Teaching chemists to think: from parrots to professionals

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There is a need in chemical education to provide students with open ended, creative problem solving activities. Problem solving case studies are being developed in order to provide students with a 'real' context to extend their knowledge of chemistry, to develop intellectual or 'thinking' skills and to practise a range of transferable skills. The case study described here is set within an environmental investigation of a river and the mechanics of delivery have been designed to be flexible, allowing it to be tailored to a particular course and lecturer. There may be no right or wrong answers and it has been designed to highlight a number of issues. The nature of the activities involved ensures that, in order to complete the case study, students must use a variety of subject specific and transferable skills.

Introduction

Employers have long been urging the Higher Education sector to produce graduates with a range of key skills that would make them more immediately effective in the world of work. Several reports[1, 2] have highlighted particularly 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 a recent report by the LGC.[3] Following a comprehensive survey carried out by the LGC,[4] the report states that employers' overwhelming concern was with the graduates' ability to apply appropriate theory and laboratory techniques to practical problems. In particular, graduates should be able to evaluate a specific problem, identify appropriate theory, methods and techniques that can provide a cost-effective and reliable solution, and ensure that this solution is implemented in accordance with rigorous quality or regulatory regimes. 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 had them.

The Quality Assurance Agency's recent initiatives all place an emphasis on these broader skills and capabilities. The subject benchmark statement for chemistry[5] quite specifically mentions transferable skills such as numeracy, team working, communication, and cognitive skills such as solving novel problems. Programme Specifications[6] also require academics to make the outcomes of programmes explicit in terms of what students should be able to do, rather than what they should know. The National Qualifications Framework[7] level descriptors for B.Sc. and M.Chem. emphasise problem solving and analytical evaluative skills. The evolution of Personal Development Plans and Progress Files[8] may make students more aware of their own skills profile and staff will have to integrate explicit skills-development opportunities within their courses.

So, in order to produce graduates who can operate in the workplace as professionals, we need to go much further than just ensuring that they have a sound knowledge of chemistry. We must produce graduates who can think critically, have an analytical approach, can interpret data and information, tackle unfamiliar and open-ended problems and apply all the chemical knowledge that they have acquired. In addition, the modern graduate must master a range of 'professional' or key skills. These include communication, team working skills, time management, information management, independent learning.

These requirements increase pressure on both academics and students. The expansion in the higher education system in recent years has not been matched by a similar increase in the numbers of prospective students applying to science departments. Whilst numbers in chemistry barely hold steady, the nature of the chemistry undergraduate intake has changed. The undergraduate population is not the homogeneous body it once was. As science becomes less attractive to students, a lower proportion of the more able ones enter our departments. As well as generally lower entry grades, students now choose more diverse A-level combinations, choose from a wide range of optional modules, and enter higher education via non-traditional routes. All this means that it is increasingly difficult to predict the starting level of any of our students at a time when, it might be argued, we expect them to learn much more.

The belief held by many chemistry academics, that students acquire intellectual and personal skills by a process of diffusion whilst ‘doing’ chemistry, is no longer sustainable. It may have been true in the past; but today’s students, employers and regulatory bodies require such skills to be explicitly developed in an attempt to ensure that all graduates have them.

The Challenge

What is missing from the traditional approach to the chemistry curriculum that would enable students to develop these intellectual and personal skills and capabilities? We produce students with a sound knowledge base in chemistry, adequate laboratory skills and rudimentary problem solving skills. In order to enhance the qualities of the chemistry graduate we need to provide opportunities to develop advanced problem solving skills, a range of key skills, and an appreciation of the range of applications within which the professional chemist works.

Problem solving activities can provide the vehicle for achieving this. Students should begin to tackle unfamiliar and open-ended activities that allow some degree of flexibility and creativity.

Table 1 Classification of problems

TYPE	DATA	METHOD	GOAL
1	Complete	Familiar	Clear
2	Complete	Unfamiliar	Clear
3	Incomplete	Familiar	Clear
4	Complete	Familiar	Unclear
5	Incomplete	Unfamiliar	Clear
6	Complete	Unfamiliar	Unclear
7	Incomplete	Familiar	Unclear
8	Incomplete	Unfamiliar	Unclear

Johnstone[9] has categorised problem solving activities and identified their characteristics according to whether the problem is familiar, has well defined aims and has a complete data set. This is shown in Table 1. Most of the problems that students encounter during traditional chemistry teaching and learning activities are firmly rooted in Type 1 or Type 2. Consider for example questions of the kind: ”Calculate the concentration of…“, ”Identify the compound from the following spectra…”,“Determine the order of the reaction of…” etc. There is a distinct lack of problems of the type that require students to do more than manipulate previously practised algorithms and methods.

