WHAT DOES GOOD ENGINEERING LABORATORY PEDAGOGY LOOK LIKE?

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INTRODUCTION

There is extensive literature on pedagogy of science laboratories; however the definitive literature for engineering typically cited is Dewey, 1910 [1]. The role of laboratory whether simulation or real experimentation is to develop students' learning and ability to apply the theory into practice, observing and analysing the experiment, reflect upon their learning from the experiment, and finally assimilating theory to construct conclusions essentially moving through Kolb's learning cycle theory, [2]. This paper presents an evaluation of student understanding of a topic from; a lecture (alone); lecture followed closely by laboratory; laboratory followed by lecture. The methodologies used were quantitative Multi-choice questions (MCQs) and qualitative viva voce discussions to ascertain the students' understanding. The initial results indicate that the lecture timing relative to the laboratory is critical to student learning.

1 BACKGROUND

Laboratory education refers to a form of practical work in which participating students are able to interact with materials and practice experiments [3]. Through material interaction and the manipulation of equipment, individuals are able to construct their knowledge of physical phenomena and scientific concepts [4].

The history of laboratory education is extensive, identified as a key part of scientific education for the past 200 years [5]. There is extensive literature on pedagogy of science laboratories highlighting that: a good science laboratory experience engages the learner at many levels [6], meaningful assessment is key to student learning [7],;

student learning can be improved through doing and discussing the science in the laboratory [8], and the use of a digital laboratory manual with required pre-laboratory activities significantly improves student academic performance of students and experience [9].

However, the definitive literature for engineering typically cites Dewey [1] to discuss how learners construct knowledge from laboratories. In the UK, the Engineering Council [10] and UK engineering accreditation institutions require engineering curriculums to incorporate laboratory based learning, for example;

"Appropriate laboratory work should be evident throughout the entire degree programme…provide the vehicle for exploring the relationship between conceptual models and real engineering systems…provide hands-on experience of the behaviour of materials and processes…" [11]

Therefore in the UK, laboratory teaching can account for up to 50% of an undergraduate engineering student's contact time [12]. The theory of engineering laboratories has been outlined in several papers. For instance, instructional laboratories should be designed to develop students' engineering knowledge, understanding and application abilities [13]. Laboratories enable the students' to experiment with contextualising an engineering theory into practice [14-15], developing students' cognitive learning, and provide an opportunity for students to learn from the experimental analysis and decision processes to draw valid conclusions, [16]. Equally, laboratory experience supports students in developing their engineering practical skills, [17] and transferable skills of communication and team work [18].

Laboratory education provides an unique opportunity for students to practice engineering and apply theoretical concepts discussed in lectures. The chronological relationship between laboratory and lecture is critical to student knowledge synthesis [13]. The learning outcomes are more likely to be achieved when the learning objectives are well thought out and clearly communicated [19]. Ideally educational practitioners should consider experiential learning theories [2, 20], and Bloom's Taxonomy [21] to clearly define the laboratory learning objectives of a laboratory. Providing students with more freedom to manipulate their own ideas can improve student laboratory learning, [22]. Supplementary experimental learning resources [23] and active engagement in the experimental design [24] have been found to enhance student learning engagement and experience.

However it has been observed and argued that laboratory education has not been adequate in practice [25]. In fact, laboratories have been identified as: very procedural and prescriptive learning experiences [26] or as an unproductive and confusing learning experience [27]. This is a relatively common viewpoint among other educational researchers. With the rising costs of laboratory equipment, this has resulted in institutions questioning the evidence of the benefits of laboratory education [5, 12]. There is a lack of clarity surrounding what contributes to an effective learning experience in the engineering laboratory [12].

This paper aims to present the research observations and results of a project that has evaluated student learning in engineering laboratories in the Extended Degree in Engineering and Maths (prep year) at Sheffield Hallam University. The paper will also provide evidence of what is effective laboratory pedagogy practice and guidance for academics designing, developing and delivering engineering laboratories for all engineering courses.

2 RESEARCH APPROACH

The project to research into engineering investigation laboratories adopted both quantitative and qualitative research methods. A quantitative methodology based on the use of MCQs aimed to gather data for statistical analysis. The qualitative research approach focused more on identifying the depth of student understanding and the student experience.

