Chemistry Education Research and Practice

Cite this: *Chem. Educ. Res. Pract.*, 2012, **13**, 490–499

www.rsc.org/cerp

PAPER

Improving the school-to-university transition: using a problem-based approach to teach practical skills whilst simultaneously developing students' independent study skills

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Received 24th July 2012, Accepted 3rd September 2012
DOI: 10.1039/c2rp20096a

Despite being criticised for placing little emphasis on thinking, the majority of laboratory work at school level is taught *via* expository 'recipe-style' labs. This has been seen to result in students struggling to be able to apply the practical techniques they have learnt in the classroom outside the narrow environment in which they were taught. This paper describes the design, trial and evaluation of a collection of ten practical activities which use a problem-based approach to laboratory instruction to deepen the students' understanding of the standard laboratory techniques they would be expected to know on entering an undergraduate chemistry laboratory. The practical activities have been trialled by over 100 students in eight different schools and feedback obtained *via* student questionnaire and informal comments provided by teachers. Compared to typical laboratory instruction, the students find the problem-based practical activities more interesting and better for making them think. Over 80% of the students indicate that the problem-based activities are '*good*' or '*very good*' for the application of practical techniques. Furthermore, the problem-based practical activities scored favourably compared to a typical laboratory activity for developing the students' independent study skills, team working and communication skills, scientific writing and research skills.

Introduction

Amongst university teaching staff, there is a strong feeling that students' practical skills on entering university have declined over recent years. Academics in the United Kingdom report that new undergraduates lack at least some confidence in the laboratory and are not well-equipped with laboratory skills (Gatsby, 2011). Students' limited exposure to practical work at school level is often cited as a major factor contributing to the observed decline. However recent research by the author revealed a possible alternative cause. With the change in the curriculum in the UK introduced in 2006, the planning element has been removed from the required practical tasks in the majority of A-level (upper secondary level) chemistry specifications. As a result 94.7% (n = 516) of first year undergraduate students questioned reported that they followed written instructions either '*always*' or '*most times*' during school practical lessons (Smith, 2012). A similar picture is seen in the United States. A review of the laboratory experiences in science of high school students in a random sample of 1800 schools throughout the United States found that teachers and laboratory manuals emphasised the procedures to be followed, leaving the students uncertain about what they were to learn (Singer, 2005). Only 8% of high school teachers indicated that they asked the students to design or implement their own investigation once or twice a week. Another 41% of teachers said students were asked to design or implement their own investigation once or twice a month, with a further 42% of teachers indicating a frequency of a few times a year. In chemistry specifically, 72% percent of the teachers questioned indicated that they engaged students in hands-on or laboratory science activities more than once or twice a week, and effectively the same percentage of teachers (73%) indicated that students were required to follow specific instructions in an activity or investigation in the same time frame (Smith, 2002).

Domin (1999) describes practical work in which students follow given instructions to obtain a known outcome as *Expository*. Such labs require little student engagement and as Johnstone (2001) comments, the "*students can be successful in their laboratory class even with little understanding of what they are doing*." The consequence of this is that the students have an understanding of practical techniques which is only surface deep, and as a result are unable to apply the tools and skills outside the narrow environment in which they have been taught.

This paper describes the development and trial of a series of practical activities for secondary level students, designed to

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deepen the students' understanding of the practical techniques they will be required to perform on entering higher education. With a deeper understanding of the practical technique it is believed that the students will be able to apply that technique more easily to new situations.

University teaching staff in the United Kingdom also report an observed weakness in students' problem-solving abilities (Gagan, 2008). The weakness is believed to stem from the difference in teaching methods between UK schools and universities. At university, students are expected to be independent learners whereas at school level much of the learning is teacher-led. In addition to developing the students' understanding of the practical techniques needed, the practical activities described in this paper are designed to introduce the students to the independent learning skills they will need to be successful in higher education and throughout their working lives (Bennett, 2003).

A problem-based approach to teaching practical science

Problem-based learning is becoming increasingly common place in university teaching. Problem-based learning is a sub-set of context-based learning. Context-based learning is any learning that places content within a meaningful context. In problem-based learning, the context is framed as an open-ended problem scenario (Overton, 2007). An important feature of problem-based learning (PBL) is that the problems or scenarios are encountered before all the relevant learning has taken place. Thus, solving the problem acts as the driver for new learning.

