Paper

A problem based learning approach to analytical and applied chemistry

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Abstract

Problem based learning (PBL) and extended problem solving activities are increasingly being used in many disciplines. The effectiveness of these approaches suggests that there is a need for such resources for use in chemistry education. A problem-based approach can produce students who are well-motivated, independent learners, effective problem solvers and who have a broad range of interpersonal and professional skills. This paper describes the development of problem solving case studies as an approach to PBL in chemistry. The case studies present a 'real' problem or scenario which students solve by application of prior knowledge, acquisition of new knowledge and by developing a problem solving strategy. The case study described here is based on an investigation of a (fictitious) suspicious death. The activities involved cover areas of analytical chemistry and forensic science. The case study is designed to be flexible, allowing it to be tailored to a particular course. There is no unique correct solution to the case study, and students must use judgement in order to come to an acceptable conclusion. The nature of the activities involved ensures that, in order to complete the case study, students must use a variety of scientific and transferable skills.

Introduction

Employers have long urged the Higher Education sector to produce graduates with a range of transferable skills that would make them more immediately effective in the world of work. Several reports[1-3] have identified, in particular, communication skills, team working, numeracy, use of IT and learning to learn as highly desirable qualities in a graduate. This view has also been highlighted as being particularly important in analytical chemistry.[4] The comprehensive survey[5] by the LGC in 1993 reported that employers' overwhelming concern was with graduates' ability to apply appropriate theory and laboratory techniques to practical problems. Good interpersonal skills were identified as being crucial to allow analysts to work effectively in a team and to evaluate problems jointly with clients. Most, if not all of these qualities would be highly regarded by any employer of science graduates, but unfortunately, those employers questioned in the survey felt that very few graduates possessed them.

The United Kingdom Analytical Partnership (UKAP) recently carried out a survey of ten university chemistry courses that contained a significant amount of analytical science. The report[6] identified several skills gaps in the undergraduate provision. These related to the acquisition of analytical problem solving skills, working with others, method selection and handling data.

To produce graduates, who can operate in the workplace professionally, we need to go much further than just ensuring that they have a sound knowledge of chemistry, adequate practical abilities and rudimentary problem solving skills. We must produce graduates who have the scientific skills of critical thinking with an analytical approach, are able to interpret data and information, can tackle unfamiliar and/or open-ended problems and thus, are able to apply their chemical knowledge. In addition, the modern graduate must master a range of 'professional' or transferable skills including communication, team working, time management, information management, independent learning and the use of information technology.

Many disciplines have used problem based learning (PBL) to achieve this balance of knowledge, qualities and skills.[7] In this, problems act as the context and the driving force for learning[8] and the acquisition of new knowledge is done within these contexts. PBL differs from problem solving in that here the problems are encountered before all the relevant knowledge has been acquired and, therefore, necessitates both the acquisition of knowledge and the application of problem-solving skills. In some cases, defining the problem itself forms part of the PBL approach. In problem solving, the knowledge acquisition has usually already taken place and the problems serve as a means to explore or enhance that knowledge.

Boud and Felleti[8] claim that a PBL approach produces more motivated students with a deeper subject understanding, encourages independent and collaborative learning, develops higher order cognitive skills as well as a range of transferable skills including problem solving, group working, critical analysis and communication. Problems that are used for PBL should address curriculum objectives, be real and engaging, be 'fuzzy' and place the group in a professional role, i.e. as scientists. Students should be required to develop a problem solving strategy, to acquire new knowledge and to make judgements, approximations and deal with omitted/excess information.[9]

A report[10] from the USA has recommended that PBL methods should be used to teach analytical science. Wenzel has commented[11] on the lack of PBL resources available and indicated the types of resources that would be needed by analytical chemistry educators. These include real-world problem based case studies, collaborative learning problems and laboratory PBL activities.