2.1 Laboratories Researched

This project focused on identifying the breadth and depth of student learning on a mechanical engineering investigation module. The student volunteers' knowledge of the theory related to a laboratory experiment was assessed, in order to identify if the practical experiments were adequately reinforcing the theoretical learning introduced in lectures.

The three experiments assessed were: The coefficient of friction; Forces in equilibrium; Elasticity, Hookes' Law & Spring Stiffness. The student volunteers were categorised into groups of those who had completed: (1) a laboratory alone, (2) a laboratory followed by the corresponding lecture and (3) a lecture followed by the corresponding laboratory. For groups 2 and 3, the number of weeks between the lab and the lecture was recorded to establish if there was any correlation between the time interval between the lecture and laboratory and the level of learning.

2.2 Quantitative Research Method

An achievement tests approach was adopted as the quantitative data collection method. Achievement tests are helpful in determining academic learning by measuring student knowledge of a topic [28], a research objective of the project. Tests can take many forms [29], however the benefits of MCQs include: much quicker to complete hence attractive to participants and administrators [30] and removal of any disparity in student's abilities to write [31]. MCQs can be designed to assess lower order cognitive skills and higher order thinking skills [30]. The disadvantage of MCQs include: they can encourage students to guess a correct answer and gain credit for something they don't actually know [30], and it is difficult and time consuming to create effective questions and possible answers [30,32]. However, the last issue is mitigated when the MCQ author fully understands the topic [33] and a suitable number of alternative answers which are well considered with none are obviously different from the others [34]. An example of the MCQs developed and applied in this research is shown in *Fig. 1*.

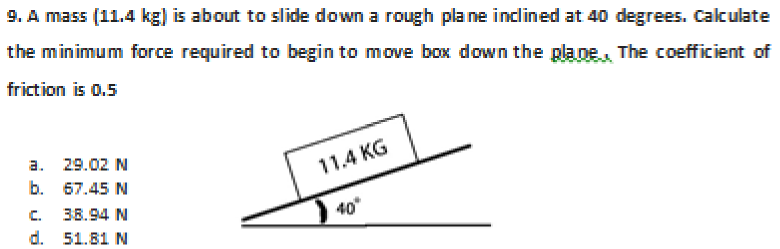

Fig. 1. Example MCQ used to assess learning from the Coefficient of Friction Laboratory

2.3 Qualitative Research Method

Viva voce interviews were chosen as the qualitative research method using a semi structured interview approach. The strength of semi-structured interviews is in understanding the experience and imaginings of the research participants [28]. This method can provide insight into the depth and detail of the participants' knowledge compared to the more general oversight yielded from quantitative data [35]. Viva voce can provide greater insight to the depth of student learning as students' verbal skills have been shown to be greater than their written skills [36]. The qualitative interview was utilised alongside MCQs to gain insight into the student's understanding of a topic and to test their higher order cognitive skills, i.e. true depth of knowledge. An example of one of the semi-structured interview questions used is shown in *Fig. 2*.

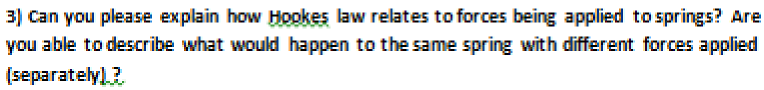
3) Can you please explain how Hookes law relates to forces being applied to springs? Are you able to describe what would happen to the same spring with different forces applied (separately) ?

Fig. 2. Example of semi-structured interview question to assess the learning from the Hookes' Law & Spring Stiffness Laboratory

3 RESULTS AND DISCUSSION

3.1 Correlation Method of Quantitative Results

One of the project objectives was to identify if there is a correlation between the time interval between the lecture and corresponding laboratory and the impact on student learning. A total of 27 multiple choice questionnaires were completed with 9 being completed for each of three experimental topics. MCQ data was collected either immediately after the laboratory or up to two weeks later. It should be noted that the data for those who had studied the lecture followed by the laboratory had variations in the length of interval between the two sessions occurring. Therefore, the effects of the time delay between the lecture and laboratory were assessed.

To aid analysis of the complex data sets, it was decided that the topic of the laboratory experiment would be ignored and all results were treated as an equal measure of student performance relating to the timing of the lecture to the laboratory. In addition the Pearson linear correlation method was used to establish a linear correlation between two variables by drawing a line of best fit through the data points and computing the correlation coefficient [37]; a correlation coefficient of 0.4 is weak, 0.41 to 0.69 is moderate and over 0.7 is a strong correlation. A negative correlation shows that when one variable increased the other decreased.