Despite its wide application in the teaching of theory, there is limited evidence of the use of a problem-based approach to the teaching of laboratory techniques, and of the studies of which the author is aware all describe the use of a problem-based approach for the teaching of laboratory techniques at a tertiary level. A brief review of each of the studies follows. Kelly and Finlayson (2007, 2009) developed a PBL laboratory-based module for first year undergraduate chemistry, with an aim of developing the students' practical and transferable skills, as well as their content knowledge and scientific understanding. Compared to traditional teaching methods, it was found that using a PBL approach provided more scope for developing the students' practical skills, and for developing the students' understanding of the concepts and of the experimental process. McDonnell *et al.* (2007) used a series of problem-based learning mini-projects to enhance the experience of second year undergraduate students in chemistry laboratory practicals. Increased class participation and engagement together with improved class morale were observed as a result. Lucas and Rowley (2011) explored a similar enquiry-based approach to teaching spectroscopy. It was shown that an enquiry-based approach has the potential to increase students' perceived confidence in spectroscopy, particularly in those students who were least confident before the course. In more recent studies by Flynn and Biggs (2012), a fourth-year undergraduate synthetic organic and medicinal chemistry laboratory was transformed from a traditional laboratory format to a PBL format. The change was seen to result in an improvement in the students' abilities to learn independently and think critically. Other studies have shown the successful application of a problem-based approach to the teaching of qualitative analysis laboratory experiments (Hicks, 2012) and general chemistry laboratories (Sandi-Urena, 2011). Finally, McGarvey (2004) gives an account of the transition process from traditional expository-style practical work to problem-based practicals in the light of a practitioner's experiences and student feedback. He notes that a problem-based approach to teaching laboratory work is certainly more demanding on student and staff demonstrators and consumes more laboratory time than that required for a traditional practical. Experience in the supervision and management of the problem-based practical work with a focus on student learning was also reported to be vital.

Similar to the problem-based learning approach described above is problem-based laboratory instruction. Domin (1999) describes problem-based laboratory instruction as a "*deductive approach in which students apply a general principle towards understanding a specific phenomenon*." In problem-based laboratory instruction, the students are presented with a problem statement often lacking in crucial information. From this statement, the students then redefine the problem in their own words and design a procedure that will lead them to a solution of the problem. Domin states that "*students working in a problem-based [laboratory] environment must apply their understanding of a concept to devise a solution pathway; this requires them to think about what they are doing and why they are doing it*." Compared to pure problem-based learning, in problem-based laboratory instruction the students must have had exposure to the concept or principle of interest before performing the experiment. Such an approach is therefore ideal for developing students' understanding of a previously met practical technique.

The practical activities designed in this study use a problem-based laboratory approach to develop students' understanding of practical techniques at secondary level.

Method

Design of the problem-based practical activities

There are many challenges facing teachers when it comes to implementing effective practical work at school level. In a recent report by SCORE: Science Community Representing Education (2008), which looked at practical work in science in the UK education system, the three most frequent responses given by practising teachers to the question "*Why does your current practice [of teaching practical science] vary from your ideal?*" were: 1. curriculum content; 2. resources and facilities; 3. time. Therefore it was seen to be paramount that any practical activities produced covered areas of subject knowledge common to the A-level specifications of all exam boards, used equipment which the majority of schools would have easy access to, and fitted in to a maximum of two one-hour lessons or a single two-hour lesson. Since problem-based laboratory instruction is a deductive approach, the students must have had exposure to the concept or technique of interest before performing the experiment. Therefore the problems were designed to be fitted in to a Scheme of Work shortly after the completion of the relevant section of theory from the syllabus.

The overall design of the practical problems was similar to that used by Kelly and Finlayson (2007). Each problem was designed to include pre-lab work, followed by group work and discussion, and finished with some form of assessment. The principal aim of the practical activities was to deepen the students' understanding of the practical techniques they would be expected to be familiar with on entering a university laboratory. This was done by setting the technique in the context of a real-life problem for the students to solve. In each case a suitable experiment which involved the required technique was either found through a literature search or known from existing knowledge, and then adapted to present a problem set in a real-life context. The problem is presented to the students in the form of a letter from an imaginary client seeking the help of the students in solving the problem scenario identified above. Only the essential facts are provided in this letter.

Since for maximum effect skills need to be developed progressively, a collection of ten practical activities designed to span a two-year post-16 programme of study was designed. A summary of each activity together with the curriculum links and the practical techniques it is designed to cover is given in Table 1. The pre-lab questions and introduction letter for '*Problem 3: Cleaning solutions*' are provided in Appendix 1 as an exemplar. The full set of problem-based practical activities are available online and can be accessed *via* the Royal Society of Chemistry's Learn Chemistry platform (http://www.rsc.org/learn-chemistry/resource/res00000939/problem-based-practical-activities).

A secondary aim of the activities was to develop the students' independent learning skills. Independent learning skills promote the students' ability to review, record and reflect on their learning. However, they take time to establish and for many students require deliberate teaching and modelling (Wilkin, 2012). Therefore, the practical activities were designed to teach and model the following skills required to be an independent learner:

- the ability to accurately decode written information and summarise the main points of a task
- the ability to use a number of different sources to locate information required for the completion of the task
- the ability to work in co-operation in a group
- the ability to demonstrate determination and organisation skills to meet deadlines
- the ability to recognise when help is needed and take the initiative to ask for that help
- the ability to see mistakes as part of the learning process
- the ability to demonstrate persistence when a task appears challenging.

Each problem was designed to be tackled by a group of three students. The activities were carefully designed such that they could not be completed by an individual, or by all three students working as a single unit, in the allocated time. Therefore successful completion of the problem was not only dependent on good communication and team work but also on effective time management.

