving: the difference between what we do and what we tell students to do, *University Chemistry Education*, **7**, 37-45.
Breslin V.T. and Sanudo-Wilhelmy S.A. (2001), The lead project - an environmental instrumental analysis case study, *Journal of Chemical Education*, **78**, 1647-1651.
Burton W.G., Holman J.S., Pilling G.M. and Waddington D.J., (1995) Salters advanced chemistry: a revolution in pre-college chemistry, *Journal of Chemical Education*, **72**, 227-230.
Carson E.M. and Watson J.R., (1999), Undergraduate students' understanding of enthalpy change, *University Chemistry Education*, **3**, 46-51.
Cheng V.K.W., (1995), An environmental chemistry curriculum using case studies, *Journal of Chemical Education,* **72**, 525-527.
Cornely K., (1998), Use of case studies in an undergraduate biochemistry course, *Journal of Chemical Education,* **75**, 475-478.
Garratt C.J. and Mattinson B.J.H., (1987), *Education Industry and Technology,* Pergamon Press.
Gutwill-Wise J.P., (2001), The impact of active and context-based learning in introductory chemistry courses: an early evaluation of the modular approach**,** *Journal of Chemical Education,* **78**, 684-690.
Hahn K.E. and Polik W.F., (2004), Factors influencing success in physical chemistry, *Journal of Chemical Education*, **81**, 567-572.
Hamilton T.M., (2003), Thermodynamics for visual learners, *Journal of Chemical Education,* **80**, 1425-1427.
Hinde R.J. and Kovac J., (2001), Student active learning methods in physical chemistry, *Journal of Chemical Education*, **78**, 93-99.
Holman J. and Pilling G., (2004), Thermodynamics in context – a case study of contextualized teaching for undergraduates, *Journal of Chemical Education,* **81**, 373-375**.**
Jervis L., Jervis L. M. and Giovannelli D., (2005), Aligning biochemistry to the interests of biology students: using haloperoxidase to illustrate reactions of environmental and biomedical importance, *Biochemical and Molecular Biology Education,* in press.
McGarvey D., (2004), Experimenting with undergraduate practicals, *University Chemistry Education,* **8**, 58-65.
Nicoll G. and Francisco J.S., (2001), An investigation of the factors influencing student performance in physical chemistry, *Journal of Chemical Education*, **78**, 99-102.
Pontin, J.A., Arico, E., Pitoscio Filo J., Tiedeman P.W., Isuyama R. and Fettis G.C., (1993), Interactive chemistry teaching units developed with the help of the local chemical-industry – applying classroom principles to the real needs of local companies to help students develop skill in teamwork, communications, and problem-solving, *Journal of Chemical Education,* **72**, 525-527.
Sözbilir M., (2004), What makes physical chemistry difficult? Perceptions of Turkish chemistry undergraduates and lecturers, *Journal of Chemical Education*, **81**, 573-578.
Summerfield S., Overton T. and Belt S., (2003), Problem-solving case studies, *Analytical Chemistry* **75**, 181A-182A.
Sutman F.X. and Bruce M.H., (1992), Chemistry in the community-ChemCom, *Journal of Chemical Education*, **69**, 564-567.
Tsaparlis G. and Gorezi M., (2005), A modification of a conventional expository physical chemistry laboratory to accommodate an inquiry/project-based component: method and students' evaluation, *Canadian Journal of Science, Mathematics, and Technology Education*, **5**, 111-131.
Wyeth P., (1997), *Proceedings, Variety in Chemistry Teaching 1997,* Royal Society of Chemistry.
Zielinski T.J. and Schwenz R.W., (2001), Physical chemistry, *Journal of Chemical Education,* **78**, 1173-1174.

The Appendixes associated with this paper can be found as separate PDF files at http://www.rsc.org/Education/CERP/issues/2005_3/index.asp