The development of effective problems is not a trivial task. However, from our experience, the effort is well rewarded when problems are based upon real contexts and scenarios. From these, students are able to see the relevance of their discipline and so approach such activities with enthusiasm and interest. Chemistry is a discipline that provides a rich source of contexts in, for example, forensic science, pharmaceuticals, environmental science, and industrial chemistry. Of the traditional 'branches' of chemistry, analytical chemistry is, by its very nature, the most applied. The scope for producing 'real' problems for students to solve is great.

Our Approach

Our approach is to use the principles of PBL to develop problem-solving case studies. These provide extended problems that are related to applications or real contexts with incomplete or excessive data, require independent learning, evaluation of data and information and do not lead to a single 'correct' answer.

Case studies have a long history in many subject areas and their value within chemistry has long been recognised.[12-20] From our perspective, a case study should

- involve the learning of chemistry by requiring students to learn independently
- be active in style
- involve a work-related context
- involve the development of transferable skills
- encourage reflective learning
- have clear learning objectives

We have chosen contexts within environmental, industrial, forensic and pharmaceutical chemistry to provide 'real' scenarios for the application of analytical chemistry. Six case studies have been developed to cover different aspects of analytical chemistry and each has been designed to encourage the development of different transferable skills. Although they require students to apply new knowledge in order to solve the problem, our case studies are perhaps more structured than the traditional PBL approach, where a problem may be presented as a single statement or short paragraph. Ours extend over several sessions and provide students with different activities at each stage of the problem. They are all flexible enough to be used in a variety of different teaching situations. One of them is described here.

The Pale Horse

Overview

This case study sets analytical chemistry within the context of a forensic investigation of a (fictitious) suspicious death. The case study begins by setting the scene as follows: On the 10th February 2001, Brigitte Barberi found her mother, Maria Barberi, dead in her home. After an initial search of the crime scene by the scene of crimes officer (SOCO), the body was taken to the morgue. Door-to-door enquiries revealed evidence of a boundary dispute between the Barberis and their neighbours and that Maria's mother had just died leaving her a farm. Her husband, Martin, did not return from fishing until later that evening. A few days later both Brigitte and Martin Barberi were admitted to hospital with suspected heavy metal poisoning.

Each group of students is told that they are investigating the suspicious death of Maria Barberi. The tutor may also discuss the intended outcomes of the case study in terms of subject specific knowledge as well as scientific and transferable skills.

The case study operates by gradually supplying information in the form of reports from various official agencies, including the police, a pathologist and a forensic laboratory. The students request analysis on the evidence collected in order to determine the cause of death (poisoning), the poison's identity and mode of administration. Results from the analysis of evidence collected are available in the form of over 120 result cards covering the three possible types of evidence that could be collected:

- Physical evidence (e.g. fingerprints on a wine bottle (see Figure 1), phone records, contents of medicine cabinet),
- Chemical evidence (e.g. graphite furnace AAS for heavy metals in food (Figure 2), FT-IR of a white powder, identity of suspected blood stain, comparison of different wines etc.),
- Toxicological evidence (e.g. XRF for heavy metals in hair samples from Maria (Figure 3), head space GC for alcohol in blood, ICP-MS for heavy metals in blood from Martin and ICP-OES for heavy metals in the blood of Brigitte.)

The requests for analysis on the evidence collected are made at three stages (see Figure 4). From the results supplied, the students should be able to determine that the poison used was thallium, which was administered in some gooseberry wine given to the Barberis by their neighbours. This was also used to make a chicken chasseur dinner eaten by Maria, Martin and Brigitte Barberi. If suitable toxicological requests are made, the students should also be able to determine that Maria died of chronic thallium poisoning over about a period of a month and other members of the family experienced acute thallium poisoning. The motives and opportunity of the various suspects are determined from the anecdotal evidence.

Figure 1. Example of physical evidence result cards

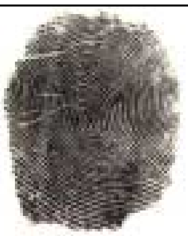
B2	**FP**	**Fingerprint request**		
Evidence No.:		10-02-0071-B2 Chateau de la Graville 1999 (white) bottle (part full)		
Prints		Powder and fixed print then photographed.		
Prints				
		Print from Mr Barberi.		Print from unknown person
Notes		The unidentified set is probably male due to their size.		