The problems were designed to be to be challenging such that all students reach a point at which they become '*stuck*.' This would be at different points for different students. Perkins (1999) would describe the knowledge required at this point as *troublesome*, being either conceptually difficult, counter-intuitive or '*alien*.' Being '*stuck*' is in fact something to be celebrated as it means that the students have reached a point where they about to learn something new. Being able to appreciate when one is '*stuck*' and having the techniques to hand to overcome this phase is also a key element in being an independent learner. '*Stuckness*' is reported as a common state in PBL activities (Raine, 2005). However, by undertaking such activities, the students learn techniques for overcoming the feeling. Suitable techniques suggested by Raine include:

- returning to the problem statement or triggers
- brainstorming
- thinking of questions to ask experts
- re-tracing their path to the current '*stuck*' position, to see whether any alternative paths or even mistakes can be identified
- approaching the problem from a new angle
- reviewing their assumptions or perhaps modifying them

In order to help the students move beyond this '*stuck*' phase and to scaffold their problem-solving skills, each problem was accompanied by a set of pre-lab questions to be completed by the students for homework prior to the laboratory session. Formal feedback on the pre-lab questions was not provided by the teacher. Instead, the students were encouraged to compare answers with other group members, and only seek clarification from the teacher if required. The purpose of the pre-lab questions was threefold:

1. By answering the questions, it was ensured that the students had all the knowledge and understanding of the chemical concepts and/or techniques required to effectively tackle the problem. They provided the students with the information they needed to move beyond being '*stuck*.' Since many of the questions required factual information beyond the remit of the A-level syllabus, by answering the pre-lab questions the students were encouraged to research beyond their usual set texts and develop their research skills.

2. Johnstone *et al.* (1994) have shown that pre-lab questions can allow understanding to increase, simply by reducing information overload.

3. Owing to the health and safety precautions and resourcing requirements associated with running a practical activity at school level, where class sizes can be anything up to thirty students, each problem was designed with a proposed method in mind. The pre-lab questions, together with timely interventions from the teacher were designed such that the students reached the proposed method independently.

In order to solve each of the problems, the students needed to think about each of the following points, highlighted by Garratt (2002) as things scientists think about before doing an experiment.

- *What question(s) are we trying to answer?*
- *What observations (data) would provide an answer to the question(s)?*
- *How can we best create conditions for making the desired observation(s)?*
- *How will we process and evaluate the observations (data)?*

To scaffold this thought process, each group was encouraged to follow the 'SET' strategy (*S*ummarise the problem; *E*xisting knowledge; *T*hings we need to find out) designed by Williams *et al.* (2010).

Table 1 A summary of the problem-based practical activities

Problem 1: Carbonate rocks!
Curriculum links: mole calculations, reacting masses, thermal decomposition of metal carbonates. *Practical skills*: top pan balance, observation skills.
The chairman of a local geology society has contacted the students to ask them to help him identify four different rock samples (all essentially metal carbonates or hydrogen carbonates). The students need to heat the samples, measure the mass change and record visual observations. Using the visual observations, the students are asked to identify each sample and using the mass changes the students are asked to determine the purity of the samples.

Problem 2: A little gas
Curriculum links: ideal gases, Maxwell–Boltzmann distribution, equation of a straight line. *Practical skills*: using computer simulations, graph plotting and interpretation.
The students are contacted to write a review on the use of computer simulations in sixth form chemistry for the student chemistry magazine *The Mole*. They are directed to a simulation on gas properties produced by PhET (University of Colorado at Boulder) and asked to use the simulation to determine the identity of the "light" and "heavy" gas used in the simulation.

Problem 3: Cleaning solutions
Curriculum links: oxidation numbers, redox, halogens, moles, reacting masses. *Practical skills*: collecting gas, accuracy.
An ad agency is putting together an advertising campaign for a new bleach. They contact the students for help with determining the amount of NaOCl in various bleach samples (found by reacting a known quantity of each bleach with hydrogen peroxide and measuring the amount of oxygen produced). Using this information, the students are asked to determine if the new bleach is better value for money.

Problem 4: Alcohol detective
Curriculum links: alcohols – nomenclature and classification, oxidation, redox equations. *Practical skills*: distillation, chemical tests.
The students use distillation to purify two samples of fake vodka seized by the local police and then identify the nature of the alcohol as either ethanol or *tert*-butanol from its boiling point. The identity of the alcohol is then confirmed using standard test-tube reactions (potassium dichromate and the iodoform test).

Problem 5: Coursework conundrum
Curriculum links: oxidation of alcohols, carboxylic acids. *Practical skills*: recrystallisation, thin layer chromatography.
A lazy student has contacted the students for help with purification of his sample of benzoic acid (contaminated with benzyl alcohol and Cr^{3+} residues). Recrystallisation of the sample is followed by TLC analysis to prove its purity.

Problem 6: Acid erosion
Curriculum links: titration, pH curves, strong and weak acids, pK_a. *Practical skills*: titration.
A dentist has contacted the students to determine which of three drinks is the least acidic, and hence which is the least likely to cause tooth enamel erosion.

