Skills Development and Practical Work in Chemistry

PERSPECTIVES

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"Chemistry is an experimental science and its development and application demand a high standard of experimental work."[1] This, and many similar statements, can be found littering chemical and education literature. It is difficult to argue against this general thesis when it comes to the pursuit and pursuance of chemistry. Dall'alba[2] extends the idea and asserts that an important factor in higher education *teaching* is to initiate students into what it is like to be a practitioner of their subject. However, nowadays only a minority of chemistry graduates make direct use of their chemical knowledge and skills in their work. This is detailed in a recent report[3], and it seems likely that many students in chemistry may have no intention of pursuing chemistry as a career. Unless this is the case in future, it is hard to see how the number of university chemistry departments can be sustained or justified. Under these circumstances we suggest that it is inappropriate to design a programme that is specifically and solely directed to the training of the professional chemist.

We do not wish to challenge the widespread assumption that laboratory work is an essential feature of a university course, but we do wish to raise explicitly the question 'What is laboratory work for?' In other words what are the objectives, what are the outcomes? It is no longer sufficient to suppose that the objective is just to train the professional scientist in laboratory skills. No-one expects all students of literature to become professional writers or poets; similarly we must not continue to operate on the assumption that all chemistry students will become professional scientists.

Another powerful reason for asking what laboratory work is for is that it is an expensive activity. Laboratories are costly to build and equip; academic and technical staffing, instruments and consumables are a drain on resources. Furthermore, restrictions imposed by safety legislation on the use and disposal of chemicals have probably had a major effect on practical work, particularly in the less well endowed institutions. In consequence, a Royal Society of Chemistry report[4] concludes that "the restrictions on resources and the time allocated to practical work are causing a decline in the extent of practical work and the standards achieved". With the decreasing resources available for teaching, we can only address any such decline in standards by ensuring that maximum benefit is obtained from laboratory work, and this means being quite clear about our objectives.

Skills

Those responsible for the design of undergraduate chemistry courses are understandably concerned to meet the criteria set by validation bodies who define minimum standards required for professional recognition. These bodies often specify a minimum number of hours to be spent in the laboratory. There is a danger that this leads to a (hidden) assumption that competence follows automatically from experience, without there being any need for an assessment of skills. This emphasis on time spent, rather than quality of experience, means that even when a course is considered from the narrow perspective of professional training, it can be argued that it does not address this aim effectively. The development of the ideas and approaches to science and scientific investigation is what really matters. It does not necessarily follow that an extensive experience in a well equipped laboratory will achieve this end.

The questions we need to ask are 'what skills should be developed in students, which of these skills are traditionally developed in the laboratory and can any of these be effectively developed outside the expensive laboratory environment?'. Probably no two people could agree precisely on a definition of these skills, but most lists would probably include:

- manipulation
- observation
- data collection
- processing and analysis of data
- interpretation of observations
- problem solving
- team work
- experiment design
- communication and presentation
- laboratory know-how

With respect to this list, we suggest that there are two key limitations to laboratory work as currently practised in most degree courses. First there is the lack of active participation in experiment design. How often does the material supplied to students read like a recipe and how often is treated like a recipe by the student? The result is that most teachers of chemistry have been faced in the laboratory with such questions as 'Is this right?' while a student proffers a white powder. The reaction to the enquiry 'What is it?' is often 'Well it's, er, this' as the student points to the middle of a narrative purporting to represent part of a laboratory handbook. There are many tales of exchanges such as this; sadly they are often interpreted as the fault of the student failing to 'read ahead'. We should ask whether some of the responsibility lies with us, the course organisers. A parallel argument arises if a train is consistently late by twenty minutes each day; it might be that the timetable, rather than the train, that requires attention. So, perhaps there is something seriously awry with the design of practical work which often does not encourage students to develop an appreciation of the process by which our understanding of chemistry progresses.

