Review

Learning in the laboratory; some thoughts from the literature [•]

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Introduction

Laboratory work and other forms of practical work have gained wide, but not universal acceptance as one of the most important and essential elements in the teaching and learning of science. For the purposes of this paper we concentrate on laboratory work, but many of the principles addressed apply equally to the range of practical work encountered in the sciences.

This paper provides a brief overview of the literature on laboratory work as a means of helping to answer three fundamental questions:

- What are the *purposes* of teaching in laboratories?
- What *strategies* are available for teaching in laboratories and how are they related to the purposes?
- How might we *assess* the outcomes of laboratory instruction?

Researchers at secondary school level have generated much of the literature, but their findings have importance and application at tertiary level also.

What is the purpose of laboratory work?

This could be answered superficially by saying that, “Chemistry is a practical subject and so we must do laboratory work”. If pressed further, we might say that the purpose of laboratory work is to teach hand skills and to illustrate theory. But is this the end of the story? If we are going to look at the variety of strategies available for laboratory work, we shall have to be clearer about the purposes of the laboratory to enable us to decide which of these strategies lend themselves best to the achievement of our purposes. Similarly, if we are to try to match the assessment to the outcomes, we will have to be clear about the outcomes we desire to see in our students.

Such ideas have been under discussion for decades, especially in places like Britain, where a great deal of time and money has been spent on using practical activities in science teaching.[1] The important aims and objectives of practical work have been considered from as far back as the early nineteenth century.[2]

Special attention to this has been given in the post World War II period by teachers and science education researchers. The need was recognised for a list of practical aims to help laboratory teachers to think clearly about their intentions and to ensure that all the important goals of the course had been pursued. There is also an awareness of the need for a list of aims or objectives on which to base the assessment of practical work.[3] If the desired outcomes are not clearly stated how could any kind of objective assessment be applied by teachers and understood by students?

Before examining the aims and objectives, which have been produced by researchers, the terms ‘aims’ and ‘objectives’ should be defined. In the literature on practical work the two terms are often used synonymously to give a general description of the intentions of the practical work. Sutton[4] defined aims as *general statements* of what the *teacher* intends to achieve, while objectives are *specific statements* of what the *students* should be able to accomplish as a result of being taught in the laboratory. We shall adopt this useful definition and examine the *aims* of practical work in some detail because they can be generalised. The *objectives* are largely specific to given experiments and are generally so numerous that we shall not consider them in any great detail.

Aims of practical work

Kerr[5] carried out an important study of practical work in 1961. Over a two-year period he conducted a survey of practical work in England and Wales asking teachers to give information about the nature, purposes, assessment, and views

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[•] This is a revised version of the review originally posted on the Web on September 17, 2001, modified by Professor A H Johnstone following receipt of the letter from Professor D. S. Domin, (see p. 90 of this issue).

about practical work they had encountered in schools. As a result of this he compiled a list of ten aims for practical work. These were:

- To encourage accurate observations and careful recording.
- To promote simple, commonsense, scientific methods of thought.
- To develop manipulative skills.
- To give training in problem solving
- To fit the requirements of practical exam requirements
- To elucidate theoretical work so as to aid comprehension.
- To verify facts and principles already taught.
- To be an integral part of the process of finding facts by investigating and arriving at principles.
- To arouse and maintain interest in the subject.
- To make phenomena more real through actual experience.

Numerous further attempts have been made to articulate the aims of practical work. Examples are to be found in the writings of, Swain,[6] Kempa and Ward,[7] Johnstone and Wood,[8] Boud,[9] Lynch and Ndyetabura,[10] Denny and Chennell,[11] Kirschner and Meester,[12] Boyer and Tiberghien,[13] Garnett and Hackling,[14] Gunstone[15] and Wellington.[16] They are in substantial agreement with Kerr.

Attempts to specify aims have been around from the early twentieth century[17] and these aims remain almost the same today. This might suggest that the science education community has reached a consensus, but it is more likely to have been a consensus of information gathered by researchers and supported by theorists. Much of the writing has been about the situation in secondary schools, but it can equally apply to tertiary level. Similar aims are proposed by other writers such as Meester and Maskill,[18] Bennett and O'Neale[19] and Laws,[20] addressing the tertiary situation. These can be summed up in the list of principal aims produced by Buckley and Kempa.[21]

Laboratory work should aim to encourage students to gain

- manipulative skills
- observational skills
- the ability to interpret experimental data
- the ability to plan experiments

To this must be added the affective aims mentioned by Kerr and others of those listed above.