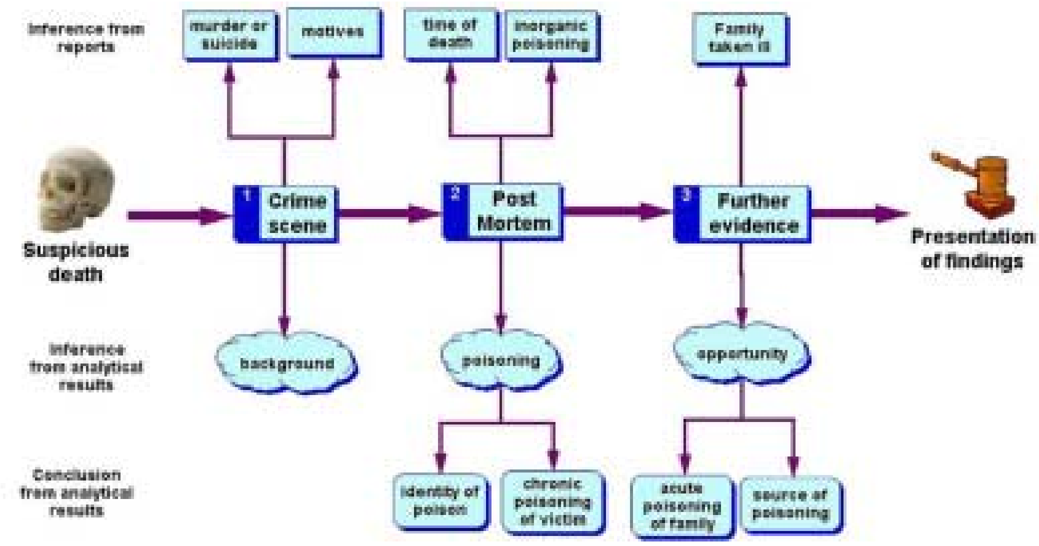
Figure 2. Example of chemical evidence result cards

H5	**GF**	**Graphite Furnace AAS of food**				
Evidence No.:		10-02-0071-H5 Part eaten plate of food.				
Test		Microwave acid digestion with 5 ml of nitric acid to 1g of sample then Graphite Furnace AAS				
Results			**Blank** **w/v**	**H5a** **potato** **w/w**	**H5b** **White sauce** **w/w**	**H5c** **Chicken** **w/w**
		Tl	< 5 ppb	0.6 ppm	26.7 ppm	3.4 ppm
Notes		Remnants of the chicken chasseur meal. GFAAS is a very sensitive quantitative method of analysis. 1000 times more sensitive than Flame AAS.				

Figure 3. Example of toxicological evidence result cards

C2	**XRF**	**XRF of Maria's hair**			
Evidence No.:		10-02-0071-C2: Hair sample from the body.			
Test		XRF is a non-destructive method requiring short sample preparation			
Result		Element	ppm (w/w)	Element	ppm (w/w)
		As Cd Cu Hg	1.2 1.1 27.5 1.8	Mn Pb Se Tl	1.2 19.4 1.0 1.2
Notes		It is difficult to distinguish between environmental deposition of metals and that from ingested sources.			

Figure 4. Overview of the case



The nature of the activities involved ensures that, in order to complete the case study, students must develop a variety of scientific (Table 1) and transferable skills (Table 2). The minimum contact time is 4-5 hours and the students are required to spend approximately 12 hours in associated independent study depending upon their experience and background. It is recommended that they work in randomised groups of 3-6 so that each group has a range of abilities and skills. One member of the group takes on the role of Chief Investigating Officer and is responsible for the overseeing of information gathering, compilation of reports, note-taking, reporting etc. So far, the case study has been successfully trialled in analytical chemistry, forensic science and professional skills modules at five universities in the UK. The Pale Horse case study has also been written so that it may be implemented flexibly over a different number of sessions of varying lengths as described in the tutors guide. For brevity, we will describe only the format where it was run over five one-hour sessions.

