

Adding Value to Physics Laboratories for Pre-service Teachers

Lorna Jarrett^a, George Takacs^b, Brian Ferry^a

Corresponding author: lorna@uow.edu.au

^aFaculty of Education, University of Wollongong, Wollongong NSW 2522, Australia

^bFaculty of Engineering, University of Wollongong, Wollongong NSW 2522, Australia

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Abstract

This project focussed on first-year physics laboratories for pre-service teachers. It aimed to make laboratories more aligned to future teachers' needs; contributing to their confidence with apparatus, conceptual understanding and effectiveness as communicators. However, our approach is also relevant to mainstream science laboratories.

First, we flagged links with practical investigations in the NSW High School year 11 / 12 physics syllabus in the lab manual. Second, we incorporated qualitative multiple-choice questions at strategic points based on the Peer Instruction work of Mazur (1996), Crouch and Mazur (2001) and Cox and Junkin III (2002). Finally we employed principles of Cognitive Load Theory to inform the design of the laboratory manual. The goal was to decrease extraneous cognitive load and make learning more efficient (Chandler & Sweller, 1991; Paas, Renkl & Sweller, 2004; Purnell, Solman & Sweller, 1991). Three experiments were modified. Evaluation involved observation, comparison of marks and a focus group interview. Peer Instruction succeeded in uncovering misconceptions and engaging participants in meaningful discussion but was too time consuming for the two-hour laboratories and increased participants' cognitive load. Recommendations include using Peer Instruction at the start of laboratories, use of Cognitive Load Theory to inform laboratory manual design and further research with a larger participant group to validate findings.

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Project aims

The project, conducted by an interdisciplinary team, targeted first year undergraduate students enrolled in Bachelor of Science Education degrees. It aimed to help prepare these pre-service teachers to teach practical investigations in the NSW High School year 11 and 12 Physics syllabus; challenge misconceptions; link theory to experiment; develop deep conceptual understanding; and foster confident communication. Our approach combined Peer Instruction activities with the application of Cognitive Load Theory to the format of the laboratory manual. We also identified and flagged links between experiments and practical investigations in the NSW physics syllabus. Although this study focused on pre-service teachers, the majority of modifications would be beneficial in mainstream first-year laboratories or for other practical subjects.

Needs of pre-service teachers

A number of factors prompted us to focus on pre-service teachers. Firstly, physics teaching in Australia and worldwide is in crisis. Harris, Baldwin and Jenz (2005) detail the looming crisis that schools face to find suitably qualified physics teachers and assert that tertiary institutions share responsibility for addressing this. Secondly, pre-service teachers have different needs to other BSc students. They will be responsible for laying the foundations of understanding of hundreds of students, so the quality of their conceptual understanding is of utmost importance. However, unlike other physicists and chemists, they are increasingly likely to be the most qualified and knowledgeable individuals in their workplace so any misunderstandings are likely to go unchallenged and be passed on to their students. Toh, Ho, Riley and Hoh (2006) found that pre-service teacher preparation had by far the greatest influence on students' achievement compared to class size, streaming, or amount of homework. According to Harris (2007, p.25) "Aspiring science teachers need tertiary preparation that provides them with the disciplinary knowledge appropriate to the teaching that they will do". Thirdly, considerable evidence exists that misconceptions are common even among successful physics students; that traditional teaching methods such as "cookbook" laboratories are not effective in overcoming misconceptions; and that strategies involving active engagement and peer interaction have the greatest potential for improving learning (Johnston & Millar, 2000; Mulhall, 2006). According to Thacker (2003, p. 1846), there are widespread concerns that pre-service teachers "often do not gain a solid conceptual understanding" from traditional teaching methods. However these issues do not apply only to students enrolled in teaching degrees: many other scientists will teach at some stage in their careers: as teachers, tutors, demonstrators or lecturers. Sound conceptual understanding is arguably important for all scientists.