- interest in the subject
- enjoyment of the subject
- a feeling of reality for the phenomena talked about in theory

Some of these aims need further consideration.

Manipulative skills

It is true that laboratories are the only place to learn hand skills, but many of the skills depend upon the particular piece of equipment available. Not all infrared machines are the same, each having its own peculiar 'flicks of the wrist' to make it operate well. Although the student has to learn the manual skills with the apparatus available, what is important is to know how to handle and interpret the spectra from *any* machine and this can be done without a laboratory! Manipulative skills have to be encountered often if they are to be well established. A large gap between learning to operate a particular balance and using it again requires almost total relearning. Problems with facility in manipulative skills can seriously get in the way of other desirable skills (Wham[22]). A student struggling to operate a piece of equipment may fail to make important observations and gather poor data. A classical information overload can occur under these circumstances. It is essential so to establish the manipulative skills that they can 'go on auto-pilot' and free the student's attention for other things such as observation and accurate recording [23].

Observational skills

Observation is a cognitive process and it becomes scientific when it has purpose and theoretical perspective. However, what is scientific observation? Young [24] made it clear that there is a difference between 'seeing' and 'observing' when he stated that learners 'see' many things, but they do not always 'observe' them. Do learners notice every observation that could be made? Kempa and Ward[7] reported that students failed to notice or record one in every three observations. They reported that 'observability' is a function of both the nature and intensity of a stimulus and the observer's perceptual characteristics. The observational stimulus must reach a certain level below which, observation will not be made (observation threshold). They pointed out that, as the intensity or magnitude of an observational stimulus is reduced, it becomes more difficult to detect. Moreover, when there are multi-stimuli, the 'detectability' of one stimulus can be seriously affected by the presence of another; the dominant stimulus obscuring, or masking completely, the less dominant ones. This psychological factor affects learners throughout their lives. It is not enough to tell students to observe; they have to be shown how. However, some of the greatest observations in science have been made by chance, such as the discovery of polyethylene, but the observers had to have prepared minds to see the possibilities behind their observations.

In practice, by using interactive demonstration techniques Al-Shuaili[25] showed that visual observational changes, which might go unnoticed in a normal laboratory, could be made to appear well above the detection threshold. Therefore, whilst demonstrating a particular task, the instructor can highlight the kind of things learners should be looking for in order to fulfil the task's aim of focusing on 'signals' and suppressing 'noise' (Johnstone[23]). Teachers also have to ensure that 'signals' offered to students should have enough observational magnitude and intensity as to be above the threshold. They should also be aware of the dominant observation in situations of multi-stimuli and manage them accordingly. The dominant stimulus may have to be played down if it is in danger of masking other important observations. This does not imply that the teacher should give all the answers before the laboratory, but rather prepare the observational faculties for what is to come.

There may well be occasions when demonstration, rather than individual laboratory work, may be the best procedure when there is a danger of vital observations being obscured by powerful, but less important stimuli. In a demonstration the teacher has control and can focus attention on the salient observations.

According to Hodson [26], observation would appear to be more than merely seeing, and seeing would appear to be more than simply receiving sense data. Raw sense data can be 'seen' almost unconsciously, without having any significance attached to them. However, when this 'seeing' is registered and interpreted in the light of previous knowledge and expectation, it becomes an observation. This emphasises the importance of having a prepared mind before setting out in a laboratory and clearly calls for some pre-laboratory experience.

The collection of observational data can only take place within a theoretical framework. What is important in science are the ideas one has about the data, rather than the data themselves. It would be a mistake not to consider the link between observation and understanding, because what is observed depends as much on what is in the mind of the observer as on what is there to be seen. In reality scientists often have to reject sense data on theoretical grounds: the Earth is not flat, a stick, partially immersed in water, is not bent, distant stars are not red. When theory and observation conflict, nothing in the logic of the situation necessarily demands that the theory should be rejected. Rejection of observational evidence is a crucial part of scientific research. Students who lack the requisite theoretical framework will not know where to look, or how to look, in order to make observations appropriate to the task in hand, or how to interpret what they see. Consequently, much of the activity will be unproductive**.**

Hodson [26] remarked, "Knowing what to observe, knowing how to observe it, observing it and describing the observations are all theory-dependent and therefore fallible and biased".

