Perspective

The role of laboratory work in university chemistry

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Abstract The place of experimental work in laboratories has always assumed a high profile at all levels of chemical education. This paper seeks to review the main strands of evidence available today and argues that the place of experimental work needs to be reconsidered at higher education levels. There is a need for a clarification of aims and objectives, and these need to be communicated to learners. It argues that higher education needs to be acutely aware of what goes on at school and to build on these skills. Pre-laboratory exercises are strongly supported by the evidence, while there needs to be a radical re-thinking of the use of laboratory manuals, with assessment being explored afresh. In addition, seeing the laboratory experience in the context of what goes on before and after, as well as other learning, will enhance the learning potential of this time. Examples of some ways forward are presented. Overall, it is argued that much more could be gained by the students if the laboratory experience, using similar experiments, was radically re-thought. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 172-185]
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Introduction

Laboratory work is an established part of courses in chemistry in higher education. The original reasons for its development lay in the need to produce skilled technicians for industry and highly competent workers for research laboratories (Morrell, 1969, 1972). Today, the aims may be different, in that many chemistry first degree graduates are not employed as bench chemists in industry (Duckett et al., 1999; Statistics of Chemistry Education, 2006), and the needs of research have inevitably become much more specialized as chemical knowledge has expanded.

This paper seeks to offer an overview of the current situation in higher education, and explores what might be the aims for today. It also argues that laboratory work in higher education cannot be seen in isolation. For most students it follows school laboratory experiences which are rapidly changing, and has to relate to material taught in lectures and tutorials. However, of greater importance is the need to see the 'hands-on' laboratory time as part of a wider process of learning. In this, there is a need to prepare students for their time in the laboratory as well as develop follow-up activities. Together, these may enrich and enhance the whole laboratory experience, and enable it to contribute more effectively to the overall learning of students in chemistry.

Historical perspective of laboratory work

The first teaching laboratory in chemistry in Britain was established by Thomas Thomson in the University of Edinburgh in 1807. In 1819, he introduced this to the University of Glasgow, when he joined this University. In 1824, Liebig established a Chemistry Laboratory at the University of Giessen. This was a most exciting period of the nineteenth century. Liebig's was the first institutional laboratory in which students were deliberately trained for membership of a highly effective research school by means of systematic research experiments (Morrell, 1969, 1972).

Laboratory classes then gradually developed over the next fifty years until eventually, in 1899, it came to be considered necessary that school pupils be allowed to carry out experiments for themselves. By this time, however, most schools in England had already adopted this way and regarded practical work as an essential requirement for science teaching in England (Gee and Clackson, 1992). Thus, practical training in chemistry sprang up in universities all over the Europe and North America. These were devoted to the teaching of skills directly used in industries and research (Letton, 1987; Johnstone and Letton, 1989; Khan, 1996). Practical work at this time played a vital role in *confirming* the theory which was already taught in the classroom. However, some doubts also arose about the efficiency of teaching through practical work in chemistry.

This work in higher education had its impact on school teaching in the sciences. Here, a century ago Armstrong advocated the direct experimentation by the pupils rather than demonstration experiments performed by the teacher. However, too much time was wasted on repetitive individual practical work (Hodson, 1990). Therefore, attention switched back once again to teacher demonstration. In 1932, the Education Board in England supported the same idea (pamphlet no. 89). This declared that there was "*too much practical work of the wrong kind ...., too much remote from the natural interests and everyday experience of the children*" (cited in Hodson, 1993). In 1935, Schlensenger studied the contribution of laboratory work to general education. He noticed that students who had previously exhibited "*real interest in chemistry developed the habit of doing their experiments mechanically to get the result expected rather than to observe what is actually going on in their test tubes*" (Letton, 1987). Little seems to have changed since then.

Towards the end of the twentieth century, more sophisticated alternatives had been introduced to facilitate effective learning in university laboratories. These included pre-laboratory experiences, films, video experiments, computer based pre-laboratories, post laboratory exercises and computer simulations [see Carnduff and Reid (2003) for a review].