Problem 7: Iodination inquiry
Curriculum links: rate equations, rate-determining step. *Practical skills*: clock reactions, accuracy.
A teacher asks the students to design a clock reaction to determine which is the rate-determining step in the iodination of propanone.

Problem 8: Compound confusion
Curriculum links: analytical methods, empirical formulae. *Practical skills*: spectral analysis, melting point determination.
The students are contacted by the data-collection manager for SpectraSchool. There has been a flood and the labels have come off a number of bottles. The students are to analyse various spectra (IR, mass spectrometry, ^{1}H and ^{13}C NMR) and use these, together with melting point determination, to identify the six unknowns.

Problem 9: Cool drinking
Curriculum links: enthalpy changes, Born–Haber cycles. *Practical skills*: experimental design, health and safety.
The students are set the problem of designing a new drinks container which will cool 100 cm^3 of a drink by 5 °C in 5 min. The students need to decide which of ammonium nitrate and ammonium chloride should be used based on the enthalpy of solution, the solubilities in water, the cost, and the relevant health and safety information for each salt. They then need to trial their method and modify the quantity of salt required accordingly.

Problem 10: Patient prognosis
Curriculum links: transition metal complexes, colorimetry, alcohols, carboxylic acids, esters, analytical techniques. *Practical skills*: dilution, colorimetry, observation skills, gas chromatography analysis.
A nineteen year old male has recently collapsed. His doctor would like the students to test: (i) the patient's urine for glucose; (ii) the concentration of salicyclic acid (the break-down product from aspirin) in the patient's urine [by colorimetry of the iron(III) salicylate complex]; (iii) the patient's blood alcohol level (by interpretation of gas chromatographs provided). Using this information the students are asked to make a recommendation as to the reason why the patient fainted.

During the activity the role of the teacher was to move between the student groups, listening to their conversations and working to bring about the best from each group. This was done by asking leading and open-ended questions, raising any issues that the students had not considered, helping the students to reflect on the experiences they were having and challenging the students' thinking.

Finally, each problem asks the group to submit a joint written report at the end of each problem. Assessment of university laboratory work in the UK is commonly based upon the completion of a written report, yet scientific writing is something which is rarely touched on at school level. A recent survey by the author revealed that 40% (n = 516) of students currently studying for a degree at a UK university were '*occasionally*' asked to complete a full written report of their experiment when at secondary school, with a further 34% reporting '*never*' being asked (Smith, 2012). In a survey of 506 US high school chemistry teachers, 28% reported asking students to complete a written science report '*a few times a year*,' 37% '*once or twice a month*' and 30% '*once or twice a week*' (Smith, 2002). Inclusion of the requirement to complete a formal group report, with formative feedback given by the teacher, was intended to both increase the students' confidence in scientific report writing and ensure that the students pulled together the data collected to reach a final conclusion and solve the problem.

Implementation of the problem-based practical activities

The problems were trialled in eight schools by a total of 106 students over a period of three months between March and July 2012. In some cases the lesson was carried out by the author, whereas in other cases the normal class teacher trialled the problem-based practical activity independently. In all cases the teacher was given clear instruction regarding the lesson structure. Only one problem-based practical activity was trialled with each group of students, with, in the majority of cases, the same practical activity completed by the whole class. In one school, however, different groups of students within the same class trialled different problem-based practical activities. The students were all aged between 16 and 18 years and class sizes ranged between 8 and 17 students. Groups were arranged either in friendship groups or to ensure a mix of abilities.

Student evaluation of the problem-based practical activities

Throughout the work, a typical practical activity refers to a practical activity the students had experienced in their studies prior to the problem-based practical activity. A problem-based practical activity refers to the problem-based practical task they completed during the study.

Prior to being introduced to the problem, the students completed a questionnaire in which they were asked to score on a scale of 1 to 5 (where 1 = very poor, 2 = poor, 3 = average, 4 = good and 5 = very good) their experiences of a typical practical activity for a number of qualities and for the development of a number of skills. At the end of the two hours allocated for the completion of the problem-based practical activity, the students completed a second questionnaire in which they were asked to score a typical practical again and the problem-based practical for the same qualities and for the development of the same skills. This was followed by a series of open questions designed to gain feedback on what the students liked and disliked about the problem-based practical activities as well as what they found challenging.

At the end of the study the data was entered into a spreadsheet for statistical analysis. In order to gather data on the observed changes in the scores allocated to the two different practical types by individual students, the data was entered as individual records and then collated as required. Frequency distributions were created for the observed change in individual student scores allocated for a typical practical activity before and after experiencing the problem-based practical activity, and for the observed change in individual student scores moving from a typical practical (after having experienced a problem-based practical) to the problem-based practical. Similarly, the overall distribution of scores allocated to a typical practical (after experience of the problem-based practical) and the problem-based practical were collated and the distributions analysed by the chi-square test to determine if there was a significant difference between the students' opinions of the two practical types. Where frequencies were small, the frequencies of scores of 1 and 2 or 1, 2 and 3 were amalgamated such that the frequency in any cell was greater than 5.