In laboratory work, a further complication to observation is that apparatus often masks a phenomenon. Frost [27] noted that "The size and the noise of the Van der Graaf generator often masks the significance of the spark being generated. The noise from the vacuum cleaner in a linear air track can distract from the significance of the movements of the air-borne pucks". People's memories of their school science often relate more to the dramatic equipment than to its significance for scientific ideas. Because of this, it is important to take some time to explain a piece of apparatus, with the intention of making it sufficiently familiar so that the class can forget it and focus attention on the phenomenon.

Observation is carried out to check on theories, not only to collect 'facts'. However, as indicated earlier, Hodson asserted that we can reject observations, just as we can reject theories. "We may reject a theory in the light of falsifying observations or we may modify those observations in order to retain a well-loved and otherwise useful theory. The view promoted in science courses, that a change in observational evidence always brings about a change in theory, implies a simple direct relationship between observation and theory which seriously underestimates its true complexity". In everyday situations the link between observation and theory (or belief) is often tenuous. People support a team and defend its superiority despite its actual performance. The saying that "Old scientists do not change their minds: they just die off" is an illustration of the unwillingness of people to give up their held beliefs even in the face of contrary evidence. Before Lavoisier, combustion was always associated with loss of mass between reactants and products. Even when it was shown that the products of burning iron in air gave an increase in mass, the Phlogistonists failed to accept it. Facts, which did not fit the theory were manipulated or rejected. Similar defence of theories is not uncommon even in recent times.

Planning experiments

This skill is usually exercised in laboratories where there is a measure of problem solving at the bench. Conventional laboratories, with closely prescribed procedures, tend to omit any exercise of this skill.

We shall discuss this later when we consider different types of laboratory experience.

Linked to this aim are the skills of problem solving at the bench, because some forms of practical problem solving require students to plan their experiments on the way to solving problems.

Affective aims

These can be divided into two main categories; attitudes to science and scientific attitudes (Gardner and Gauld[28]). Attitudes to science include interest, enjoyment, satisfaction, confidence and motivation. Scientific attitudes apply to styles of thinking such as objectivity, critical-mindedness, scepticism and willingness to consider the evidence. (Garnett[14]) Some of the affective aims mentioned above will be discussed on the way through later parts of this paper.

Laboratory Objectives

Overall, attempts to list the objectives of the science laboratory are hindered because the stated objectives are either so detailed that they can be of use only in specific disciplines or are so general that they can include almost anything one can think of. Kirschner and Meester [12] have catalogued more than 120 different specific objectives for science practical work.

Having now looked at the purposes of laboratory work, we shall turn our attention to the variety of methods (or styles) available for laboratory work.

Types of laboratory work

What does the learning environment in the laboratory look like? Does it have different forms of instruction designed to promote the variety of aims we have considered in the earlier part of this paper?

The following section attempts to review laboratory instruction types and to relate them to the aims.

In this section we have drawn heavily upon the analysis of laboratory instructional types set out in a recent paper by Domin.[29] Sections of the paper are presented verbatim, interspersed with our own comments and observations to link Domin's analysis to the situation in UK universities. Readers are encouraged to consult Domin's original paper for the full analysis.

In chemistry education distinct styles of laboratory instructions have been in evidence: expository, inquiry, discovery, and more recently, problem-based. Three descriptors can differentiate these styles: *outcome, approach,* and *procedure* (Table 1[29]). The outcome of any laboratory activity is either pre-determined or undetermined.

Expository, discovery and problem-based activities all have *predetermined* outcomes. For *expository* lessons, both the students and the instructor are aware of the expected outcomes. For *discovery and problem-based activities*, usually it is only the instructor who knows the expected result.

Expository and problem-based activities typically follow a deductive approach, in which students apply a general principle to understand a specific phenomenon.

Discovery and inquiry activities are inductive. By observing particular instances, students derive the general principle. This procedure can be criticised on the grounds that students are unlikely to discover, in three hours, what the best minds took many years to find.

The procedure to be followed for any laboratory activity is either designed by the students or provided for them from an external source (the instructor, a laboratory manual, or a handout). *Inquiry and problem-based methods* require the students to develop their own procedures. In *expository and most discovery activities* the procedure is given to the students.