Literature

Effective learning in laboratories

The most frequently cited problems with student learning in science and physics laboratories are lack of meaningful discussion and engagement, with students focusing on completing a list of tasks without necessarily understanding them; and failure to link experimental practice to underlying theory and concepts (Aufschnaiter & Aufschnaiter, 2007; Domin, 2007; Mestre, 2001). Cox and Junkin III (2002) specifically set out to tackle misconceptions in the laboratory. Their strategy for increasing cognitive engagement in introductory physics laboratories was based on the Peer Instruction methods of Mazur (1996). Multiple-choice conceptual questions were integrated into the laboratory manual and groups of students who had chosen different answers were directed to discuss their ideas before continuing with the procedure. Pre- and post-tests revealed a difference in learning gain of 50% to 100% between experimental groups and control groups, who had answered the conceptual questions individually but had not discussed them in groups.

Cognitive Overload as a barrier to effective learning in laboratories

Domin (2007) notes that the excessive amount of information in "cookbook" laboratory manuals and the task of separating relevant information from extraneous content often imposes considerable demands on students' working memory, leading to overload. Cognitive Load Theory (CLT) asserts that humans have essentially unlimited long-term memory but a limited working memory, which can process typically no more than four elements at a time. These limitations apply to novel information, but when information is successfully transferred into long-term memory, large amounts can be handled as one element in working memory (van Merriënboer & Sweller, 2005). If too much novel information is presented at once, working memory becomes overloaded and effective learning fails to occur (Sweller, 1994). Cognitive load can be characterised as intrinsic, ie: imposed by the nature of the information to be

learned, extraneous, ie: imposed by the format of instruction and unrelated to the information to be learned, and germane, ie: imposed by the format of instruction but relevant to learning (Paas et al., 2004). Research associated with CLT suggests that extraneous cognitive load can be reduced through appropriate design of learning materials (Chandler & Sweller, 1991; Purnell et al., 1991). As our project involved adding extra background information and Peer Instruction activities, we needed to take something out. By applying Cognitive Load Theory to the format of the manual we hoped to reduce extraneous cognitive load enough to compensate for the increase in germane cognitive load imposed by our modifications.

Peer Instruction

Cox and Junkin III's (2002) approach had the potential to meet a number of our project's objectives. Firstly, Peer Instruction has proven effective as a technique for overcoming misconceptions in physics (Crouch & Mazur, 2001; Fagen, Crouch & Mazur, 2002; Mazur, 1996; Mulhall, 2006). It involves students answering mostly qualitative, multiple-choice questions then discussing their responses with other students until they agree on an answer. Secondly, it requires students to discuss and defend their understanding, thereby helping to build confidence in communicating. Interactive engagement (Thacker, 2003), and the construction and peer evaluation of qualitative arguments (Mestre, 2001) have been recommended as strategies for enhancing conceptual understanding. Cox and Junkin III (2002) assert that peer instruction improved their students' critical thinking and communication skills. Appropriate concept questions are unambiguous and target key concepts; they should not be solvable by resorting to formulae or memory; and 35% to 70% of students should answer them correctly at first attempt. Multiple-choice questions reduce the time spent wording answers, and distractors should involve common misconceptions, such as those previously observed in student work (Cox & Junkin III, 2002; Crouch & Mazur, 2001; Mazur, 1996). Berry, Mulhall, Gunstone and Loughran (1999) suggest that predicting the outcome of experiments increases cognitive engagement. Cox and Junkin III (2002) required their students to make predictions, describe their observations or explain observations and results. According to Mestre (2001), it is important for prospective teachers to learn about the process of science, "using equipment to design experiments and test hypotheses", but research casts doubt on the effectiveness of such discovery-based approaches (Domin, 2007; Kirschner, Sweller, & Clark, 2006). However, the inclusion of concept questions about experimental aims, hypotheses, choice of apparatus and experimental design is anticipated to increase students' understanding of science as a process.

Methods

Syllabus Mapping

Syllabus mapping was carried out to identify areas of correspondence between prescribed practical investigations in the NSW year 11 / 12 physics syllabus and our first year experiments. Three experiments were selected for the study: using a resonating air column to determine the speed of sound in air (experiment 13); electrical properties of a photocell (experiment 18); and internal resistance of voltmeters and ammeters (experiment 21).