Bennett and O'Neale (1998) proposed guidelines for the design of laboratory courses in chemistry in higher education in terms of the "*logical sequence*" of ideas, "*opportunity for real investigations very early in the course*" and "*pre- and post-laboratory sessions which actively engage the students*". These principles reflect the ideas of Denis Diderot, the French philosopher, who outlined three principal means of acquiring knowledge available to us: observation of nature; reflection; experimentation. Observation collects facts; reflection combines them; experimentation verifies the results of that combination (cited in Lester, 1966). All of these illustrate the need to decide what the aims are for using laboratory work in the teaching of chemistry in higher education.

Why have laboratories?

Laboratories are one of the characteristic features of education in the sciences at all levels. It would be rare to find any science course in any institution of education without a substantial component of laboratory activity. However, very little justification is normally given for their presence today. It is assumed to be necessary and important. It is taken for granted that experimental work is a fundamental part of any science course and this is especially true for chemistry courses. Very frequently it is asserted that chemistry is a practical subject and this is assumed, somewhat naively, to offer adequate justification for the presence of laboratory work. Thus, the development of experimental skills among the students is often a suggested justification. Nonetheless, this argument needs to be questioned to justify the position or role of the laboratory in the field of chemistry education.

One of the main reasons to question the place of laboratory teaching is that laboratory programmes are very expensive in terms of facilities and materials, but also, more importantly, in terms of staff time (Carnduff and Reid, 2003). University students' reactions to practical work are often negative and this may reflect a student perception that there is a lack of any clear purpose for the experiments: they go through the experiment without adequate stimulation (see for example, Johnstone and Letton, 1988 and 1990).

It is important to think about goals, aims and objectives in the context of laboratory work. Laboratory work here is used to describe the practical activities which students undertake using chemicals and equipment in a chemistry laboratory. Of course, the word 'practical' can include other activities as well, and it is interesting to note the use of the word in so many titles in papers. However, this paper is discussing *experimental activities* conducted in the laboratory by students although other practical activities may have their place and be important.

Many years ago in a schools context, Rose and Seyse (1974) raised a fascinating question: could many important aims still be attained even if practical work were abolished? They suggested that this depends partly on our view of science. Science can be seen as established human knowledge, a problem solving activity, or concerned with the relation between theory and experiments. A similar question may be posed for higher education chemistry: what would be lost if laboratory work vanished from higher education courses? It is likely that students would still pass the examinations based on lecture courses with little or no change. However, would the students have any 'feel' for chemistry, for chemicals, for instrumentation, or for the way experimentation is conducted or reported? In some ways, this starts to define what could be the important aims which can be uniquely achieved through laboratory courses.

Hawkes (2004) has challenged the place of the laboratory in many higher education chemistry courses. He argued that the evidence does not support the idea that the laboratory assists in achieving many of the aims for chemistry courses. He noted that, "*The enormous expenditure of time and treasure and student dislike of laboratory teaching demands substantial evidence that it has value commensurate with its cost and with the loss of subject matters that must be omitted to make time for it.*" Given that today many students taking chemistry courses do not intend to become bench practitioners in any sense, his argument has some substance. However, the absence of the laboratory experience may leave students with perceptions of chemistry that are very abstract and theoretical. Since it is not possible to know which students will become bench practitioners, it is important not to reject the important place of the laboratory. However, Hawkes's basic argument does challenge the over-emphasis on practical skills and suggests that it is important to think through the aims of laboratory work so that some of the wider scientific skills may find an appropriate place. Specific laboratory skills may be rarely used even by bench practitioner chemists in their careers but the place and nature of experimentation will be a very important understanding to be gained.

Wills (1974) quoted results of a survey of students' opinions on the teaching of practical biochemistry as part of a medical course. He observed that half of the students showed little enthusiasm for laboratory work. Its perceived relevance was low, while students noted that theoretical understanding is gained relatively slowly through practical work, providing a poor reward in knowledge gained for their future medical career. Although these comments were written long ago and in a different context, many still apply in chemistry where students do not always see the point of what they are doing (Shah, 2004). Of course it is not always easy for students to see the importance of certain activities until later on in their studies but a perceived lack of relevance at any stage will not help learning, and this has to be addressed.

In thinking of laboratory work, there are some inevitable tensions. Students are not always best placed to see the relevance and importance of all the elements of their course. On the other hand, there is a tendency for specialists to think in terms of presenting their subject rather than of meeting the students' needs. Here again, the need for clearly formulated objectives, communicated effectively to students, is seen to be important.