An attempt was made to produce novel problems for chemistry undergraduates in the 1999 publication *A Question of Chemistry*.[10] In this book problems of several different types were presented. The categories used were: ‘understanding argument’, ‘constructing argument’, ‘critical reading’, ‘using judgement’, and ‘reference trails’. The aim of the book was to develop critical thinking skills in students. The nature of the problems meant that their styles would be unfamiliar to most students as they were generally non-numerical, open-ended, and without a single correct solution. This approach means that students gain most benefit from using them when they work in small groups, and share opinions and ideas and develop strategies co-operatively.

An example of a problem from the ‘using judgement’ chapter is given here. It is based on the requirement to carry out a ‘back of the envelope’ calculation in order to obtain a rough answer that gives the student some insight into analytical processes and scale of analyses.

The proverbial expression ‘looking for a needle in a haystack’ might be used by scientists trying to detect or identify traces of compounds.

If there is one needle in a haystack, estimate its concentration in parts per 10^n *on a weight or volume basis.*

Suppose you made up a solution with a concentration of ‘one needle per haystack’. What volume of the solution would contain a single molecule of solute?

Is the task of looking for a needle in a haystack comparable with using atomic absorption spectroscopy to detect a metal ion at a concentration below 1 ppb?

When problems of this type are used in classes of students, in addition to developing their range of thinking and problem solving skills, it is immediately obvious that other ‘key’ skills and competencies are being developed. The students have to formulate and defend ideas, communicate their ideas to each other clearly, and they have something to discuss for which they are entitled to hold and defend an opinion that may differ from that of the tutor. There is no longer a single correct answer, so students have to realise that answers are not always right or wrong.

Through using these problems from *A Question of Chemistry* for several years in many different situations and observing the students' responses, I have become convinced that the best way to address the skills development agenda is through problem solving activities. Those in *A Question of Chemistry* are fairly short, so they can be worked on within a tutorial session. If the problem-solving activities were extended so that they required students to learn some chemistry content in order to make progress and, if the problems were carefully developed, these should then stimulate students to expand their knowledge and develop a wide range of professional skills. If these problems are also set within a realistic context then they should also enable students to appreciate the range of applications of chemistry and enhance motivation and enthusiasm.

This reasoning has led to the development of problem solving case studies. Our model provides real problems that cannot be described as exercises. They are related to applications or real contexts, provide 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.[11, 12, 13]

A case study should:

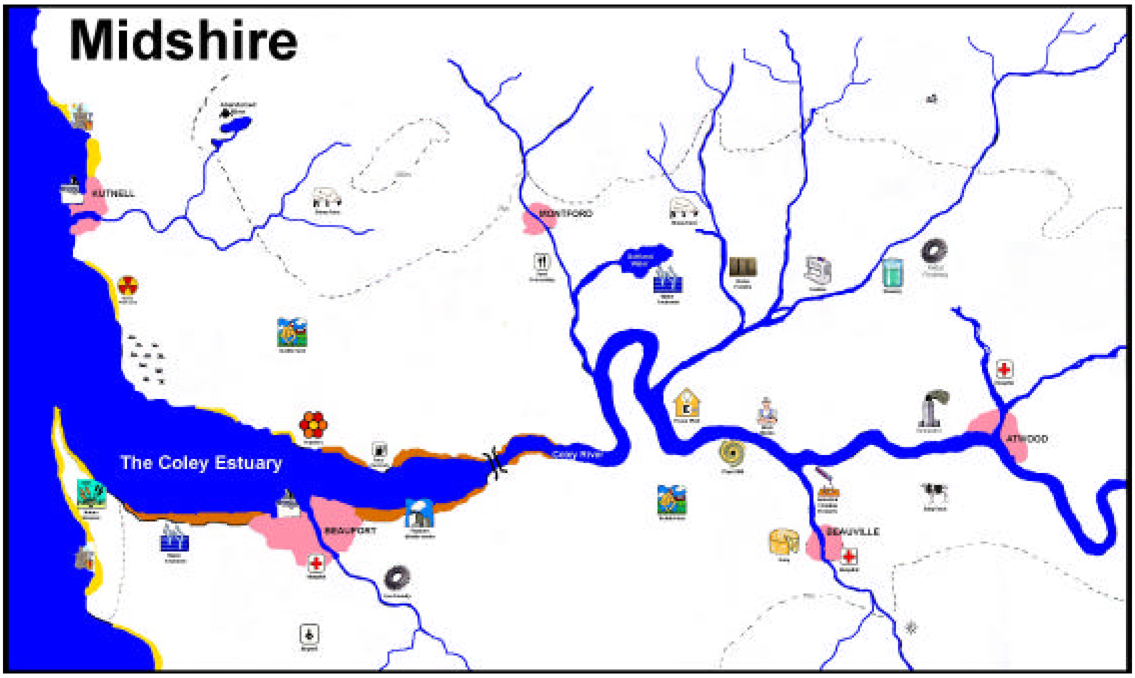
- involve the learning of chemistry either by building on and showing the relevance of prior learning, or by requiring students to learn independently in order to tackle the case
- be active in style
- involve a work-related context
- involve the development of personal skills
- encourage reflective learning
- have clear learning objectives for students