3.2 MCQs Results Lecture and Laboratory Timing

The MCQ results provided quantifiable insight into the student learning and impact of the timing of lecture to laboratory and are summarised in *Table 1*. Omitting the students who had studied the laboratory only, the computed correlation coefficient was -0.33; upon removal of student outliers, the correlation coefficient was -0.75. As the time between the laboratory and lecture increased, the student learning decreased. This is exemplified by the Friction Laboratory students G-I who experienced 4 weeks between Lecture and Laboratory, *Table 1*, and completed the MCQ immediately after the laboratory. The results listed in *Table 2* demonstrate that these students struggled to synthesize the theory learnt in a lecture for reapplication in the laboratory. Equally students B-D who had no lecture on Hookes' Law prior to the laboratory and undertook the MCQs immediately afterward, *Table 1-2,*, clearly demonstrated that they were struggling to synthesise the learning.

Table 1. The effects of duration between lecture laboratory sessions (-ve duration students completed laboratory before the lecture, +ve vice versa).

Moments Lab			Friction Lab			Hookes Law		
Student	Duration between lecture/lab	Grade	Student	Duration between lecture/lab	Grade	Student	Duration between lecture/lab	Grade
A	0	55%	A	1	66%	A	-1	63%
B	0	100%	B	1	50%	B	-1	36%
C	0	33%	C	1	41%	C	-1	27%
D	0	44%	D	2	83%	D	-1	18%
E	0	22%	E	2	83%	E	0	54%
F	0	89%	F	2	58%	F	1	81%
G	0	33%	G	4	25%	G	1	73%
H	1	78%	H	4	25%	H	1	73%
I	1	78%	I	4	25%	I	1	90%
		59%			51%			57%

Table 2. The effects of reflection on student knowledge synthesis

Moments Lab			Friction Lab			Hookes Law		
Student	Duration between lab/MCQ	Grade	Student	Duration between lab/MCQ	Grade	Student	Duration between lab/MCQ	Grade
A	immediately	55%	G	immediately	25%	A	Immediately	63%
D	immediately	44%	H	immediately	25%	B	Immediately	36%
G	immediately	33%	I	immediately	25%	C	Immediately	27%
E	immediately	22%	D	2 weeks	83%	D	Immediately	18%
I	1 week	78%	E	2 weeks	83%	E	Immediately	54%
C	1 week	33%	F	2 weeks	58%	F	2 weeks	81%
B	2 weeks	100%	A	3 weeks	66%	G	2 weeks	73%
H	2 weeks	78%	B	3 weeks	50%	H	2 weeks	73%
F	2 weeks	89%	C	3 weeks	41%	I	2 weeks	90%
		59%			51%			57%

3.3 MCQs Results Learning as a function of Timing of MCQ

Whilst the results in *Table 1* provide insight to when best to schedule a laboratory after a lecture, the results don't tell the entire story. Students were allocated a laboratory topic on the day. Students who completed the MCQs immediately after their laboratory session scored lower than those who were given the test in subsequent weeks, *Table 2.* The strong improvement in both Friction and Hooke's Law performance after 2 weeks may be because students were required to produce a laboratory report on these experiments two weeks after performing them.

The Pearson linear correlation testing reveals, there was a moderately strong correlation of 0.64 between student learning and timing of the MCQs after the laboratory. When the outliers were removed the correlation grew to a borderline 'very strong' correlation of 0.71, indicate students need time to synthesise their learning through reflection/laboratory report write up.

3.4 Qualitative Results Semi-structured Interviews

Semi-structured interviews were used alongside MCQs as a means of identifying the depth of student learning. This method should make it easier to identify the depth of student learning of a topic, opposed to how well they can choose the correct answer. Seven interviews were conducted split between the three experimental topics, *Table 3* presents interview results and the relevant variables.