Aims and objectives

Several writers and researchers have discussed the rationale for laboratory work in Higher Education and have presented their aims and objectives for specific science courses as well as for laboratory instruction. Some of these are discussed below.

It does seem important that, for practical work to be effective, the goals, aims and objectives should be well defined. Thus, Boud et al. (1986) stressed that, when planning a course it is important to state clearly the course aims, goals and objectives: what to be taught, who is it to be taught to, by what means, and most importantly, what are the intended outputs? The issue is to find some agreement about what these aims and objectives might be. Such a question has been under investigation for decades, especially in the UK where much money and time has been spent on laboratory work in schools as well as in universities (Woolnough, 1994). Quite apart from the setting up costs for building laboratories and the costs for running them in terms of heating, resources and technicians, the labour costs for 3 hours of laboratory teaching may well be around 15 times the costs for a one hour lecture for 100 students. Is the learning gain 15 times greater?

Much of the research effort has looked at the place and nature of laboratory instruction at school level. It is important to note the outcomes from such work in that the university classes are drawn from those who have experienced laboratories at school before they arrive at university. At the school level, there have been many lists of aims and objectives offered in the literature (eg. Shymansky and Penick, 1975; Johnstone and Wood, 1977; Black and Ogborn, 1979; Johnstone and Al-Shuaili, 2001). They all tend to refer to skills and techniques as well as skills related to the conduct of experiments in a scientific way. Some have emphasized affective aims strongly (e.g. Kerber, 1988; Johnstone and Al-Shuaili, 2001) while others have emphasized other aims (e.g. Pickering, 1987, argued that laboratories might illustrate scientific method, might build confidence and might improve understanding).

Thinking of university chemistry laboratories, Kirschner and Meester (1988) suggested the following student-centred objectives for practical work:

1. To formulate hypotheses
2. To solve problems
3. To use knowledge and skills in unfamiliar situations
4. To design simple experiments to test hypotheses
5. To use laboratory skills in performing experiments
6. To interpret experimental data
7. To describe clearly the experiment
8. To remember the critical idea of an experiment over a significantly long period of time.

Their list is interesting in that traditional university laboratories often do not give opportunities for the development of some of these skills. Thus, for example, formulating hypotheses and designing experiments to test them is largely out of the range of most undergraduate laboratory experiences, although such an approach might well be possible (Johnstone et al, 1994). Very often, solving problems is seen as an algorithmic process in which students put experimental data into a formula, or solve some problem by applying a routine procedure (see Reid and Yang, 2002, for a discussion of problem solving in chemistry). Experimental problem solving is very different from the algorithmic exercises that may be part of the calculations in some chemistry laboratory work in university classes, especially in physical chemistry.

The eighth aim on their list is fascinating in that it suggests that there are critical ideas in experiments or, indeed, that there are critical experiments in the sense that the outcomes offer precise insights relating to a specified hypothesis. This is the fundamental nature of the place of experimentation in all science-based research. There is little research on how this might be achieved, other than suggesting that giving students many experiences may assist in developing the right ways of thinking and developing experimental ideas. Reid and Serumola (2006a, 2006b) considered this with younger school pupils, and found little evidence that much could be achieved. Later work showed the same with school pupils at the final stages of their education, but the latest observations showed that recently graduated science students (50 students drawn approximately equally from the biology, chemistry and physics) could handle this way of thinking very clearly (Alsamawat, 2007). Clearly, there has been a change. Was it the actual degree in the science discipline? Was it the laboratory work experiences? Was it simply that the graduates were, on average, about 4-5 years older than senior school pupils? (is it simply developmental or experience of life?)

Carnduff and Reid (2003) outlined the need of the laboratory work in chemistry in higher education in terms of three broad areas:

1. *Practical skills* (including safety, hazards, risk assessment, procedures, instruments, observation of methods);
2. *Transferable skills* (including team working, organisation, time management, communication, presentation, information retrieval, data processing, numeracy, designing strategies, problem solving); and
3. *Intellectual stimulation*: connections with the ‘real world’, raising enthusiasm for chemistry.