Introducing the case

Depending upon the background of the students and the module, a preliminary introduction may be required in order to introduce the role of forensic science. A series of overheads are provided, entitled the 'The Place of Forensic Science', that cover the various stages of an investigation from the scene of crime to forensic laboratory and, finally, to court.

Scene of Crime

In the first one-hour session, the students are given reports from the first attending officer and the investigating officer detailing the initial actions of the police officers, the police surgeon and the SOCO. After the students have discussed the information, two crime scene photos are provided that show the room before and after the body was removed. Once these have been studied, the students are given transcripts of the door-to-door interviews with the neighbours. The students are prompted to consider the types of physical evidence that they would ideally want to collect from the scene of crime.

Table 1. Summary of scientific skills developed

SCIENTIFIC SKILLS	
Disciplines covered	Analytical chemistry, toxicology, forensic science, forensic pathology.
Scientific knowledge	Matching analytical techniques to the application. Organic analysis (e.g. identification of white powder, alcohol in blood.), inorganic analysis (determination of heavy metals by AAS) and forensic science (fingerprinting, DNA, and serology)
Handling information	Manipulation and evaluation of information and data to make realistic decisions on the evidence available.
Problem Solving	Tackling unfamiliar problems, using judgement, evaluating information, formulating hypotheses, analytical and critical thinking.

Table 2. Summary of transferable skills developed

TRANSFERABLE SKILLS	
Communication skills	Oral presentations and report writing.
Improving learning and performance	Using feedback to reflect upon group and individual performance. Drawing the experience within the group.
Information technology	Word processing reports and preparing material for presentations.
Planning and organisation	Managing an investigation, individual judgement, taking responsibility for decision making and time management.
Working with others	Brainstorming, discussion, division of tasks and reporting back to the group.

When the students have completed these considerations, they are given the SOCO report that details the evidence that was actually collected. The students make a limited number of requests for analysis of this physical evidence, which may include, for example, fingerprints on a wineglass, contents of a wine bottle, telephone records, identification of a white powder on a table, etc. From these results, the students should be able to determine the background of the case, and develop some theories concerning how and why Maria Barberi died.

Post-mortem

At the start of the second one hour session, the students are given the results of their requests in the form of result cards and are given a little time to look over these before being given the next police report. This states that Maria Barberi was pronounced dead at the scene by the police surgeon before being taken to the morgue for the post-mortem. Photographs and some background notes on the persons involved are then distributed. This normally promotes some interesting discussion among the students about the appearances of the witnesses, their background and possible motives.

Finally, the students are given the pathologist's post-mortem report. From the information contained in this report, they should realise that they ought to be looking for heavy metal poisoning, although some students do not always realise this at this stage. The students are then invited to request chemical analysis of the urine, blood, kidney, liver and hair samples taken at the post mortem. They are provided with a list of samples that have been collected and must identify the analyte and preferred analytical method. The requests are submitted to the tutor before the next session. In our trials, students spent about 3-6 hours in independent study in order to decide which pieces of evidence to analyse and select the most appropriate analytical technique for their chosen analyte.

Additional Evidence

At the start of the third one-hour session, the students are given the results of their requests for analysis of the samples taken from the dead body. They should be able to determine whether a poison was used and, if so, what it was and when it was administered.

The students are then given the final set of reports from the investigating officer. From these they are able to discover that additional evidence was collected from the scene of crime a few days later after both Martin and Brigitte were admitted to hospital with suspected acute heavy metal poisoning. The evidence collected included the chicken chasseur that Martin had been eating before he was taken ill, wine from the kitchen and blood and hair samples from the family. The students are able to make further requests for chemical analysis on this or on any previous piece of evidence. The requests are submitted before the next session. Again, the students had to spend time in independent study in order to select the appropriate analytical technique for their chosen analyte, especially if they did not receive useful results from their previous requests.

At the start of the fourth one-hour session, the results are returned to the students. At this stage the students should have sufficient evidence to start preparing a short presentation and a written report that consider the following.