Results and discussion

Comparison of the student feedback for a typical practical activity compared to the problem-based practical activity

Table 2 shows a comparison of the frequency distribution of the scores allocated for the problem-based practical activity

Table 2 Frequency distribution of scores allocated to the problem-based practical activity and to a typical practical activity (after experience of the problem-based practical activity) (n = 106)

	Typical practical (after experience of problem-based practical)						Problem-based practical								
Score	1	2	3	4	5	**4+5**	1	2	3	4	5	**4+5**	χ^2	d*f*	*p*
For															
Enjoyment	1	1	36	52	16	**68**	4	5	18	60	19	**79**	5.0	2	n.s.[a]
Interest	1	2	38	45	20	**65**	2	4	17	59	24	**83**	13.1	2	<0.005
As a learning experience	2	1	25	54	24	**78**	3	6	13	52	32	**84**	4.0	2	n.s.[a]
Linking theory to practice	2	4	26	51	23	**74**	3	2	22	50	29	**79**	2.4	2	n.s.[a]
Application of practical techniques	2	0	31	48	25	**73**	2	5	14	56	29	**85**	6.3	2	<0.05
Understanding chemistry	1	7	22	61	15	**76**	4	5	22	49	26	**75**	10.6	3	<0.025
Making me think	2	12	30	39	23	**62**	3	1	17	38	47	**85**	37.1	2	<0.005
Ease of completion	1	7	35	46	17	**63**	3	13	49	34	7	**41**	22.6	3	<0.005
Best use of lesson time	1	7	34	48	16	**64**	4	11	26	50	15	**65**	8.2	3	<0.05
For development of the following skills															
Practical skills	1	3	26	51	25	**76**	1	4	21	54	26	**80**	0.7	2	n.s.[a]
Team working	2	5	34	35	30	**65**	2	4	17	40	43	**83**	15.0	3	<0.005
Communication	0	7	43	32	24	**56**	2	4	25	45	30	**75**	14.5	3	<0.005
Independent study	6	15	42	33	10	**43**	5	10	34	40	17	**57**	9.6	3	<0.025
Scientific writing	6	11	43	33	13	**46**	5	7	32	48	14	**62**	11.2	3	<0.025
Research skills	7	13	39	34	13	**47**	5	6	23	52	20	**72**	23.9	3	<0.005

[a] n.s. = not significant.

and the frequency distribution of the scores allocated for a typical practical activity after the students had experienced the problem-based practical activity. For the majority of qualities, the differences between the distribution of scores allocated for the two practical types were observed to be significant by the chi-square test (see Table 2).

80% of students found the problem-based practical activities either '*good*' or better for the '*application of practical techniques*.' Similarly, 79% of students found that '*as a learning experience*,' the problem-based practical activities were either '*good*' or better.

The percentage of scores of 4 (= good) or 5 (= very good) allocated for the problem-based practical activity was higher than the percentage allocated to a typical practical for all qualities except for '*ease of completion*' (typical practical, 4 or above = 59%; problem-based practical, 4 or above = 39%) and '*understanding chemistry*' (typical practical, 4 or above = 72%; problem-based practical, 4 or above = 71%). For this latter quality, the percentage of students indicating a score of 5 (= very good), increased from 14% for a typical practical to 25% for the problem-based practical activity. The biggest increase in score for the problem-based practical activity was seen for '*making me think*,' where the percentage of students who allocated a score of 4 (= good) or above changed from 58% for a typical practical to 80% for a problem-based practical. Many students went on to comment further on these elements:

- "*I liked how you had to understand exactly how everything worked to be able to complete the activity*"
- "*There weren't instructions given so we needed to think for ourselves*"
- "*It challenged me but I understood the chemistry and practical side of the experiment much better than being given a set of instructions*"
- "*Initially trying to work out what was required [was challenging]; but this made me understand it more thoroughly*"

Table 3 gives a comparison of the scores allocated by individual students for a typical laboratory activity (after having completed the problem-based practical activity) to those allocated for the problem-based activity. A decrease in score equates to the score allocated to the problem-based practical activity being lower than the score allocated for a typical practical activity. It is clear that the students' reactions to the problem-based activities were mixed, with some students liking them and others not. One teacher commented "*the scientific thinkers were very positive; the plodders were disconcerted.*" This is illustrated further in comments by two students. Whereas one student liked the activity because "*it was well worked and contained many steps to solve the problem; good challenge*," a second student commented "*I would have liked to have been guided through it more; I understand this was to try and bridge the gap between A-level and university, but I think the gap was too large.*" Table 2 shows that consistently more of the students allocated a score of 1 (= very poor) to the problem-based practical activity compared to the typical practical activity for all qualities except '*application of practical techniques*,' where the number of students allocating a score of 1 is the same for both practical types. Although the percentage of students allocating this score is still small ($\leq$4%), it is worth further comment. From the trials, it was clear that some students, and not necessarily the academically

Table 3 Comparison of individual student scores for the problem-based practical activity compared to the score allocated to a typical practical activity after having experienced the problem-based practical (n = 106)