This still highlights the practical skills element but sees it in terms of more generic skills rather than the specific ones such as handling a burette appropriately or purifying a reaction product. They (Carnduff and Reid, 2003) offer a long list of transferable skills that go well beyond the confines of chemistry (assuming that when developed in one context, they do indeed transfer). The making chemistry real is also stressed, and the absence of a laboratory course would make this very difficult to attain. In their summary, some aspects of scientific thinking emerge as well. Thus, most of these aims will be, and perhaps can only be, achieved in laboratories or in laboratory related activities.

Carnduff and Reid (2003) went on to provide a set of possible reasons for the inclusion of practical work in undergraduate courses in chemistry:

- Illustrating key concepts
- Seeing things for ‘real’
- Introducing equipment
- Training in specific practical skills and safety
- Teaching experimental design
- Developing observational skills
- Developing deduction and interpretation skills

- Developing team working skills
- Showing how theory arises from experimentation
- Reporting, presenting, data analysis and discussion
- Developing time management skills
- Enhancing motivation and building confidence
- Developing problem solving skills.

There are some very important aspects here. For example, ‘teaching experimental design’ may be incredibly important, but it will not easily be achieved in the kind of set experiments which are often seen in university laboratory manuals. Similarly, ‘showing how theory arises from experimentation’ stands in strong contradiction to the idea of confirming theory which was seen so strongly in the 19th century and which still persists today. The development of powers of observation, measurement, prediction, interpretation, designing of experiments are dependent on laboratory work. However, laboratories at undergraduate level (perhaps also at other levels) do not seem play their role very well to gain these goals and objectives (Carnduff and Reid, 2003).

Overall, these are some of the tasks or objectives which more or less demand the presence of laboratory work in chemistry courses. Of course, laboratory experiences do not guarantee that such tasks and objectives can be achieved in the present situation. There may be a major need to change or improve the present situation to create more opportunity for the students to fulfill these objectives.

The lack of a clear sense of purpose in the design of laboratory courses is another factor which emphasises the need for review and change. From a study of first-year chemistry manuals in UK universities, Meester and Maskill (1993, 1995a) reported that the aims of the course were stated in only half of the manuals while in only one manual of the 49 surveyed were the learning objectives for each experiment clearly stated.. It might be more reasonable to conclude, however, that the main problem is the plurality of purposes.

Meester and Maskill (1995b) reviewed briefly, but usefully, the range of developments in these areas, before noting that little had been achieved in practice among the range of courses sampled. They suggested that:

> “*The reason little has changed in practical classes is probably that university teachers concentrate on the experiments to be performed by students and on the time available, rather than on the educationally best way to achieve their teaching aims .., although all the evidence that they need to improve practical teaching is easily available.*”

This is quite an amazing statement. It pinpoints the root of the problem: too much emphasis on the *experiments to be performed* and not enough emphasis on what the *students should be gaining.* It asserts that ‘all the evidence to improve practical teaching is easily available’. Perhaps the word ‘all’ is somewhat optimistic but, certainly, there is a wealth of evidence available that would enable university laboratory experiences to become much more effective in benefiting students.

This leads on to the question about the students’ perceptions about the purposes of the practical work and how they match the perceptions of the experts. Little work has been carried out on this comparison. However, Kirschner et al. (1993) compared the students’ perceptions with those of experts’ using a list of possible objectives. An interesting result was that the objectives set by ‘experts’ were not those that the students expected to happen and did not match what they actually found. The reasons were that students were not well prepared to perceive the purposes of the practical work and also the students have limited or no experience of this type of exercise. The authors pointed out that the value of laboratory work must be severely limited by the students’ unpreparedness, a conclusion, which would apply to many practical exercises. In a recent study, Shah (2004) found, with a total sample of 708 drawn from two countries in various stages of a first degree and after completing the degree, that enjoyment and illustrating theory were the most frequently selected aims chosen by students. The former is encouraging, while the latter, if it means that the experimental merely illustrated what was being taught in the lecture course, is a matter of concern.

The conventional way of preparing students would be to encourage them to read their laboratory course manual, but these typically overload them with information to be held at the same time. Equally, if there is an incessant barrage of information, the students get completely lost in the argument and sequence of ideas. The manuals need to be re-written with simplicity in mind if it is desired that students do not use them as 'cookbooks' (Johnstone and Letton, 1990). Experienced university lecturers know that only a minority of students do read the manuals before entering the laboratory unless specific tasks are allocated to them! Indeed, the question of information overload turns out to be rather important, and will be discussed later when considering the place of pre-laboratory experiences.