Consultation

One of our aims was to help pre-service teachers learn to use apparatus and methods which they would be using in their future careers. Therefore it was important to understand how the practical investigations corresponding to our modified laboratories are actually carried out in schools. Three experienced physics teachers participated in interviews to discuss their approach to teaching the investigations; problems they had encountered; possible alternative procedures; the reasons for their choice of procedure; and impact of the investigations on students' understanding. The first author is also an experienced former high

school teacher and has carried out the relevant investigations in a number of schools. Two investigations were carried out as we had expected and involved similar equipment to that used in our laboratories. However the third investigation was substituted by one that we considered lacked validity. The teachers made this substitution because concepts beyond the scope of the syllabus were required in order for students to understand the prescribed procedure. We had stated at the outset that modification of our experiments would only take place if we were satisfied that the procedures were sufficiently valid. Therefore we decided not to modify this experiment but to provide background and scaffolding to help pre-service teachers to carry out the investigation in schools.

Reformatting the laboratory manual

Strategies to overcome misconceptions and enhance communication skills

Our small cohort of ten students meant that organising students into groups for discussion did not require software such as that used by Cox and Junkin III (2002). Questions were inserted at points in the experimental procedure where key concepts appeared, or where past research (Driver, 1985; Gilbert, 1977) suggested that misunderstanding was likely to occur. Mazur (1996) recommends allowing up to four minutes for student discussion, so no more than five questions were incorporated into each experiment.

Application of Cognitive Load Theory to the laboratory manual format

We met with John Sweller (4th June 2010, University of Wollongong), originator of Cognitive Load Theory, to validate our approach to re-formatting the laboratory manual. We initially focussed on the split-attention effect (Purnell et al., 1991), where Cognitive Load is generated by the need to mentally integrate diagrams and text that cannot be understood separately. For the first modified experiment (the speed of sound) we removed a set of diagrams representing apparatus not involved in the procedure. We enlarged the remaining diagrams and integrated explanatory information and formulae onto them, taking this from paragraphs on the facing page. Information on the end correction, which had been spread over three sections and two pages, was integrated into one labelled diagram. A written description of the procedure for determining the speed of sound by graphing the data was replaced with a labelled exemplar graph. Instructions for using an oscilloscope, consisting of a photograph with all the controls numbered and paragraphs explaining the function the numbered controls, were replaced with one labelled diagram showing the function only of the controls required for the procedure. Part of the instructions for experiment 18 illustrating these principles is given in Appendix 1.

Background and linking theory to experiment

Each of the modified experiments included references to the related practical investigation in the NSW year 11 / 12 syllabus. For the first experiment we added diagrams representing longitudinal and transverse waves and the generation of standing waves through reflection and superposition. Again, diagrams were labelled with the information needed to understand them. The diagrams of standing waves in pipes were altered to correspond more closely with the actual apparatus and procedure. The formulae supplied in the manual were re-arranged to correspond with the formulae used in calculations.

Evaluation of the project

Because of our small cohort it was not feasible to run experimental and control groups. However, to increase the credibility of our results through triangulation, evaluation involved comparison of student responses to concept questions before and after discussion, observation of student interactions during the laboratories, a focus group with participating students and statistical comparison of participants'

laboratory marks with those of the students doing unmodified experiments in the mainstream laboratories. Ethics approval and participant consent was obtained for teacher interviews, modifications and data collection from students.

Results and discussion

Statistical analysis of laboratory marks

Participants' laboratory report templates were marked by demonstrators in the main first-year laboratories, to satisfy ethics requirements and enable statistical comparison of participants' scores with those of students using unmodified instructions. Participants' performance was compared with that of students in the mainstream laboratories whose work had been marked by the same demonstrator for a total of six unmodified experiments and three modified experiments. It should be noted that the experimental and control groups belonged to two different cohorts and that a number of differences between the cohorts may have acted as confounding factors. The experimental group were enrolled on a Bachelor of Science Education degree while the control group were BSc and BEng students and the UAI (University Admissions Index) for the two groups were likely to be significantly different. Further, the control group worked in the large first year physics laboratories on the main campus while the experimental group worked in a small general-purpose laboratory on a satellite campus and used slightly different apparatus for some experiments. However, as detailed below we found no statistically significant difference between the scores for the two groups, so it does not appear that the different degree intentions, possible UAIs and working conditions of the two groups were reflected in their laboratory scores.