	Change in score		
	Decreased	Stayed the same	Increased
For			
Enjoyment	25	47	34
Interest	21	47	38
As a learning experience	22	53	31
Linking theory to practice	25	43	38
Application of practical techniques	26	43	37
Understanding chemistry	24	50	32
Making me think	11	44	51
Ease of completion	49	46	11
Best use of lesson time	27	56	23
For development of the following skills			
Practical skills	29	45	32
Team working	15	52	39
Communication	16	52	38
Independent study	15	54	37
Scientific writing	21	48	37
Research skills	10	55	41

weaker ones, did not like the PBL approach. In some cases the students were put off by the fact that they did not know what answer they were expected to get. In one case, students were found carefully studying the label of the bleach bottle to see if they could find a NaOCl(l) concentration so that they could work backwards and find out what their answer should be. This group later commented in the open questions that the unknown nature of the problems hindered their confidence. By removing the structure of the practical work these students lacked confidence in their ability, despite being very good students. Another student commented that she found "*having so many things on the go a challenge.*" For this student, the time management and independent work required to successfully complete the problem was unsettling. Kelly and Finlayson (2009) noticed that although some students struggled initially with the PBL approach, over time and through practise they became more confident. In addition over the course of the module in which their PBL approach was implemented, they noticed an increase in the students' preference for a PBL approach over a traditional laboratory approach from 47% to 83%. Each student in the study described in this paper completed a single problem-based practical activity and so had only a limited opportunity to develop their problem-solving skills and hence grow in confidence. To ensure all students remain focused and motivated during future problem-based practical activities, careful facilitation by the teacher and suitable arrangement of groups and delegation within the groups would be needed.

Overall, more students indicated a higher score than a lower score for the problem-based practical activities compared to a typical practical activity for all qualities except for '*ease of completion*' and '*best use of lesson time*.' It would be expected that the problem-based practical activity would score lower for the ease of completion as a high score equates to the practical being easy. The scores allocated for the best use of lesson time reflects that, in some cases, the problem-based practical activities were completed as revision exercises in the run-up to the exam period. In these cases, some of the students resented the loss of revision time, which is reflected in their scoring.

The biggest percentage of students increasing their score was seen for '*making me think*,' where 48% of students allocated a higher score to the problem-based activity than to the typical practical activity. In studies looking into the effect of cooperative problem-based laboratory instruction on students' learning, Sandi-Urena *et al*. (2012) found a similar result. By placing students in an environment in which they are forced to use and practise scientific skills, such as asking scientific questions and critical thinking, measurable changes in students' problem-solving abilities and metacognition were seen. In addition, their findings presented evidence for the relationship between experiences in the laboratory and the development of metacognitive skilfulness.

Comparison of the student feedback for a typical practical activity before and after completion of the problem-based practical activity

Table 4 shows how the scores allocated by individual students for a typical practical activity changed after completing the problem-based practical activity. For each quality, approximately half of the students did not change their score. For the students who indicated a change in score, overall more students lowered their score than raised it, although the results are quite divided. The largest numbers of students decreasing their score for a typical practical activity are seen for the qualities of '*best use of lesson time*' and for development of '*practical skills*' and '*independent study skills*,' followed closely by for '*making me think*' and for developing '*research skills*.' The exceptions to the general decrease seen are for '*ease of completion*,' where the increase in score indicates that after completing the problem-based practical activity the students considered a typical practical easier to complete than they thought originally, and for developing '*scientific writing skills*,' where slightly more students increased their score than decreased it (25% *vs*. 23%).

Table 4 The change in scores allocated by individual students for a typical practical activity after completing the problem-based practical activity (n = 106)

	Change in score		
	Decreased	Stayed the same	Increased
For			
Enjoyment	27	62	17
Interest	28	62	16
As a learning experience	33	49	24
Linking theory to practice	30	52	24
Application of practical techniques	31	51	24
Understanding chemistry	23	62	21
Making me think (5 = easy)	34	47	25
Ease of completion	23	51	32
Best use of lesson time	36	48	22
For development of the following skills			
Practical skills	36	50	20
Team working	30	51	25
Communication	32	54	20
Independent study	36	45	25
Scientific writing	24	55	27
Research skills	34	42	30

Student feedback on the development of skills

The principal aim of the problem-based practical activities was to deepen the students' understanding of practical techniques. Over 75% of the students indicated that the problem-based activities were either '*good*' or '*very good*' for developing their practical skills (Table 2). This is similar to the final score allocated for a typical practical activity (72%; $df = 2$, $p < 0.80$, n.s.). The scores allocated here depended in part on which problem was completed. Problems that were clearly focused on traditional practical techniques such as Problem 5 (practical skills: recrystallisation, thin layer chromatography) scored highly (4 = good, 44%; 5 = very good, 56%; n = 9), whereas problems where the practical skills developed were less obvious such as Problem 3 (practical skills: gas collection, accuracy) scored lower (2 = poor, 2%; 3 = average, 29%; 4 = good, 45%; 5 = very good, 24%; n = 42).