Some conclusions

In this quick overview of laboratory work in university chemistry courses, a number of issues have become clear. Firstly, there seems much agreement that laboratory work has a rightful place in undergraduate courses. Secondly, there is much evidence which indicates that all is not well: an expensive learning experience is not bringing the benefits which justify the outlay. Thirdly, there is lack of clarity about the aims for laboratory work, and students' perceptions and experiences do not match aims.

Drawing things together, it is possible to present the aims for laboratory work under four headings, although there is some overlap:

Skills relating to learning chemistry. There is opportunity to make chemistry real, to illustrate ideas and concepts, to expose theoretical ideas to empirical testing, to teach new chemistry.
Practical skills. There is opportunity to handle equipment and chemicals, to learn safety procedures, to master specific techniques, to measure accurately, to observe carefully.
Scientific skills. There is opportunity to learn the skills of observation and the skills of deduction and interpretation. There is the opportunity to appreciate the place of the empirical as a source of evidence in enquiry and to learn how to devise experiments which offer genuine insights into chemical phenomena.
General skills. There are numerous useful skills to be gained: team working, reporting, presenting and discussing, time management, developing ways to solve problems.

Two things are important. The students do not come, in general, with no experience of laboratory work. Although school laboratory teaching is heavily circumscribed by examination requirements, in some courses there are open-ended projects (e.g. the Scottish Certificate of Sixth Year Studies, 1969, which then later changed to Advanced Higher Grade Chemistry in 1999). The planners of first year university courses need to know what is being done in schools and how it is being done so that the first year laboratories can build on this. Secondly, there needs to be progression so that, over a degree, there is a build up in all the four areas of skills listed above.

The important issue is that the university teacher needs to decide which skills are to be developed in a particular laboratory course, to set these out in clear, unambiguous terms for the students, and to ensure that the whole design of the laboratory experience is consistent with the specified skills. With this in mind, the next stage is to explore what evidence there is to enable such aims to be achieved.

Issues for today

It is possible to compare what happened over 40 years in typical Scottish universities (Table 1). The figures are approximate in that there are minor variations from year to year. However, the general pattern is likely to have been similar in most university chemistry departments, and it illustrates that there has been a considerable reduction in time allocated to laboratory learning.

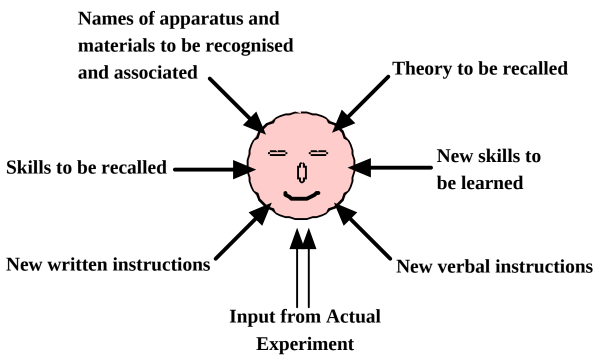
Table 1. Time spent in chemistry laboratories.

	1960s	2000s	Proportion Left
Level 1	5 hours for 22 weeks	3 hours for 16 weeks	44%
Level 2	12 hours for 22 weeks	6 hours for 16 weeks	36%
Level 3	12 hours for 22 weeks	12 hours for 16 weeks	73%
Level 4	Every waking moment!	Large amount	Unquantifiable

The time reduction may have arisen for many reasons: costs associated with staffing; reduction in student time available because of jobs; general student resistance to the vast time spent on laboratories when compared to other (mainly non-science) courses. However, given the reduction in time, it is *imperative that what time is left is spent extremely effectively and efficiently*. There have been several useful contributions in seeking to achieve this (e.g. Johnstone et al, 1994; Hunter et al, 2000).