The Expository Laboratory

Expository instruction is the most common type in

Table 1 Descriptors of the laboratory instruction styles.

	Descriptor		
Style	**Outcome**	**Approach**	**Procedure**
Expository	Predetermined	Deductive	Given
Inquiry	Undetermined	Inductive	Student generated
Discovery	Predetermined	Inductive	Given
Problem-based	Predetermined	Deductive	Student generated

use. Within this learning environment, the instructor defines the topic, relates it to previous work, and directs students' action.

The role of the learner here is only to follow the teacher's instructions or the procedure (from the manual) that is stated in detail. The outcome is predetermined by the teacher and may also be already known to the learner. So, as Pickering[44] stated "Never are the learners asked to reconcile the result, as it is typically used only for comparison against the expected result, nor confronted with a challenge to what is naively predictable". Lagowski[30] stated that, "Within the design of this laboratory (expository), activities could be performed simultaneously by a large number of students, with minimal involvement from the instructor, at a low cost, and within a 2-3-hour time span. It has evolved into its present form from the need to minimise resources, particularly time, space, equipment, and personnel". However, this procedure, although administratively efficient, may defeat the main purposes of laboratory work, leaving the student uneducated in this area of learning.

Expository instruction has been criticised for placing little emphasis on thinking.

- Its 'cookbook' nature emphasises the following of specific procedures to collect data.
- It gives no room for the planning of an experiment
- It is an ineffective means of building concepts.
- It is unrealistic in its portrayal of scientific experimentation.

It is possible that little meaningful learning may take place in such traditional laboratory instruction.[22] Two reasons can be suggested to explain the inability of this type of laboratory to achieve good learning. Firstly, it has been designed so that students spend more time determining if they have obtained the *correct* results than they spend thinking about planning and organising the experiment. Secondly, it is designed to facilitate the development of lower-order cognitive skills such as rote learning and algorithmic problem solving. It has been reported[18] that most university laboratory experiences are of this kind.

When placed beside the aims of laboratory work already discussed, the expository laboratory seems to be incapable of helping students to achieve many of them. It may be a place for exercising manipulative and data gathering skills, but may fail to provide training in design and planning and may offer little motivation and stimulus. However, in our experience, small modifications of expository laboratories can offer the possibility of introducing some of those desirable experiences.

For example, an expository laboratory in which a copper complex is to be synthesised and characterised, can take on a new life if the task is presented in another way. If the similarities in behaviour of other metal ions in the first row of the Transition Series exist, it should be possible to synthesise the same complex of a series of metals by the same method. The students can work in groups of four to synthesise four different complexes using the method provided and compare the products for appearance, spectroscopic behaviour and other characteristics. This provides the students with freedom to allocate the tasks, generate a feeling of ownership and give a sense of responsibility to the group. The appearance of enthusiasm and co-operation is an evident bonus. It would not take too much ingenuity on the part of laboratory organisers to modify many experiments in this way and extend the range of aims achievable.

To motivate, by stimulating interest and enjoyment is one of the reasons given by teachers for engaging in practical work. Hodson [31] says that "motivation is not guaranteed by simply doing practical work; we need to provide interesting and exciting experiments, and allow learners a measure of self-directed investigation." He adds that learners need an interest in and commitment to the learning tasks that conventional laboratory work frequently does not provide. That commitment, he says, comes from personalising the experience by focusing on the conceptual aspects of the experiment, by identifying for oneself a problem that is interesting and worth investigating or by designing the procedure to be adopted.

Inquiry Laboratory (Open-Inquiry)

This is best represented by a final year research project, but it need not be confined only to final year. As shown in Table 1, inquiry-based activities are inductive. They have an undetermined outcome and require the learners to generate their own procedures. They are more student-centred, contain less direction, and give the student more responsibility for determining procedural options than the traditional format. It effectively gives students ownership of the laboratory activity, which can result in the students' showing improved attitudes towards laboratories.

Student ownership, represented in such activities, requires learners to formulate the problem, relate the investigation to previous work, state the purpose of the investigation, predict the result, identify the procedure and perform the investigation.