A secondary aim of the activities was to develop the students' independent study skills. From the scores given for development of the skills of '*team working*,' '*communication*,' '*independent study*' and '*research skills*,' this secondary aim of the problems has clearly been met. For each of these skills, the problem-based practical activity scores significantly more highly than a typical practical activity (Table 2). Many of the students commented on these skills in the open questions at the end of the questionnaire. Comments included:

- "*It helped me improve my lab skills and I got better with communicating with other members – became more responsible with my work*"
- "*I liked doing the lab and recording as a group. I gained better knowledge doing this as a group rather than by myself*"
- "*I liked working with other people in groups because we can communicate and collaborate to find a solution or reach a common goal*"
- "*It made the group discuss and think deeply about the topic*"

Feedback from teachers

The practical activities were received very positively by the teachers involved in the trials. Comments included:

- "*The students genuinely were motivated by the science*"
- "*The level of the thinking, the need to design, the demands to adjust and then finally pulling together all of their data and an assessment of how well they had done in solving the problem was good to observe*"
- "*They seemed to really enjoy it. They like 'meaty' challenges*"
- "*We have enjoyed carrying some of them out, and they have definitely made us think more about providing the students with more open-ended tasks to develop their independent study skills and their problem-solving skills*"

In all cases, all abilities of student were able to actively engage with the learning. Where individual students were observed to be struggling, the groups were seen to be very good at working collaboratively to help each other out. Only if, following discussions within the groups, the groups were clearly still struggling was it necessary for the teacher to intervene and encourage the students to use one of the previously mentioned techniques to move beyond their '*stuck*' phase.

In the majority of cases the practical activities required equipment and resources which were either readily available to the teacher or could be prepared with minimal time allocation of the technician. Where equipment or chemicals were loaned to the school, the equipment could be purchased cheaply for future studies, *e.g.* thin layer chromatography plates, sodium chlorate(I).

Reflection

Experimental planning

When presented with the problem, it was not uncommon for groups to be ready to start practical work within a matter of minutes. However, it was only when the teacher intervened that the students would begin to realise that they were missing some vital elements in their plan. For example, in Problem 6: Acid erosion, the students are required to carry out a titration to determine the concentration of acid in an everyday drink. The students very quickly used their pre-lab answers to work out that as the drinks all contained weak acids they would need to titrate an aliquot of the drink against a strong base with phenolphthalein as indicator. However, no thought was given as to what concentration of base was required or how this was to be decided. The students simply expected that only one would be provided and that would be the one to use. Similarly, in Problem 5: Coursework conundrum, the students are asked to purify a sample of benzoic acid contaminated with benzyl alcohol and anti-bumping granules. From the pre-lab questions, the students all quickly realised that they needed to do a recrystallisation but they had not thought about which solvent to use. Only once the teacher intervened and asked them this question did they begin to think more deeply about the recrystallisation process and how a suitable solvent is chosen. In Problem 3: Cleaning solutions, the students determine the concentration of sodium chlorate(I) in different bleaches by oxidising hydrogen peroxide and measuring the volume of oxygen produced. In this problem, the real question is one of determining a suitable scale for the reaction (based on the volume of the equipment available for measuring the gas produced), and understanding the concept of one reagent being in excess, meaning that the accurate measurement of its volume is not required. Many students found this a challenge. Indeed, understanding when things needed to be done accurately and when a more approximate method could be used was generally found to be hard. To understand this, the students need a deep understanding of what they are doing and why.

Effectiveness of the pre-lab questions

The students' response to the pre-lab questions was positive. One student commented "*I enjoyed how we had to do some research prior to the experiment because it gave me the overview of the lab*." Similarly the pre-lab questions served their purpose of guiding the students thought processes well with all groups deciding to solve the problem using the proposed method with minimum guidance. The students needed repeated prompting however to refer back to the pre-lab questions and use the information they had found out. Making the connection between what they saw as a homework exercise and learning in a lesson was clearly something unfamiliar. Where students had not completed the pre-lab questions, either as a result of absence when they were set or failure to complete the homework, these students were clearly at a disadvantage and were forced to rely on their group for guidance. As one student commented, "*I wish I had done them now*." It is to be hoped that, through this experience, this student will begin to see the importance of out-of-class work and take more responsibility for his own learning.

Conclusion

The trial of the problems has been successful in its initial phase. The problems have met the aims with which they were designed and have been shown to develop both the students' practical skills and their independent study skills. Compared to typical laboratory instruction, the students found the problem-based practical activities more interesting and better for making them think. Over 80% of the students indicated that the problem-based activities were '*good*' or '*very good*' for the '*application of practical techniques*' (*cf.* 69% for a typical practical activity). Furthermore, the problem-based practical activities scored favourably compared to a typical practical activity for developing the students' team-working skills, communication skills, independent study skills, scientific writing and research skills. Although the problems were challenging, all abilities of students were seen to be able to successfully participate, with the group work aspect of the problem solving helping to support all students' learning.