The second limitation we suggest is that time available for developing manipulative skills is not always well used. In a recent analysis, based on work by Maskill and Meester[5], we have concluded that, on average, a first year student in a chemistry course of a typical English university performs over fifty titrations. Even though the contexts for each of these is different, it cannot be a valuable learning experience to carry out such an extensive repetition of this relatively simple manipulation.

For maximum effect, skills need to be progressively developed as the student moves through an undergraduate course. In many courses each laboratory experience may be valuable and worthy in its own right. However, the next session (or even the next semester) in the laboratory may not take into account the extent of skills developed in the earlier sessions. Indeed, even today, it is not usual to find laboratory programmes analysed, let alone designed, in a context of progressive skills development. To move in the direction of a skills driven programme is not only central to quality student progress, but will result in a more efficient use of the laboratory resource.

In the past, too little consideration has been given to where learning in the laboratory is effective and where it is weak. The advent of electronic media (and, in particular, the CD-Rom) has helped bring the development of skills to the fore, and encouraged a consideration of which practical skills can be developed (at least to some extent) outside the laboratory. As with all learning experiences, an evaluation of outcomes is a more useful parameter than the amount of time allocated.

Recipe laboratories

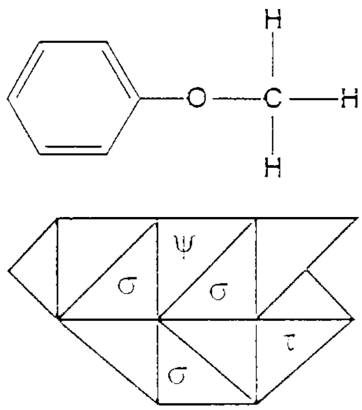
Students following a recipe are not ‘doing an experiment’, but ‘carrying out an exercise’. The problem is in the way that ‘recipes’ are used. Often the student reads through the notes line by line, mechanically carrying out the manipulations, with no real thought as to why certain actions are taken and how they fit into the overall outcome. ‘Recipe experiments’ can be criticised for making limited intellectual demands on the students, who often seem to go through the motions of laboratory activity with their minds in neutral. However, in the research laboratory, workers often use recipes[6]. The difference is that here the user of the recipe is the person who wrote it. The literature search, the ensuing discussions, the design of the experiment, the estimation of quantities, are all necessary inputs to the development of the recipe that the researcher takes into the laboratory. In most undergraduate work, these stages are missing. However, it is clear that the first year student does not have the experience to cope simultaneously with too many different aspects of practical at once, and so the process must be simplified somehow. The question is how best to do this. It may help to introduce the analogy of learning to drive a car. Imagine a driving instructor announcing to a pupil ‘today we will learn gear changing; you can overlook the need to steer, accelerate, brake, watch your mirrors, while we concentrate on gear changing’. We know that all the skills need to be developed together and gradually. The good instructor achieves this without leaving out anything crucial, and without losing the motivation of the learner.

So how is it that experienced drivers are able to drive safely and at the same time do other things like talk to passengers, admire the scenery, and listen to the radio? The answer lies in the concept of ‘working space’ expounded by Johnstone[7]. According to this principle it is only possible to process or work with a limited number of pieces of information (usually six to eight) at the same time. Experienced practitioners overcome this limitation by gathering all the steps in gear changing under one activity, a process known as ‘chunking’. In this way, changing gear is a single activity. Chemists use the same process in (for example) recognising methoxybenzene (Figure 1a). The chemist immediately recognises two components, the methoxy group and the phenyl group. To the uninitiated, the picture is of fourteen lines and five symbols (three of which are the same), too many separate items of information to take in. Figure 1b also comprises fourteen lines and five symbols. Try asking a chemist and a non-chemist to write down from memory both Figure 1a and 1b after a moment’s viewing!