- The state of Maria Barberi's mind at the time of death.
- Whether the death of Maria Barberi was suicide, murder, accidental death or death by misadventure.
- The cause of death.
- The identification of any poison used and how it was administered
- Whether the illnesses of Martin and Brigitte Barberi could be linked to each other and/or to the death of Maria Barberi.
- How might the poison have been obtained
- Whether further evidence is required and if a warrant should be obtained to search for this evidence
- The suspect(s) motive and opportunity.
- Whether the person the students suspect could be charged on the evidence they have gathered so far.

When students have made their presentations and/or handed in their reports in the final one-hour session, the tutor leads a review or debriefing session. This is an essential feature within the PBL framework. It is especially important when the case is relatively complex, and is an opportunity to discuss the details of the case from a number of different perspectives. The role of analytical science in solving the case can be emphasised and students can be encouraged to reflect on their own development in terms of knowledge and skills. It can also provide an opportunity to allow those students who have missed some of the essential points to re-group if necessary.

Requesting Analysis

Students make requests to the forensic laboratory on ‘Evidence Request Forms’ and must specify clearly the analytical technique required. By making sensible requests, students should be able to identify the cause of death, the poison used and the method of administration. The number of requests permitted is limited to encourage critical thinking and avoid an excessive number of requests being made. This forces the students into asking sensible questions and thinking carefully about choosing the correct analytical technique. It is made clear to the students that a rule of the case is that no useful results will be obtained if they do not specify a suitable method of analysis for the desired analyte. It is for the tutor to decide how rigorously this rule is enforced and this may depend on the desired learning objectives.

Submitted requests are useful in charting the changes in the student's attitude towards the case. They also indicate issues on which the tutor may wish to comment. For example, it may be helpful to remind students that while certain techniques are often considered to be extremely ‘powerful’ (e.g. NMR spectroscopy and ICP-MS), they are not necessarily always the most appropriate methods for all analytical problems.

When making requests, students are encouraged to consider (amongst other things) the following:

- What samples they want analysed
- What they are looking for (specifically) from each analysis
- What analytical techniques are most appropriate
- What detection limits can be achieved by each method
- What would constitute a ‘normal’ concentrations
- Whether the sample is likely to be a mixture of components
- If qualitative analysis is required
- If quantitative data is required
- What the meaning of a negative result might be

Results of analyses are given back to the students on prepared 'Result Cards', examples of which are shown in Figures 1-3. There are over 120 such cards contained in the case study, including blank ‘Results Cards’ that are provided for any other responses that have not already been covered. This also allows the tutor to assist the students however he/she chooses, perhaps in indicating why the results from a particular chosen method of analysis would not be useful and thus, suggest the selection of another method. The degree of assistance given would depend on the background of the students and the aims of the module.

The students are expected to make clear how the analytical data they have received has informed their judgement and whether any of their conclusions are based upon the anecdotal evidence. Criminal law requires proof beyond reasonable doubt and as there should still be a considerable amount of doubt at the end of the case, students should be able to make recommendations for further investigations that should be carried out by the police and the forensic science service.

Assessment

The Pale Horse case study offers a number of opportunities for assessment depending on the learning outcomes set by the tutor; a couple of assessment schemes that have been employed successfully are shown in Table 3.

Table 3. Example assessment schemes

Case summary	20%
Summary of results	20%
Oral presentation	30%
Contribution to group	30%
Total	100%
Or	
Written report	60%
Oral presentation	40%
Total	100%

The 'case summary' provided with the case study is a series of questions about the case that could be completed and submitted instead of a full report or used to focus the students' ideas before they produce oral presentations. The one-page results summary should outline the evidence that has been gathered by the group from their requests for analysis. This is useful for the tutor who can easily see on what evidence the assumptions have been based without referring back to the evidence request forms. The written report may be either group or individual and could be as short as one page. The duration and focus of the oral presentation can be varied at the discretion of the tutor and could be peer assessed. Marks for the contribution to the group could be awarded by the students for each team member to give an indication of each individual student’s contribution.