There are several problem areas that need to be addressed. In order to make laboratories manageable, laboratory manual development is quite sophisticated, giving, typically, 'recipes books' (Carnduff and Reid, 2003). This has led to too much emphasis on 'product' and not enough on the processes of thought. Frequently, there is excessive repetition of relatively unimportant skills (Meester and Maskill, 1995a 1995b). However, of even greater importance, typical laboratories involve vast information overload for students and, therefore, actual learning (in terms of understanding) is minimal (see, for example, Johnstone and Wham, 1982). In this early work, they observed some quite bizarre student behaviour (such as endless repetition of familiar tasks to avoid the new ones) as students struggled to cope with the bombardment of information coming at them in a typical laboratory (see Figure 1).

Figure 1. Sources of information for students in undergraduate laboratories (derived from Johnstone and Wham, 1982).



Pre-laboratory instruction

Pre-laboratory exercises were introduced as a means to reduce the information overload on students. It was found that these can have a major effect (Johnstone et al., 1994; Johnstone et al., 1998). They can allow laboratory manuals to be reduced in length. They can encourage the laboratory planning process to focus on what is really important and to ensure that the students share these perceptions. Of greatest importance, they can allow understanding to increase simply by reducing information overload. Many examples exist and most are paper-based (see Carnduff and Reid, 2003) but the use of computer based pre-laboratory exercises is not uncommon (e.g. Nicholls, 1999; McKelvy, 2000; Tomlinson et al., 2000).

Humans all learn in fundamentally the same way. New knowledge and experiences have to be processed in a part of the brain known as the working memory. As this is limited and cannot be expanded, it has to be used efficiently. The working memory is where a person holds information temporarily. However, it is also the place where many important processes take place: thinking and reflecting; understanding and applying; analysing and synthesising; problem solving; being critical and even sceptical!

A pre-laboratory exercise is a short task or experience to be completed before the laboratory starts. It can take around 15-30 minutes to complete, depending on the experiment and on the background knowledge of the individual student. It may need to be submitted and checked before work begins. Its fundamental aim is to *prepare the mind for learning.* It can reduce the information load for the student, releasing mental capacity for thought. Sources of overload might include the laboratory manual, verbal instructions, equipment and materials, theoretical background, terms, symbols, representations, skills: what to do, how and when.

The pre-laboratory exercise can be used to do many things, although it is more or less impossible that it can do them all for any specific experiment. A pre-laboratory exercise may be able to:

1. Stimulate the student to think through the laboratory work, with a mind prepared for what will happen.
2. Encourage students to recall or find facts such as structures, equations, formulae, definitions, terminology, symbolisms, physical properties, safety hazards or disposal procedures.
3. Check that the experimental procedure has been read and understood and it can offer practice in data handling, drawings or calculations of the kind to be used in the write-up.
4. Lead the student into thinking about the procedure or the concepts and may encourage the student to connect and revise prior knowledge, thus providing some reassurance about the grasp of the topic.
5. Offer experiences in planning (the apparatus, the procedure, the quantities and the data presentation).
6. Bridge the (common) gap between laboratory and lecture, experiment and application.
   (Drawn from: Carnduff and Reid, 2003.)

Carnduff surveyed the university chemistry scene in the UK and beyond, and found many examples of pre-laboratory work (Carnduff and Reid, 2003). However, the most comprehensive system found was that developed and described by McKelvy (2000) in the US. This did depend on high levels of facilities and organisation, which are not so common in many parts of the world. Nonetheless, it reveals a well thought out and consistent pre-laboratory experience which shows what is possible.

Do prelabs work?

In a series of experiments, the effectiveness of pre-laboratory activities has been shown to be effective. In a study in undergraduate physics laboratories, pre-laboratories increased performance on traditional demonstrator marking by around 5%. However, in a test of understanding, the pre-laboratory exercises were found to increase performance by around 11%, while it was found that students were dramatically more positive about laboratories (Johnstone et al, 1998).

In an earlier study, in an undergraduate inorganic chemistry laboratory course, the power of pre-laboratories to improve understanding was demonstrated, but the authors also observed that pre-laboratories enabled mini-projects to be particularly effective; the power of the pre-laboratory to make more open-ended work accessible being shown very clearly (Johnstone et al., 1994). This is an important finding. More open-ended work is not so easy in university classes and this finding shows a possible way forward.