Figure 1

1a

1b



Johnstone’s analysis has had significant impact on the learning of chemistry, but it is arguably in the laboratory these lessons need to be heeded most. The first year student enters the laboratory cold except for perhaps a short discourse on ‘safety rules’. The inputs of information are huge: location of chemicals and identification of the particular materials needed to begin the prescribed work, recognition of equipment and its handling, instrumentation, safety requirements etc. It should not be surprising that most students are unable to give much intellectual effort to the theory behind the laboratory activity or to experimental design. Indeed, the ability to plough through a ‘recipe experiment’ line by line could be regarded as a major achievement in such circumstances.

There are some simple things that can be done to reduce the ‘clutter’ and ease the student into unfamiliar surroundings. For example, provide each student with simple drawings or photographs of the equipment to be used. A plan of the laboratory with the location of all the chemicals and equipment would help avoid many of the ‘Where is it?’ questions that typically occupy much of a demonstrator’s time in the early part of a laboratory session. It is simply not fair to expect the new student to spot a Hirsch funnel at twenty paces! The layout and presentation of practical 'instructions' can, in many cases, be improved. The narrative 'recipe' presentation leads to a focus on the immediate manipulation and to a loss of the overall plan and logic of the experiment. We have found that an overall perspective is greatly helped by dividing the experiment into logical stages and presenting it to the student as a flow chart. The student works with the flow chart on the bench and a single sheet that summarises the instructions for a particular stage on the flow chart. This system has helped students to pinpoint exactly where they are in the experiment[8].

To work successfully in the laboratory, the student must master a range of manipulative skills and instrumental techniques. There is a temptation to introduce the student to a portfolio of techniques early in the course. Whilst there may be a logic in this approach, it has the dual disadvantage of delaying the introduction of the student to the excitement of investigative chemistry, and of risking that techniques developed early in the course have been forgotten when they are required later. A more satisfying approach might be to develop a small number of techniques that can be used in a simple investigation, then introducing more techniques to be used in another investigation and so on. The bonus for the student is that there is a feeling of being able to do real investigative work at an early stage rather than having a long apprenticeship in learning how to use the tools. Even so, students find the provision of video reminders of the techniques valuable[9].

Skills analysis

In an attempt to limit the demands on the student (and the poor learning experience that ensues if demands are unreasonable), we have collected and developed twenty-two laboratory activities which span a wide range of chemistry[10]. These tried and tested activities are intended to be representative and not comprehensive and are directed toward the early part of an undergraduate chemistry programme. Each activity has been analysed from the standpoint of skills, rather than of content, and the activities have been ordered according to demand for increasing skills (both in level and sophistication). This approach takes due regard of the entry behaviour of the student and acts as a focus for defined outcomes.

Our series of activities is not intended to prescribe a programme and it would be entirely appropriate to select individual activities and slot them into an existing course. However, the series illustrates the possibility of developing a programme that covers a range of chemistry and allows students to develop a coherent portfolio of laboratory skills. A different analysis of the required skills would necessitate a different programme. However, the main point is that by starting with desired outcomes, and selecting and developing activities that collectively achieve the desired outcomes, there is much less risk of omitting the development of important skills and of the unnecessary over-emphasis of others.

Each activity which has been included in our pack includes a Student Guide. These notes have been written in several styles, one of which is the 'flow chart style' outlined earlier. The Student Guide is accompanied by a Demonstrator Guide for the teacher. These notes include detailed safety information, specific comments on the processes and comments on the questions included in the Student Guide. There are also suggestions for pre-lab activities. The importance of pre-labs has been stressed[11]. Pre-lab is not simply telling students that they should read through the notes before the next session. Pre-labs should involve student's active participation, and can compensate for the features generally missing from the 'recipe' type activity (e.g. problem identification, solution strategy and experiment design). An often neglected area is the post-lab session which is always valuable and is essential for those activities that involve a team approach when individual members work on different aspects of a problem (see, for example, [12]).

