The role of laboratory work in engineering education: student and staff perceptions

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Abstract Most science-based courses include practical experimental activity in the laboratory. Many academics and authoritative bodies would claim that a significant level of such activity is essential to the formation of technologists. This paper reviews the literature on laboratory practice. It also reports on an internal survey of staff and student perceptions of the practical work and its value in their courses in the School of Engineering at the Robert Gordon University, Aberdeen. It discusses the degree to which practices both within and outwith the School appear to match the declared aims of participants. It concludes by suggesting some strategies, which may lead to laboratory work becoming more effective.

Keywords laboratory practice; curriculum development

Considering the importance that is generally attached to practical activity there is relatively little published research on its effectiveness. Many publications provide a general appraisal of the usefulness of its practice.[1,2] It is generally agreed that the aims of practical work fall into four broad groups.[3,4]

- *Cognitive learning* which is often elucidated as the integration of theory with practice.
- *Inquiry methodology* which includes hypothesis forming, experimental design and methodology and evaluation of results.
- *Vocational aims* which include awareness of current practice and the inculcation of professional ethics.
- *The development of personal skills* such as communications, report writing and team working skills.

Authors of published work are predominantly from the science disciplines as opposed to engineering or medicine. It is perhaps a reflection of this orientation or because the authors themselves are researchers that inquiry methodology aims are generally promoted as the most important of the four groups. Anderson's view of these skills is that they should acquaint the learner with ways in which natural phenomena can be tested in the laboratory through structured experimentation.[4] The learner thus gains a more comprehensive perspective of the orderliness of nature and the tentative nature of scientific theories and models. We are in accord with Nuttgens who suggests that engineering is almost the obverse of science.[5] Science postulates theory and then tests its predictions. Engineering commences with practice and formulates models whose rigour is predicated mainly by the level of accuracy needed to ensure adequate prediction of performance. It is perhaps to be expected therefore that such opinion as has been published relating to engineering stresses cognitive aims, particularly the integration of theory with practice. Doughty *et al*. believe that 'practical experiments lie at the heart of the relationship between meaning and understanding'.[6] Magin and Churches were concerned that students appreciated the deficiencies of the predictive power of models.[7] Researchers with a foot in both camps, such as Drake *et al.*, gave 'equal importance to experimental selection, design, analysis, group problem solving skills and peer communications'.[8] Our own staff were broadly in sympathy with the views of these engineers.

The survey

Staff

The majority of the 17 staff in post were educated as engineers but had limited industrial experience. Of the academic staff, 13 (77%) responded to a relatively open questionnaire which sought their perceptions of the principles and practice of experimental work. This was followed up by semi-structured audiotaped interviews of 10 (59%) members. Given the nature of the inquiry methods, a degree of interpretation was needed in classifying responses. Respondents listed from 2 to 12 objectives. The individual who gave the longest list summarised his response in an overall aim, which emphasised the preparation of the student to conduct projects, research and professional practice competently. Table 1 summarises staff responses on laboratory objectives. These views were well illustrated by one interviewee who said applications 'provide a relationship between the material in lectures and how it might be used in industry. . . . Worked examples only go so far because they get no feel for the numbers'. Through labs students do 'get a feel for what the numbers mean'. Table 1 shows that illustration of actual plant was a major concern of most lecturers. In interview they made it clear that they felt that, despite the laboratory equipment being 'just toys' the students learned that theory was not just abstraction but an imperfect model of real plant. Although several staff members had included equipment selection as an objective none was able to give examples of where and how this was achieved. As will be discussed below, there was little scope for students to influence the range of work carried out.

Several academics thought that learning how to use plant, controls and gauges

TABLE 1 *Academic staff responses on laboratory aims*

Cognitive outcomes	
Laboratory practice and equipment selection	9.8%
Appreciation of plant construction and operation	35.2%
Inquiry methods	
Research methodology	9.8%
Data capture, analysis and appraisal of accuracy	13.8%
Personal transferable skills	21.6%
Professional skills, judgement and ethics	9.8%

was an important aim of laboratories. One said, ‘Learning to use test equipment, learning to handle data and produce reports. I think it is the basis of obtaining the results that is important’. It seems from the interviews, however, that this is not seen as the development of skills in inquiry methods but as preparation for professional practice. Another interviewee described labs as ‘a vital part of their (the students’) preparation for going into industry’.