In his account of the transition from expository-style practical work to problem-based practicals, McGarvey (2004) concludes that the "*elimination of expository laboratory experiments from the undergraduate chemistry laboratory is not necessarily desirable, since such experiments fulfil different purposes*." The author agrees whole-heartedly with this conclusion and sees expository and problem-based laboratory instruction running side by side throughout a secondary level chemistry course. McGarvey comments that expository-style laboratory instruction is only a concern if the student adopts a passive approach to the activity. By running the problem-based practical activities alongside expository laboratory activities, the student is frequently being reminded of the things a scientist must think about when planning an experiment. Therefore the student will approach an expository style laboratory activity with a more active and critical mind, and thus the learning from both types of laboratory instruction will increase.

The Rocard report on Science Education in Europe (Rocard, 2007) highlighted the need for a change in science teaching models in order to reverse the declining interest of young generations in science studies. It is hoped that, through using the resources created for this study, teachers will become aware of the benefits of a problem-based approach to teaching and learning and implement such an approach regularly in their classroom environment.

To date, each problem has only been trialled by an individual class so it is not possible to measure any development in the students' overall skills. Future work will focus on incorporating the collection of practical activities into a Scheme of Work for an A-level class and evaluating the long term impact on the student learning.

Appendix 1 – Problem 3: Cleaning solutions

Problem 3: Cleaning solutions

Pre-Lab questions

(Remember to give full references for any information beyond A-level that you find out)

1. For each of the species below, indicate the oxidation state of the chlorine atom;

a) Cl^- d) ClO_2^- h) ClO_4^-

b) Cl_2 e) ClO_2

c) ClO^- f) ClO_3^-

2. The active ingredient in household bleach is sodium chlorate(I), NaOCl, which is sometimes also known as sodium hypochlorite. This is formed when chlorine reacts with cold, dilute sodium hydroxide.

a) Write an equation for the reaction which occurs (HINT: NaOCl is not the only product).

b) This reaction is an example of a disproportionation reaction. Explain why.

3. Sodium chlorate is such a strong oxidising agent that it will oxidise hydrogen peroxide. In this process the chlorate(I) anion, ClO^- is reduced to a chloride anion and the hydrogen peroxide is oxidised to oxygen gas. The sodium ion is a spectator ion in the reaction.

a) Write two half equations for the reduction and oxidation processes respectively and combine to give a full redox equation for the reaction occurring.

b) A student reacts 20.0 cm^3 of bleach with an excess of hydrogen peroxide and measures the volume of oxygen produced. According to the label, the bleach contains 5% by volume of NaOCl (molar mass 74.5 g mol^{-1}).

i. What volume of NaOCl is present in the 20.0 cm^3 solution of bleach?

ii. If NaOCl has a density of 1.27 g cm^{-3}, what is the mass of sodium chlorate used in the reaction? How many moles of sodium chlorate(I) is this?

iii. The student reacts the bleach solution with an excess of H_2O_2. What is the minimum volume of a 1.67 mol dm^{-3} (often labelled *20 vol*) solution of hydrogen peroxide that the student must have used?

iv. Assuming the sodium chlorate is the limiting reactant and the reaction is run at room temperature and pressure, what volume of oxygen gas will be produced?

Problem 3: Cleaning Solutions

Introduction

Billion Dollar $
Ad Agency, London

Dear team,

We are delighted to announce our recent success in securing the contract to advertise the brand new bleach, Best Bleach, designed by The Chemical Cleaning Company. Our job now is to come up with the most amazing advertising campaign to showcase its phenomenal bleaching ability.

In order to create the finest ad campaign for Best Bleach, we need to compare the concentration of the active bleaching agent in Best Bleach with that of the current brand leaders, Domestos and Milton solution. In order to satisfy the Advertising Standards Agency we need to know the **concentrations of sodium chlorate(I) in each of the bleaches given in g dm^{-3}** to the nearest whole gram. However, in these increasingly tight economic times we feel that the **cost per gram** of sodium chlorate(I) present in each bleach will provide an easy, direct and more understandable comparison for housewives across the country. At the time of writing, the costs of the Bleaches are as shown;

Domestos Original Bleach £1.12 for 750 mL

Milton Sterilising Fluid £2.39 for 1000 mL

Best Bleach 99p for 1 L

There is a tight deadline for the ad campaign. We need this data fast but it must also be accurate and able to stand up to the considerable scrutiny of the Advertising Standards Agency. A full report detailing all experimental procedures with accurate and valid experiment results is essential. You can assume that the concentration of sodium chlorate(I) in each bleach is not more than 5% by volume.

We look forward to receiving the results of your work.

Many thanks,

Acknowledgements

The author would like to thank the National HE STEM programme for funding and the Royal Society of Chemistry and the University of Leicester for her appointment as an RSC School Teacher Fellow during the academic year 2011–2012. The author would especially like to thank the teachers and classes for volunteering to trial the problems and for their excellent feedback. The author would also like to thank the College of School Teacher Fellows past and present for their support and useful discussions relating to this topic, Dr Dylan Williams for the introduction to problem-based learning and Dr Maarten Tas for help with the preparation of the student questionnaire.

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