Observations

As the Pale Horse case study has been piloted at five institutions and with over 250 students with varying backgrounds taking analytical chemistry, forensic science and professional skills modules, we have been able to gather a significant amount of feedback. As shown in Table 4, the student feedback has been very positive.

Table 4. Student feedback for the Pale Horse (n = 45)

1=disagree and 5=strongly agree.	Response (1-5)
By taking part in this case study, I feel I have developed the following skills:	
• Solving unfamiliar problems	3.8
• Working with others	3.9
• Thinking logically / critically	4.2
• Communicating my ideas	4.0
• Link between theory and practice	3.8
I have enjoyed taking part in this activity?	4.3

The case study presents a novel way of working for the majority of students and staff involved. It is noteworthy, that the enthusiasm and engagement of students swiftly increases throughout the activity as they become more involved in the decision-making processes and engaged with the story. The following comments were given by students when asked "*What did you like best about the case study?*"

"*Something different and interesting."*
"The way you were given evidence to draw conclusions from and not all at once."
"Getting new evidence and forming them into new ideas."
"It was different to normal modules and was very interesting."
"Putting all the evidence together to solve problems."
"Being able to choose your own evidence rather than simply being handed it."
"The challenge of solving an un-solvable problem."
"The idea of there being no correct answer but based upon the evidence alone."
"Preparing the talk and drawing conclusions."
"How each time there was something new introduced. We still had to work at it. It was never all given away and thus kept us curious."

Initially, many of the students seemed surprised that they were not given meaningful results when they had not specified a suitable method of analysis, assuming that the tutor would offer some flexibility. This was especially true amongst the students whose main subject area was outside of analytical chemistry. However, students quickly improved in this regard and carried out independent learning (where necessary) about analytical techniques in order to specify the appropriate analytical methods. The formal assessment of each component of the case study helped in overcoming the students' initial reluctance to work outside the classroom sessions.

Additional feedback from the students showed that the case study had not only provided them with the opportunity to develop their knowledge of analytical and forensic chemistry, but had increased their transferable skills capabilities. Examples of their responses to the request: "*Describe one thing that you have learnt about yourself from this activity*" are given below: -

"I lack the ability to defend my arguments and know when to compromise."
"It is good to discuss things with other people, to get lots of different ideas about things."
"Improved my time management skills."
"I can put forward my case well but must also listen to others."
"I can work well within a group."
"Group participation is essential to ensure all group members benefit as well as myself."
"I didn't think I would be so nervous about speaking."
"I can think logically sometimes. My time management is better than I thought."
"I didn't have as much of a problem public speaking as others do."

We believe that using this case study achieves the initial objective of using problem solving to develop subject knowledge in analytical chemistry and forensic science as well as a range of other scientific and transferable skills. Students are required to use a range of skills in order to achieve a satisfactory outcome, and the applied, 'real' context engenders enthusiasm and motivation towards solving problems.

Other case studies

To date, we have developed six problem-solving case studies (Table 5), each with a focus on analytical science within environmental, forensic, industrial and pharmaceutical chemical contexts. These have been piloted with students representing all three stages of

Table 5. Titles and contexts of case studies developed

Level 1/2	**Context**
New Drugs for Old	Drug discovery and organic spectroscopic analysis
The Titan Project	Industrial inorganic chemistry and statistics
Level 2/3	
A Dip in the Dribble	Investigation of the environmental impact of a fire
Launch-a-Lab	Setting up industrial contract analysis
Tales of the Riverbank	Investigation of pollution of a river
The Pale Horse	Investigation of a suspicious death.

undergraduate study, and in some cases, at post-graduate level. In our experience, these types of activities work equally well with students at all levels of their development and within many chemistry-related disciplines. The level of support given by the tutor may be greater in the early stages of academic development or with students who are tackling a case study that is outside of their area of specialism. Further accounts of the remaining five case studies will appear in future publications. A copy of 'The Pale Horse' can be obtained from Dr. Tina Overton, Department of Chemistry, University of Hull, Hull, HU6 7RX or e-mail T.L.Overton@Hull.ac.uk

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