However, there are some warnings, as a later experiment in a physical chemistry laboratory course revealed (Shah, 2004). Attitude surveys suggested that students found the pre-labs too long, while the demonstrators were not pleased with the extra marking. However, interviews with some 60 students revealed that the students saw the purpose of the pre-laboratories very clearly and considered them valuable. This experiment revealed very clearly that all aspects of the laboratory experience must be seen as a whole. Simply adding on extra work was not acceptable. The interviews also showed that there was a 'black market' in pre-lab answers! A later implementation reduced the pre-lab exercise length, and this seemed more acceptable.

Developing the actual laboratory

The pre-lab exercise development serves a number of purposes. It reduces working memory overload, and prepares the students for what they are to experience in the laboratory. This enables the laboratory manual to be reduced in size. However, the actual laboratory experience may also need to be developed and changed. This is where the specification of clear aims can be helpful. For example, some laboratories can be developed that illustrate the chemistry being covered in lecture classes and make it real for the students. Thus, some synthetic organic chemistry may be covered, while in the inorganic area, the synthesis and study of the spectra of various metal complexes may be highly relevant. However, much can be enhanced with a little thought. The literature is full of papers describing all kinds of ingenious ways to make experimental work more interesting, relevant, safe, and yet exciting (e.g. feature articles, 'In the Laboratory', in issues of the Journal of Chemical Education).

Thus, instead of every student synthesising and purifying the same organic compound, students might work in groups of four to discuss how to synthesise a type of compound (eg. an azo dye) and then each goes on to make a different dye. They can then compare uv spectra and try to develop an understanding of why their spectra are similar but not identical. This might involve another group of four students with another set of azo dyes. A parallel approach can be used with complexes where groups can synthesise and purify similar complexes of the same ligands with different transition metals, comparing the spectra obtained and making deductions about structures and d-electron energy levels.

Analysis experiments can also easily be adapted. Thus, for example, phosphomolybdate analysis for the phosphate ions in water can be made much more real by allowing a group of, say, four students to develop the calibration curve *together* by undertaking two analyses of standard phosphate solutions each and then working together to analyse river water sampled from an industrial river at various points on its flow. The results can be related to the environment, using a simple map and involving the students in discussion. In such ways the traditional experiments involving analysis or synthesis can be adapted to achieve different aims. However, the assessment may have to be re-thought so that it does not distort the whole experience. Marking for right answers is not appropriate. Perhaps a group report might be an interesting way forward, with recommendations based on the accumulated evidence.

Post-lab tasks

This leads to an important aspect: what happens after the experimental work is completed in a laboratory? Very often the writing up of a report is seen by the students as pointless, particular when it is marked for the production of a 'correct' result. It is here that post-lab tasks can be invaluable, provided that they are designed to match the aims for the laboratory.

Some of the ideas above implicitly involve post-lab tasks. Much can be built around discussion, looking for patterns in results and seeking to relate data obtained to underlying understandings in chemistry. This may involve a report or it may involve reaching a group conclusion. It may involve an application of a finding in a new situation, ideally, related to life outside the laboratory. For example, in the phosphomolybdate experiment described above, the phosphate levels were found to be related to bus washing depots, with their extensive use of low temperature soaps and the wash-out into the local river. Assessment may simply require the completion of the task adequately rather than producing a graded mark.

Overall conclusions

With time at such a premium, it is vital that university chemistry laboratory experiences are used efficiently and effectively. The key is to have clear aims. While specific practical skills are relatively unimportant, there needs to be an opportunity to handle equipment and chemicals, to learn safety procedures, to master specific techniques, to measure accurately, to observe carefully. However, of greater importance is the importance of making chemistry real and exposing ideas to empirical testing. Skills of observation, deduction and interpretation are important as the place of the empirical as a source of evidence in enquiry is offered. In addition, there are many other important practical skills to be developed (e.g. team working, reporting, presenting and discussing, time management, developing ways to solve problems).

Many school courses seek to develop some of these outcomes and often offer considerably *more* freedom for students to think scientifically. University students are capable of building on these successful outcomes. Indeed, it is important that those directing university chemistry laboratories are aware of what is currently happening at school by means of curriculum documents and, even better, visiting typical schools to observe. In this way, it is possible to plan university chemistry laboratories so that they can avoid repeating school laboratory experiences but also *build on the kinds of thinking skills* which school courses seek to inculcate. This alone might improve student attitudes.