Chemistry is a discipline that provides many contexts for developing teaching and learning activities. We have chosen contexts within environmental, industrial, forensic, analytical and pharmaceutical chemistry to provide 'real' scenarios or case studies. Each requires students to work both individually and as part of a team to solve an extended problem. Each case study is flexible enough to be used in a variety of different teaching situations and each has been designed to encourage the development of different transferable skills. One such is described here.

Tales of the River Bank

This case study is set within the Coley River system in the fictitious county of Midshire (Figure 1). The river rises from springs in the limestone hills. The water in the upper reaches is clear; not until the tidal reach does the water become turbid. The river is navigable to just beyond the town of Atwood. The River Authority and the County Council led the clean-up of the previously heavily polluted river. The dumping of untreated industrial waste and sewage has been stopped. The building of new sewers and treatment works has meant that raw sewage should no longer get into the River Coley. It has in the last couple of decades once again become renowned for trout fishing.

Figure 1 Map of Midshire



The purpose of this case study is to produce a multi-layered problem that becomes more complex as the students proceed. To introduce it students are provided with copies of two letters: one from the chairman of the local angling club to the Environmental Agency complaining about his members' perception of a lack of fish in the river, and a copy of the reply from the Agency. The students are provided with a map of the area (Figure 1) and have to decide whether an investigation is required and, if so, how to proceed with it. The results of analyses of river water samples are provided or can be requested at various stages. Additionally, assistance is provided along the way in the form of briefing papers and exercises

The industries and land use are simplified compared with the complexity that would be found along a real river. If there is a problem with the water quality and fish stocks, the cause may or may not be identified, but the students should be able to consider all possible causes and suggest methods of remediation or preventative action.

Initially, students should identify a seasonal variation associated with nutrient runoff from the land that could cause problems. Further investigation should show a recent increase of conductivity due to an industrial effluent, and finally the presence of estrogens / phthalates should be considered. The students will have to consider whether any or all of these factors could have influenced fish stocks.

Table 2 Summary of chemical skills developed

Subject Specific Skills	
Technical Approach	Selecting appropriate analytical methods.
Knowledge	Environmental classification, chemical and biological indicators, water quality, sampling, pollution, toxicity, spectrophotometry, electrochemical testing.
Independent study	Background to analytical techniques, environmental science and remediation. Study of industrial processes and effluent streams.
Interdisciplinary skills	Analytical chemistry, environmental science, toxicology, ecology, geography, hydrology, etc.
Interpretative skills	Manipulation and evaluation of information and data to make realistic decisions on the evidence available.
Practical skills (Optional)	Instrumental manipulation, observation and recording.

Table 3 Summary of transferable skills developed

Key Transferable Skills	
Communication	Oral presentations to scientists and to other interested parties, report writing for different audiences.
Information retrieval	Collection and classification of information.
Personal	Individual judgement, taking responsibility for decision making, time management, working to deadlines.
Problem Solving	Tackling unfamiliar problems, using judgement, evaluating information, formulating hypotheses, analytical and critical thinking.
Team working	Brainstorming, discussion, division of tasks and reporting back to the group.

Tackling the problem

The students take the role of the investigation team. They must consider:

- Whether there is a problem
- What factors could cause the reduction in the fish stocks
- Where they should sample along the river
- What analyses should be carried out
- Whether the problem is due to organic or inorganic effluent
- Whether the problem is continuing, seasonal or recent
- Sources of the problem
- Possible remedial action

The class is organised into groups of three to six, with four being the optimum number. The groups are gradually supplied with information in the form of reports and briefing papers, and at various stages are invited to request analyses or carry out independent investigations. After gathering the final pieces of evidence and completing the required independent study, the students are expected to have identified what had caused the reduction in fish stocks.

The chemical topics and issues that the students have to cover are given in Table 2. In addition, the professional skills that should be used in order to complete the case study successfully are outlined in Table 3.

The case study can be tackled over two 2-hour workshops or over four one-hour sessions with about eight hours of additional student study time. The project comprises several short tasks so it is inherently flexible. Its background material includes a number of briefing papers and exercises that can be used to help students with varying backgrounds. The overall structure for two teaching sessions is shown in Table 4.