Most lecturers, either in response to the questionnaire or at interviews, said that they felt that laboratory work helped to develop personal skills. The most frequently cited of these was report writing. Several respondents were at pains to differentiate between essays and technical reports, which they perceived as qualitatively different. They emphasised structure, rigour, presentation of results and the matching in the conclusions of results with the predictions of theory. It is not surprising to find little in the nature of freedom or challenge in the activities. Perhaps surprisingly few mentioned team working skills and leadership although at interview they agreed that these were valuable outcomes of the experience. One in particular expanded on what he described as the ‘essential skills in industry’.

Approaches to preparation for laboratories varied but various factors militated against the ideal many staff would like to see. Class sizes meant that a rota was used. A dedicated weekly timetable slot was allocated and students in groups of 6–8 conducted one lab a week. This meant that labs could not be synchronised with lectures. Some students conducted an experiment before the theory had been covered, others some considerable time after. Often too, research students were employed to conduct the sessions and so the direct link with class work was lost. A small number of staff did try to ensure that students were prepared in class for a coming laboratory but they admitted to difficulties in doing so. Typically, preparation amounted to a short talk by the lab supervisor on the conduct of the experiment. Most staff felt that there could be advantages in having the practical work precede the theory. What they saw as problematic was that some in the class would have done the practical prior to the theory while others needed the theory as preparation for a forthcoming lab.

Typically, the equipment is set up before the students arrive. They follow a prescribed routine of making adjustments and taking readings. Analysis too is generally suggested in the handout. Pointers are generally offered by the supervisors on the nature of the discussion. Only one lecturer said that he would observe the students’ approach to conducting the experiment and take this into account in marking. In general, staff agreed that the report was the sole basis of assessment. One described the approach as being ‘on a very cursory surface basis’.

Students

Informal discussions of perceptions of laboratory work were held with individuals and groups of students from all years of both the undergraduate courses. Although these were not audiotaped, notes were written up immediately afterwards. Additionally, eight students were interviewed more formally in audiotaped sessions. It was difficult to get them to define the objectives of laboratories as care was being taken to avoid leading them. In general, they felt that it was to give experience and to relate theory and practice. They did not feel that gaining practical skills was an important outcome. Supplementary objectives included developing skill in methods of inquiry and developing awareness of industrial practice.

Most said they do little preparation for a session. One admitted that he listens to the supervisor before the activity but does 'the background reading after to help with the report'. Teamwork on the day is largely unplanned. Little attempt is made to ensure that all are participating or gaining an understanding of all aspects of what may be a fairly complex procedure. Students said that they rarely had a need for recourse to the supervisor but felt that it was comforting to know that advice would be available if they needed it. Perhaps surprisingly, few students said that they would welcome more freedom to influence the conduct of experiments. It is salutary that it was a student who identified a key objective of engineering practice. Engineering plant is often complex and cannot be operated single-handedly. Failure to follow procedures and to work in harmony cannot simply lead to errors; it can be positively dangerous. One student said: 'We need to know how to follow procedures. It's how industry works. It is your job to prepare us for when we go into industry'.

Students generally felt that assessment on the basis of the report was fair. They felt that it was the best means of gauging their understanding of the integration of theory and practice. One said '. . . you learn most when you're doing the report. That's when it all sort of comes together'.

Analysis of laboratory handouts

Virtually all laboratory exercises were supported by a short handout, typically 2–5 sides of typed A4 sheet. Table 2 is an analysis of the handouts in use at the time of the survey. A typical handout did not specify the objectives although these were usually implicit either in the procedure or analysis of results section. Most gave an outline of the methodology to be adopted and included an outline of the theory to be tested. In all cases, the apparatus to be used was specified and the handout included a short description of it. In some cases a schematic of the equipment was included. Where numerical results were required, the readings and number of sets were described. In many cases a proforma for recording readings was provided. All handouts included guidance on how to analyse the readings. In many cases this was extended to suggestions on how to present results. The latitude allowed seemed to owe more to the author's preference than to the level of the class. Although, in general, some suggestions were given of points for discussions, this section was mostly reasonably open.

TABLE 2 *Analysis of laboratory handouts in use at the time of the survey*

Year	Objectives	Apparatus Selection	Apparatus arrangement	Procedure Methodology	Readings	Analysis	Presentation of results	Sample size
1	2	10	10	10	10	10	8	10
2	1	8	8	8	7	8	6	8
3	4	9	9	8	8	8	5	9
All	7	27	27	26	26	26	19	27

Discussion

Aims and delegation of control

In contrast with much of the literature, the development of inquiry skills was not seen by our staff as the primary aim of laboratory work. This may be because engineering tends to be focussed more on preparation for professional practice than on research. Researchers, it is to be admitted, need to be fully versed in inquiry methods.