Table 3. Breakdown of semi-structured interview results

Student ID	Topic	Duration Between Lab and Lecture	Duration Between Lab and Interview	Learning
A	Friction	5 weeks	Immediately After	This participant was only able to loosely describe frictional forces; demonstrated poor knowledge of forces to move a block, coefficient of friction and friction on an incline.
B	Friction	3 weeks	1 Week	This student offered a much stronger explanation of frictional forces, good knowledge of forces to move a block, and coefficient of friction. However knowledge of friction on an incline is similar to **Student A**.
C	Friction	4 weeks	Immediately After	Only able to provide a brief explanation of forces to move a block. Indicated that they knew what factors affect the coefficient of friction, but provided no evidence. No knowledge of friction on an incline.
D	Moments	1 Week	1 Week	The student was able to adequately discuss forces acting on an object and the conditions for equilibrium. They had a good understanding of the effect of distance in relation to the magnitude of a bending moment and were able to confidently discuss the presented diagram.
E	Moments	0 Week	1 Week	The student only offered brief discussion of forces acting on an object and the conditions for equilibrium, but no true explanations. Showed an understanding of the effects of the distance of an applied force on the bending moment and confidently discussed the problem presented diagram.
F	Hooke's Law	1 Week	2 Weeks	This student had a solid base of knowledge for most of elasticity in springs, Hookes' law and potential energy. They were only able to discuss elasticity in relation to springs, struggled to apply in general. A good explanation of spring stiffness, and relevance to engineering practice. Understood laboratory aims, where errors occur, but not their impact.
G	Hooke's Law	4 Weeks	1 Week	This student was able to confidently explain elasticity and Hookes' law. Briefly explained spring stiffness and forces, lacked depth and confidence in comparison to **Student F**. Lacked depth of knowledge and understanding of spring stiffness, and aims of experiment. Aware of potential experimental errors, but not their impact.

There are a number of key points which can be taken from the analysis of the semi structured interviews.

- Students **A and C** showed a severe lack of confidence in the topic, had a long gap between the Lecture and Laboratory, and were tested immediately after their laboratory. There could be a question as to how effectively students worked to understand this laboratory before the report was written. The lecturer confirmed that it was not unusual for students to seek clarification of aspects of the theory and analysis in the week before the report was due (two weeks after completing the lab).

- Students **C and D**, were in fact the same student. However, in one of the interviews the student had a larger depth of knowledge and confidence; there was a shorter time frame between the corresponding lab and lecture sessions.
- The student **E and G** were also the same participant. Despite the larger time frame in between the corresponding laboratory and lecture this student was much more knowledgeable, aptitude and motivated to learn, particularly as Hooke's law experiment was summative assessed via a laboratory report.

4 CONCLUSION

The literature offers a multitude of aims for practical laboratories, however there is no single agreed upon aim, with great variation across programmes and with different desired learning outcomes. In the case of the course reported here, the teaching team's primary aim for the mechanical laboratories is to reinforce the theory presented in lectures into practice. However the current timetable configuration is not truly consistently supporting this aim or helping the students. The qualitative viva voce results indicates the current laboratory implementation encourages the students to surface learn, as demonstrated by their inadequate knowledge of the laboratory learning, inability to relate their knowledge back to the actual theory, and inability to think beyond the scope of the experiment into engineering practice.

The quantitative results indicated that timing of the lecture to corresponding laboratory is critical to student knowledge synthesis. Both the qualitative and quantitative testing methods indicate student knowledge synthesis improves when student learning is assessed at a later date.

Due to timetabling constraints most corresponding lab and lecture sessions will have a considerable time gap between them. When the sessions aren't synchronised an environment is created were students struggle to connect the learning [38]. This argument holds true for this project and has a dramatic effect on student synthesis of theory into practice. The lowest MCQ results were scored by students who hadn't studied any relevant theory in lecture, or students who had a large gap between the two corresponding sessions. Students exposed to inadequate theory leads to a lack of cognitive engagement, ultimately rendering the laboratory experiment learning useless [38]. The term 'useless' may be a bit extreme, but it does significantly reduce the learning effectiveness of the laboratory. Under these circumstances it is argued that the students are overwhelmed with information to process and are distracted from the practical learning [39-40]. Therefore laboratories should be carefully planned to maximize consolidation of the theoretical learning into practice [41].

The research suggests that in only 2 out of 12 laboratories is the learning adequately reinforced (through the use of a written report), as indicated by the students viva voce results. However, while the write up may have reinforced the learning, it had not helped the students to further understand of the theory and abstract contextualize the laboratory learning to the outside world.

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