Students are provided with information from Environmental Agency monitoring stations along the river. This includes longitudinal data on COD, BOD (which indicate the amount of organic matter present), dissolved oxygen and ammonia. This information, together with the relevant briefing paper, allows them to consider the quality of the water along the river. They should be able to identify a seasonal variation between two sampling points, indicating agricultural runoff. Students can request more recent data that indicates that there is currently no problem with dissolved oxygen and nitrogen levels but that there is high conductivity, indicating inorganic pollutants and the possibility of a problem originating at one of the industrial or

Table 4 Timetable for two 2-hour workshops

Session 1a	Overall aims of the case study are described. Students are divided into groups. The letters from the Angling Association and the Midshire River Authority are given out. The Midshire map with the accompanying information about the ColeyValley describes the area and associated industries. The briefing paper on river quality is given out.
Task 1	To consider the industries and other potential sources of pollution down the Coley Valley. The water quality exercise is used to bring the students' attention to the aspects of water quality.
Session 1b	Students are given analytical data from four Environmental Agency sampling points.
Task 2	Discuss whether there is a real problem. (If they decide that there isn't one, they have to justify that decision.) Decide how they would narrow down their search. Discuss possible sources of the problem. Plan sampling exercise to highlight issues related to sampling in various conditions.
Session 2a	Students are handed larger scale map of area between Coley Bridge and Atwood with possible additional sampling points marked.
Task 3	Choose two additional sampling points, request analysis. Given the results on result cards. After discussion, request analysis from two further points along river. Consider the industrial and commercial activities along the river and identify potential sources of pollution.
Session 2b	Groups may request analysis of fish and are given the fish autopsy results. Students given briefing paper on toxic substances.
Task 4	Request further chemical analysis; receive results. Decide on source of problem. Discuss remediation, prevention. Prepare an oral presentation and / or reports.

commercial enterprises along the riverbank. Careful further sampling should enable them to narrow down the problem area. Students must then survey all the relevant industries and activities to ascertain the nature and source of possible effluents. They may then request chemical analyses from their chosen sampling points. The number of allowed sample points and analyses is strictly limited in order to encourage the students to think carefully and critically about the requests they make. This restriction may be justified to the students on grounds of 'cost'. If they request the correct analyte and method they will receive meaningful results, which should enable them to identify the source of the second problem. If students are unsuccessful at this stage they may be prompted by the tutor or allowed to make additional requests.

Additional support on specialised areas such as water quality is provided in the form of briefing papers. Additional exercises can be run within the case study to emphasise particular topics, such as sampling.

Assessment

A case study may be assessed in a variety of ways and the chosen method may depend upon how the it is being used. The activity has been trialled with students on analytical chemistry, environmental science and professional skills modules; and the assessment focus differed in each case. For example, for an analytical module the focus may be on using the correct analytical technique and solving the problem effectively. For a skills-based module the focus may be on effective group work and the quality of oral presentations. Assessment tools which have been successfully used include oral presentations to other scientists, oral presentations to a lay audience, written reports, summaries of data collected, peer assessment of group participation, and individual reflection on skills development.

Observations

The case study has been piloted with students on analytical chemistry and environmental science modules at three institutions. Student feedback on these activities has been very positive. Feedback questionnaires provided evidence that the students realised that they had developed a range of skills during the activity (Table 5)

The case study presented a very new and different way of working for all these students and they required some support to encourage them to take the activity seriously. They showed a tendency to believe that they would be given meaningful results even if they had not asked the right questions. They also had to be encouraged to take the independent learning aspect seriously and accept that it was an integral part of the exercise. The students recognised that the outcome of the study was that they had practised a range of skills and had gained a grasp of analytical and environmental science. Their enthusiasm increased throughout the project as they became more involved in the decision-making processes. Ensuring that the exercise is properly assessed and counts toward the module helps in overcoming the students' initial reluctance to work outside the classroom sessions.

Table 5 Feedback from Students

Do you feel you have developed any of the following skills? (scale: 1 = not at all, 5 = a lot)	Score
solving unfamiliar problems	3.8
working with others	4.0
thinking logically/critically	4.0
using judgement	4.0
forming and defending arguments	4.0
communicating your ideas	3.9
link between theory & practice	3.7

The case study achieved the initial objective of using problem solving to develop knowledge and skills. The study presented students with an open-ended, unfamiliar problem for which there was no single correct solution. They had to use a range of skills in order to achieve a satisfactory outcome, and the applied, realistic context engendered enthusiasm and engagement with the problem.

Other case studies

We are currently developing a suite of problem solving case studies, each with a focus on analytical science whilst utilising contexts within environmental, forensic, industrial and pharmaceutical chemistry. They will be suitable for use at levels 1, 2 and 3 and will cover a range of analytical science and a broad range of transferable skills. Those currently being developed include scenarios such as a suspicious death, smuggling of illicit drugs, pharmaceutical preparation, industrial processes, validation of analytical measurements, setting up a laboratory, and land reclamation.

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