Analysis of skills used in an activity is never simple. There is a hierarchy based on intellectual and on manipulative demands and within this specific skills require careful definition. The only effective way of defining a skill is by detailing exactly what the student is able to *do* once that skill has been acquired. An outcome that states 'be able to interpret an infrared spectrum' is too vague. (What kind of spectrum: gas or liquid (or mull), absorption or reflectance, what frequency range, group frequencies or normal modes etc?). To be useful, outcomes need to be written in terms of the behavioural objective. However, even a superficial attempt to analyse activities for skills can lead to useful indicators. Identification of over- and under-emphasis of particular skills and subsequent fine-tuning of the practical programme can result in an increased efficiency in the use of laboratory time. It is particularly worth considering which skills can be acquired (at least in part) outside the laboratory. Experiment design can be seen in this context[6] and it would not be unreasonable to suggest that all of the skills in the earlier list (with the exception of manipulation and laboratory know how) can be developed to some extent outside the laboratory. The continuing improvement of the quality of multimedia software makes this approach increasingly fruitful.

Our analysis of skills is based on one proposed by Kirchner and Meester[13]. Each activity has been allocated to one of the four general categories they proposed:

- the academic or formal laboratory which employs didactic methods to verify and illustrate laws and concepts;
- the experimental laboratory in which exercises are open-ended and relatively unstructured;
- the divergent laboratory which offers tasks with an initial, standard, structured component which may be developed in a number of different ways;
- the investigatory skills-teaching laboratory in which the procedures of investigation are the principal subjects of study.

(It is possible to change the category of some of the activities by using a different style of notes or by changing to the information supplied to the students.)

The skills analysis system has been distilled onto a single form (Figure 2). The major skills categories have been subdivided into their different facets. For example, team work can include problem identification and analysis (skills which could also be placed under problem solving). Team work skills also include identification of the personal skills required to solve a problem, selection of the team on the basis of the members strengths (and weaknesses), development of a strategy, assignment of roles to team members based on individual strengths, organisation of the team operation (time-scales, reporting, redirection etc), evaluation and optimisation of resources and development and communication of outcomes. Each of these categories can be further sub-analysed and so it is for all skill categories. We have tried to limit the analysis of each activity to a level that is quick and easy to carry out yet carries sufficient information to provide a useful

Figure 2: Skills analysis form

Activity type

formal (verify concepts)	experimental (rel unstructured)	divergent (variable dev from common start)	investigatory skills

Skills

	weighing	vol meas	handling			
manipulation						

	reflux/dist	recryst	chromatog	inert atm	spectros	titration
techniques						

	colour	volume	temp	press	phys state	
observation						

	qualitative	numerical	spectral	electronic		
data collection						

	calculation	computing	matching			
data processing						

	selection	validation	deduction	prediction		
interpretation						

	identificatn	in/output	breakdown	methods	assembly	
problem solving						

	skills ident	analysis	role assign	organisation	resources	outcomes
team work						

	input	output	precision	techniques	validity	
expt design						

	report	poster	oral	audience		
comm/presentn						

	COSHH	application	review	disposal		
safety						

The form as it stands apparently gives equal weighting to each box. Some boxes should have greater prominence than others and this can be incorporated by a simple system of requiring greater numbers of entries. With an electronic system, differential weighting can be easily incorporated.

input to the complete package of course skills. The analysis form is not unique and an amended version may be more useful for particular programmes.We have found that a quick and simple way of using the form is to reproduce it on a transparent sheet. By overlaying the completed sheets for the practical programme it is easy to see which categories may be being over-developed and which neglected.

Based on our experience, we propose the following set of guidelines for the design of laboratory courses in chemistry:

- review carefully and take into account the range of unfamiliar ideas and concepts faced by first year students starting laboratory work (many of which may be scarcely relevant to chemical understanding, but which can affect a student's ability to engage with the chemistry);
- design the laboratory course so that a range of skills is introduced in a logical sequence as a coherent package;
- introduce the opportunity for real investigations very early in the course;
- introduce pre and post laboratory sessions which actively engage the students.

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