This type is designed to help the learner to construct thinking processes, which, if done properly, will give students the opportunity to engage in authentic investigative processes. Raths[32] lists the following higher-order thinking processes as components of inquiry: hypothesising, explaining, criticising, analysing, judging evidence, inventing and evaluating arguments. This type of practical work could be criticised for placing too much emphasis on the scientific process and not enough on science content. It can provide an environment in which many of the aims can be fostered, but it is time consuming, potentially costly and very demanding on those who have to organise large laboratory classes. However, there is a strong case for its use from time to time and at all levels. There is no reason why a short inquiry should not be attached to the end of an expository laboratory using the skills and knowledge gained in the laboratory but with no fixed instructions. An expository laboratory on acids and bases could be followed by a variety of short investigations on commercial vinegars, path cleaners, antacids and so on, using the skills gained in the laboratory. In this way it is possible to exercise the skills and knowledge gained in the laboratory and so reinforce the learning. There is an opportunity for planning, designing and interpreting and the bonus of ownership and enthusiasm. This kind of approach is already gaining acceptance, but is as yet not reported as common.[18]

Real inquiry can only come after certain knowledge of facts and practical methods have been gained. These foundations can be laid in an expository laboratory. Students must learn the language of chemistry, its symbols and nomenclature, so that they can understand the problem, plan the procedures and communicate their discoveries. Part of the training of a chemist is to learn the techniques of manipulation of materials. "When an artist knows when and how to use his brushes he can be creative. When the chemist becomes skilled in the use of his spatula, he may discover."(Jones[33])

But more than this, a student must learn that often the research chemist has a definite design in his work. He researches along a particular line of thought and he examines the literature in order not to retrace the steps of some other chemist. So we do need some method of education in chemistry, which cultivates and teaches the recognised scientific attributes of observation; the formation of a hypothesis to explain the observation; the experimentation that tests the hypothesis; and the development of the refined theory that possibly relates several hypotheses.

Berry[34] stated some factors, which contribute to such mental engagement in an inquiry laboratory: confidence in content knowledge, ownership and purpose.

***Content Knowledge*:**
To what extent do students have the content knowledge assumed by the task? For instance, if they have little or no relevant content knowledge, they will not be able to suggest why a solution has changed in colour; they simply make an 'observation'. The same thing applies for working out an appropriate procedure. Students may puzzle over the results from their procedure but lack the knowledge to tell them that their results are meaningless because their experimental design was incorrect.

Therefore, teachers have to determine how much content knowledge is necessary for learners to be able to engage mentally with a particular investigation and to what extent students have acquired this prior to beginning a task. This is the essence of what Johnstone[35] means by Pre-Laboratory work. Investigation is very knowledge dependent and cannot take place in a knowledge vacuum. Any suggestion that investigation is a free-standing skill, capable of ready transfer, is unlikely to be true.

***Ownership*:**
When learners have some input into the design of the task, they are likely to have more interest in its outcome and be more motivated to persist. Open laboratory tasks offer greater opportunity for students' ownership of the work and they are truly involved in the process, but this may be offset if they do not already have sufficient background knowledge.

For practical work to be convincing it requires that the learner becomes a 'partisan experimenter'. Solomon[36] argued that "the great experiments of the past were performed in a partisan spirit by scientists who were proving that their hunches were triumphantly right, and that students also were happiest and most successful when they were doing the same".

***Purpose and Aim*:**
As stated before, the aim refers to the scientific reason for a particular investigation and the purpose is the way in which that investigation fits into the work being covered at that time. During the laboratory session, students may ask themselves questions such as: *Why are we doing this? What should we be looking at? What do the results tell us?* Therefore awareness of the aim is important as it helps learners make sense of what they are doing while awareness of the purpose can encourage them to seek links between the activity and the rest of their science work.

Discovery laboratory (Guided inquiry)

The heuristic method taught by Armstrong in the early 20th century,[17] can be regarded as the origin of discovery laboratory teaching in which students were required to generate their own questions for investigation. No laboratory manual was used and the teacher provided minimal guidance. The student was placed in the role of discoverer.

Similar to the inquiry method, the discovery approach is inductive but differs with respect to the outcome of the instruction and to the procedure followed. Whereas in the former the outcome is unknown to both the teacher and the learner, in the latter the teacher guides learners toward discovering a desired outcome. The disadvantage of discovery learning (shared with the other non-traditional forms of instruction) is that it is more time-consuming and potentially more costly than expository learning.