Most authors advocate delegating some of the control of the progress of an experiment to the students. Herron, for example, proposes four levels of control.[9] Initially all elements are pre-set and students simply follow instructions. Progressively, however, the answer, then the methodology, and finally the aims, are left open. By this means, the learner is progressively taught to devise and conduct experiments while avoiding the unrealistic proposals or bafflement detected by Thornton when control was delegated too early.[10] Our survey, both internal and of the literature, suggests that with the exception of project work most laboratory work remains almost completely closed. Delegation of control can have benefits as reported by Cooper.[11] Her students 'devise and control their own experiments with assistance from teaching assistants'. The learners are 'more positive about the experience and believe they learn more'. Drake *et al.* report an ambitious attempt to link experimental work with real industrial problems in work which takes more than a year to complete.[8] Support was needed to overcome initial anxiety but an atmosphere of accomplishment was created when key results were presented. This need for support initially is reinforced by Tattje's findings that 'learning to experiment, to solve problems with the apparatus and to apply new theory was too much at one time'.[12]

As we have noted, both staff and students identified the integration of theory and practice as the primary aim of experimentation. Whether or not the students fully appreciated that the intention was to explore the extent to which an imperfect model depicted reality rather than vice versa is a moot point. Joseph and Julien report on an altogether different approach.[13] They separated lab work for their electrical engineers from taught parts of the course. Experiments became self-contained vehicles through which the students both learned and tested new theory. They found that their students took the exercises more seriously and developed expertise in practical and problem-solving skills.

In part, as a result of our surveys we are now introducing more adventurous approaches to experimentation. We do not altogether agree with those who have suggested that inexperienced first-year students cannot be given a large degree of freedom in the conduct of investigations. There are reports of primary school children devising and conducting their own tests. Also, Taime, having devised an index to measure the level of demanded inquiry skills in practical work, found that a level of 1.2 in secondary schools fell to 0.5 in universities. We are introducing devolved experiments to the first year by using familiar objects such as kettles and providing substantial tutor support. We hope to report on the outcomes of these approaches in the near future.

Assessment and achievement

Our findings that assessment was based almost without exception solely on a written report of the work conducted appears to be the norm elsewhere too. Doughty *et al.*, for example, report that 'the work (experiments) is assessed by marking the laboratory record, which is often 'doctored' at home after the event'.[6] Prior to the introduction of their 'self-contained' labs, the students taught by Joseph and Julien received no credit for their work and it appears did not even write it up.[13] They are now assessed by written and oral report but even here no mention is made of assessment of the conduct of the work. One suspects that Stringer's findings hold good today.[15] These were that the average mark tends to be high and that this leads to a devaluation of the standing of the work in the eyes of the student. Boud *et al.* make further criticism of using the report as a basis of assessment.[16] Our staff agree with them that as it is usually completed away from the scene, is subject to collusion and takes no account of practical skills, it fails to address to espoused aims.

We provide an introductory course in the first year on experimental methods and report-writing skills. Subsequently, however, students rarely systematically criticise experimental design, or analyse the source of errors. One of our staff summarised our failure to realise our objectives as being 'because we don't test for them after . . . so we can't expect the students to take any notice of them'.

It may be argued that assessment of the skills necessary to conduct the experiment is problematic on two counts. Firstly there is the question of what is to be judged. In closed laboratories this would mean gauging the effectiveness with which a student interpreted and followed a prescribed procedure. In an open experiment judgement would be more subjective. In the latter case, we contend that the assessor should attempt to define in advance what is being sought. This could include enunciation of the objectives, analysis of the needs, synthesis of possible solutions and, after evaluation, selection and implementation of the most suitable. Thus laboratory work could cease to be at a low level of cognitive attainment. The second problem is, however, less tractable. Engineering experiments are generally team efforts. This necessarily implies that all participants do not carry out the same activities. How then is the learning of any individual to be assessed? It should also be accepted that there is an element of symbiosis. The team achieves more than an individual can. Assessment of individuals in groups was identified as the most difficult issue in a recent survey conducted by the Learning and Technology Support Network (LTSN) Engineering Working Group on Assessment Issues. Whatever decisions are made, we maintain that the assessment should first be designed to augment the learning process and secondly be made explicit to the students.