Translating such goals into a stimulating laboratory experience is the next stage. The laboratory course must be seen as a whole and the experimental experiences introduced to develop such outcomes. The pre-lab draws out prior experiences and ideas and sets the scene for the actual laboratory. The student now knows and understands more of the purpose and nature of the laboratory experience ahead. Laboratory manuals need to be shortened considerably and students encouraged to plan the actual experiment, and see why it is they are doing what they are doing. Greater open-endedness will be helpful and students are found to respond to this most positively. There needs to be more emphasis on the process of thought and enquiry and much less on getting a 'right' answer.

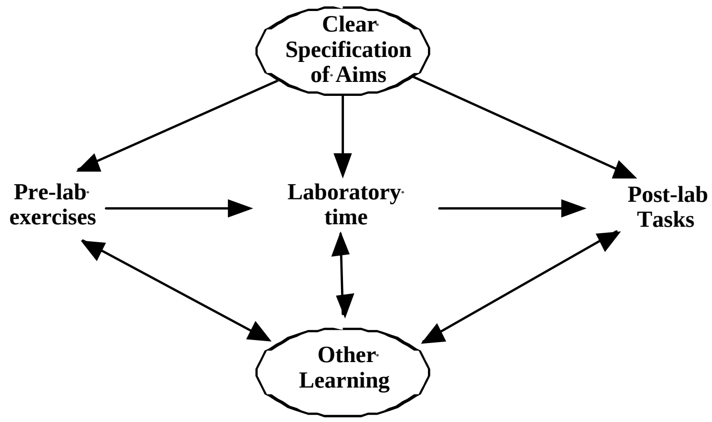
The post-laboratory experience also needs careful thought. In the work described by Johnstone et al (1998), imaginative post-laboratory exercises were used. These allowed students opportunities to apply the ideas they had learned, as well as offering some insights into their understanding. A range of ingenious post-laboratory exercises in physics were also developed by Skryabina (2000) and were considered very valuable when she conducted student interviews. A formal 'write-up', with answers marked for accuracy fails to offer the student a stimulating intellectual experience, especially when there is frequently a 'black market' in right answers.

Table 2 summarises what needs to be done in order use time more efficiently and effectively, the aim all the time being to encourage the maximum student learning. The laboratory experience must, therefore, be seen holistically (Figure 2).

Table 2. Summary of recommendations.

Stage	Activity	Tasks
Planning	Clear Aims	Make chemistry real Expose ideas to empirical testing Develop skills of observation, deduction and interpretation Develop general practical skills (eg team working)
	Background	Know what happens at school and why Don't underestimate school experiences
Before the Laboratory	Pre-labs	Share aims for experiments Establish background information Plan experiments
During the Laboratory	For the experimental	Keep manual brief Allow experimental freedom
After the Laboratories	Post-labs	Apply ideas learned in a 'real-world' setting For assessment, look at process not 'right' answers

Figure 2. The laboratory experience.



The aim in this paper has been to develop an acceptable set of aims under the general headings of:

Skills relating to learning. Making chemistry real, illustrating ideas, empirical testing ideas, teaching new ideas.
Practical skills. Handling equipment and chemicals safely, measuring and observing carefully.
Scientific skills. Learning skills of deduction and interpretation, seeing a science at work, devising experiments.
General skills. Team working, reporting, presenting and discussing, developing ways to solve problems.

These aims cannot be met easily (if at all) by lectures and tutorials. They are part of giving the student an appreciation of the way chemistry, as a science, works. Meeting many of the aims will offer skills and insights which will be useful in numerous employment opportunities. Above all, the aims offer possibilities where the student learner can be challenged to think, to argue, to weigh evidence, to explore chemical ideas.

The traditional laboratory experience in higher education can be enhanced by applying these aims and setting the laboratory learning in a context of pre-learning and post-learning.

The former enables the student to make more of the time in the laboratory while the latter allows the student to think through and apply ideas.

Examples have been offered of ways by which the traditional experiments can be re-thought so that different aims can be achieved. The aim is to move away from following a recipe, not matter how well written. The aim is to move towards laboratory experiences which stimulate and challenge, allowing students to see chemistry, as a science, at work.

The conclusion can be summed up thus: "*To change the experience, you don't need to change the experiment, just what you do with it*." (Cited in Carnduff and Reid, 2003.)

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