Hodson[31] described discovery instruction as not only philosophically unsound, but also pedagogically unworkable. He asserted that the learner couldn't discover something that he is conceptually unprepared for. The learner does not know where to look, how to look, or how to recognise it when he has found it. We find ourselves in agreement with this view.

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Problem-based instruction

Wright[37] stated that this type of learning is becoming a popular alternative to the other styles of laboratory instruction, not only in general chemistry but also in other chemistry courses. The teacher, in problem-based learning, adopts an active, stimulating role by posing a problem to the learners, providing the necessary reference materials and, by occasional group meetings, carefully moving the students towards a successful solution to the problem. The teacher is very much a facilitator rather than a direct provider of student learning. In this style, students are presented with a problem statement often lacking in crucial information. From this statement the students redefine the problem in their own words and devise a procedure for finding the missing information. With that in place, they then proceed with an experiment, which will lead them to a solution. The problems are 'open-entry' that is, they possess a clear goal, but there are several viable paths toward a solution. Wright emphasised that the problems must be designed to be conceptually simple so that students can concentrate on the methodology without being overwhelmed by the topic. Students are required to devise a solution pathway, think about what they are doing, and why they are doing it.

Like discovery and inquiry instructions, this style is time consuming and places a greater demand on both the teacher and the learner than does traditional instruction. Similar to inquiry instruction it fosters the development of higher-order cognitive skills through the implementation and evaluation of student-generated procedures. It is, however, a deductive approach. Learners must have had some exposure to the concept or principle of interest and the experimental techniques, before performing the experiment. (Domin[29]) Problem Based Learning is very commonly used in the training of medical students in North American universities and is now gaining acceptance in some British and other European centres. It demands a rethink on the part of teachers to redefine their roles. The change from expositor to facilitator is not an easy transition to make, but reports from research indicate that it is very worthwhile.[38] Interest in this kind of laboratory work in chemistry is growing in Britain. It is, of course, not confined to the laboratory and whole courses are being built around the basic principle of Problem Based Learning. An early example of this in chemistry was the 'Eaborn Degree' in the University of Sussex in the 1970's.

While it is recognised that problem-solving situations are complex and variable, and they cannot be tackled by a single 'scientific method', science educators have come to accept that there are certain basic steps that make up a scientific process.

- Identifying a problem for investigation and putting forward a tentative hypothesis.
- Designing an experiment to test a hypothesis.
- Performing the experiment and recording the results in appropriate forms.
- Interpreting the results and evaluating the conclusions with reference to the hypothesis to be tested.

These four steps do not proceed in a linear way but rather in a cyclical manner. The conclusion of an investigation is not the end of the problem-solving process, but by raising a new problem, it becomes the starting point for another investigation. However, this model represents only a simplified outline of the scientific process. The actual problem-solving situation is usually more complex, with links and interactions across the different stages such as collecting data or recalling knowledge to predict, and evaluating the design and implementation as necessary in light of the information collected.

Many of the available published manuals are highly prescriptive and teacher-directed, offering little opportunity for students to pose problems and formulate hypotheses, or to design experiments and to work according to their own design. Students are provided with detailed instructions from the teacher or manual, and all they need to do is to follow the given procedure mechanically. This sort of recipe-type practical is primarily used as a means of verifying or demonstrating principles described in textbooks. They fail to provide experience and training in developing the skills and understanding of the scientific process. Such practicals, are concerned with investigating the *teacher's* problem and finding the *teacher's* answer. They need have little relevance to real life and so fail to promote in students a genuine interest and motivation for practical work.

Some concluding thoughts about laboratory types

This brief tour round a sample of the literature on laboratory work has found that, although many of the references have been to research in the secondary sector, there is much here for the tertiary teacher to consider. It would be naïve to imagine that all this thinking has resulted in a revolution in laboratory work in schools and that researchers on tertiary level laboratory work are unaware of it.[18, 19, 20, 39]

'Pure' discovery learning, if it ever existed, has come and gone. Guided discovery still has a place, but teachers, driven by external pressures, have little time to indulge in it. Worksheets and blow-by-blow manuals are still alive and healthy, leading to apparently efficient coverage of laboratory activities, while missing much of the point of what undergraduate laboratories have the potential to achieve.