Resources and contacts

While it is accepted that much can be done to enhance the laboratory experience it must also be recognised as resource intensive. 'Laboratory based courses' used to attract considerably higher funding from the funding bodies. This difference has been constantly eroded. We live in an era when resources must be justified by utilisation. Engineering plant is expensive and requires considerable floor area but there are only a limited number of occasions on which an engine test bed, for example, can be exploited. Staff loadings also have increased and the use of research assistants and part-time staff in supervision of experiments is common. It is unlikely, therefore, that Cummings and Jensen's plea for 'a large, open, spacious area' for laboratories will be realised.[17] Barring independent sources of funding we will increasingly find ourselves required to use scaled-down model rigs and simulations. That should not deter us from making best use of what we can provide. Scale models are used by professionals. Interpretation of the results is an essential technical skill. With explicit objectives and well-designed experiments 'drawbacks' can be turned to advantage. We must also recognise that students will need support to overcome early anxieties as these more demanding objectives are introduced. If research assistants are to be employed as supervisors, they themselves must be well versed in the objectives and support needs of the students.

Motivation

Many of the published analyses of laboratories report low motivation among participants. Brimberry describes mandatory laboratory attendance as being 'to the dismay of most (Pharmacy) students'.[18] Cooper says that 'it is little wonder that many students find chemistry irrelevant and boring'.[11] This lack of motivation to conduct practical work is widely reported in science-based courses.

In contrast most surveys, including our own, report engineering students as having an enthusiasm for laboratory work. Indeed, our students lamented that it was not given more prominence in their courses. This should not lead us to complacency, however. If ways can be found both to enhance the learning experience and to raise the already high level of motivation they should be adopted. Our students identified the need for an engineer within a team to follow complex procedures accurately. Should this skill not be made explicit and assessed in closed laboratories? As we noted in the previous section, we believe that a greater degree of licence could improve the learning experience and, if well designed, also be highly motivational. Gold *et al.* maintain that investigative experimentation can generate high motivation.[19] Fernández-Iglesias *et al.*, reporting on an ambitions extended laboratory, attribute high motivation to:[20]

- the requirement of groups to collaborate on subsystem design;
- assessment reflecting performance in the meeting task objectives;
- the best systems being selected and applied in the next year's work.

The last of these they say gave students selected a 'flying start' in the subsequent year. We suggest that it also invoked competition between groups. This too is a factor which we have found to engender motivation.

Conclusions

The design and role of engineering laboratories

Professionalisation of the individual is the process by which an undergraduate is transformed into, in our case, an engineer capable of fulfilling the role and performing the duties of his/her calling. Self-identity is a key to this. We have found that engineering students see themselves as essentially practical. Laboratory work is, therefore, seen as an important component of their formation. The importance of practical work, we believe, cannot simply be measured, as Walton sought to do, by the proportion of a student's time spent in the lab.[21] Poorly designed experiments may offer little added value. Well-designed work may be the cement that binds the curriculum together and may make an invaluable contribution to the engineer's professionalisation. Following our survey we have been reviewing and enhancing our approach. We agree with our students that the ability to work as a team and to follow complex instructions accurately is one important outcome. With this aim added we agree with Walton that 'The undergraduate engineer needs to gain experience in the three important areas of fundamental phenomena and techniques, engineering modelling and organisational capability in a way which develops his function as a decision maker and implementor'. We emphasise that it is unlikely that all of the objectives can be met in any one experiment. We also stress the need to make objective explicit and to design assessment instructions which truly gauge their achievement. We make a plea for more innovative approaches to be adopted. As previously noted we are introducing a greater degree of openness early in the courses. Grant and Gilchrist describe a different approach in which by observing the effects of variations, students attempt to deduce the nature of a system.[22]

Whatever approach is adopted we maintain that practical work must be integrated with the rest of the engineering curriculum. 'The separation of practical work and lectures causes a division in the mind of the student rather than relating the theory to the application which reinforces the basic concepts', concluded Doughty *et al.*[6] We have found that our students see themselves as becoming competent in dealing with practical problems.[23] They take pride in their occupational title. Well-designed laboratory work can capitalise on their conceptions. The vast majority of the students expect to enter industry, not become researchers. The design of practical work must reflect industrial needs. We believe these to include team working skills and dealing with technical rigour with the demands of novel problems.

We conclude by endorsing Doughty *et al.*'s comment that 'in engineering, practical experiments and projects lie at the heart of the relationship between meaning and understanding'.[6]

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