The literature cited earlier in this paper has had useful things to say about observation, and particularly to point out that observation is largely conditioned by what we are expecting to find. The observation then either confirms our expectations or challenges us to rethink them, but this can only take place when there are expectations in mind. Otherwise, students may observe irrelevant trivialities and miss what is important, but this begs the question of what is trivial and what is important. The teacher has expectations in mind to enable this judgement to be made, but unfortunately these are not always shared with the students.

The necessity for some kind of pre-laboratory preparation is patently obvious. It applies as much to conventional laboratories as it does to more open-ended and investigative laboratories. A student entering a laboratory without some preparation is likely to spend hours in fruitless, routine handle turning and non-learning. As learning environments, laboratories are very costly in terms of specialist accommodation, consumables, breakages and staff time.[40] If they are not being used for their potential strengths and the time is spent unproductively, they are a massive sink of scarce resources.

Pre-laboratory preparation is not just "read your manual before you come to the laboratory". Many students ignore this because they know that they can survive the laboratory, quite comfortably, without doing it. The conventional laboratory may not be engaging the mind, merely exercising the ability to read and follow instructions. The kind of pre-laboratory work which is being recommended must be as carefully prepared as the laboratory manual itself. It can take many forms, but it must prepare the student to be an active participant in the laboratory. This theme is taken up in a number of publications by tertiary teachers,[40, 43, 39] the last of these being a compilation of pre-laboratory exercises from around the world

It would seem that laboratories that are totally expository miss some of the desirable aims of laboratory work. Totally inquiry laboratories are probably impracticable in the present situation in universities. A core of expository laboratories with substantial 'inserts' of inquiry will go a long way towards achieving the desirable aims of laboratory work.

Assessment of laboratory outcomes

If students are going to take laboratory work seriously, they must see some reward for their efforts. This brings us to consider the objectives set out earlier. They are, in general, a laudable compilation of desired outcomes, but how are they to be assessed?

Let us stay with the general categories set out by Kempa et.al.[21] to simplify our discussion.
The student should exhibit

- appropriate manipulative skills.
- the power to observe.
- the ability to interpret observations and results.
- the ability to plan experiments.

The conventional laboratory report, upon which the assessment is commonly based, can possibly make some kind of measurement of the second and third categories above, but is not 'designed' to handle the first and the last.[18] We might assume that the quality of the results is an indication of the manipulative skills of the student, but it is all too possible for the student to get 'good results' while knee-deep in water and broken glass! It is even possible to get satisfactory results without doing the experiment at all, provided one has good friends! For manipulative skills to be assessed, the student has to *exhibit* them to an assessor. In large laboratories, this has to be done by making demonstrators act as assessors and, for this to operate fairly, each demonstrator has to have some objective and criterion-referenced measure of the skills to be assessed. This may take the form of a set of questions for the demonstrator each of which has only a yes/no answer. In fairness these questions have to be shared with the students so that they can appreciate what is important in the manipulative part of the laboratory.[42]

The planning of experiments is a desirable skill, but how might it be assessed? This operation can take place before entering the laboratory. One possibility, from our own experience, is to give the design task to small groups and ask each group for an agreed written plan. This can be done by forming a small e-mail group and sending a copy of the practical problem to each member. Each member of the group must send the teacher (and the other members of the group) a possible design. Then each student is required to comment on the other designs (several times if need be) until a commonly agreed plan is reached. The teacher now has a written record of the contributions of all the members of the group and can make an assessment of each. This is then returned to individual students with comments. This last step then becomes part of the training in experimental design since experimental design skills are not acquired by osmosis, but need to be taught.

There still seems to be a wide gap between the 'vision' of the researcher and the practice in most laboratories.[18] Could it be that the practitioners view the researchers as unrealistic idealists divorced from the real business of teaching? Or do the practitioners see the arguments of the researchers as reasonable in principle, but unattainable in practice in large, busy undergraduate laboratories? Some might believe that the ideas of experimental design and open-ended projects are for final year undergraduates only because, before then, students do not know enough chemistry or have the requisite skills. This means that many undergraduates will never be exposed to 'real' investigative work at any time in their studies and be denied the excitement experienced by students who have tasted this freedom. How many students confess to never having enjoyed laboratory work till their final year project?

It should not be beyond the ingenuity of tertiary teachers to find ways of giving students, at all levels, the joy of experiencing laboratory work to the full. It is achievable at secondary level[41] and so must be possible at tertiary level.

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