We pooled scores for the modified laboratories (experiments 13, 18 and 21) and unmodified laboratories (experiments 12, 17, 22, 24, 25). To determine the correct statistical test we performed Bartlett's test for inequality of variance between the experimental and the control group. For the modified laboratories, this was statistically significant ($F=10.69$, $df=1$, $p < 0.01$), ie: the variance of the control and experimental groups was unequal. For the unmodified laboratories this was not statistically significant ($F = 2.12$, $df=1$, $p > 0.05$), ie: variance between the control and experimental groups was equal. Therefore the correct statistical test for the modified laboratories is the independent sample t test, with unequal variance assumed, and for the unmodified laboratories, the independent sample t test with equal variance assumed.

One tailed t tests (null hypothesis that the mean score for the experimental group was less than or equal to the mean score for the control group) were carried out. Neither showed any statistically significant differences (modified laboratory: $t=0.62$, $df=73.6$, $p > 0.05$, mean score experimental group 7.91, 95%CI=7.44-8.38, mean score, control group: 7.79, 95%CI=7.56-8.01; unmodified laboratory: $t=1.50$, $df=439$, $p > 0.05$, mean score experimental group = 8.04, 95%CI=7.77-8.32, mean score control group: 7.82, 95%CI=7.71-7.93).

The lack of statistical significance was unsurprising given the small sample size of the experimental group ($n=10$): in order for a statistically significant difference to be detectable, the difference between control and experimental scores would have had to be very large. A recommendation of this study is that the research be repeated with a larger experimental group in order to provide a more sensitive measure of improvements in students' scores. However, improvement in laboratory scores was not anticipated to be the most important measure of evaluation of the project, which sought primarily to enhance students' conceptual understanding and communication skills. These were evaluated through observation of, and discussion with the students themselves, and are described below.

Participant observation and feedback

Summary of concept question results

Table 1 shows the number of correct responses to each concept question before and after group discussion. The concept questions for the three experiments are given in Appendix 2.

Table 1: Summary of Students' responses to concept questions before and after group discussion

<i>Expt</i>	<i>Q.</i>	<i>% of participants correct before discussion</i>	<i>% correct after discussion</i>	<i>Notes</i>
13	1	30	100	Two participants referred to the introduction document during discussion and inferred the correct answer.
13	2	0	100	Correct answer explained by researcher
13	3	-	-	Not completed due to lack of time
18	1	30	60	Group members who initially chose the correct response were persuaded to change their response by more confident members
18	2	100	-	
18	3	None incorrect		Not all students recorded an individual answer
21	1	30	N/A	Free response question
21	2	60	N/A	Free response question. Two participants did not record an answer
21	3	60	N/A	Tested the same concept as question 2
21	4	70	N/A	The answer to this question was given in a diagram immediately above the question
21	5	90	N/A	Four students answered this question after asking the researcher about part of the procedure that related to the same concept, suggesting that they had been unsure about the concept. This would bring the total of initial correct responses down to 50%

These results confirm the value of concept questions in identifying student misconceptions, and show that misconceptions were widespread among participants. Although initially reluctant to interrupt their experiment, participants evidently enjoyed their discussions, reflected on their ideas and worked cooperatively to construct understanding. Misconceptions that may have gone unnoticed were voiced and challenged. However when discussing a specific incident during the focus group participants vividly recalled frustration with the interruption but not overcoming the misconception. They felt they had benefited from answering concept questions, but suggested that time should be set aside for this at the start of the lab, in order to check for misunderstandings and reinforce comprehension, without distracting them from carrying out the procedure. Participants appeared to achieve better individual results for concept questions in the second modified experiment; however as not all recorded an answer for the third question the results for this question are not known. Concept questions initially answered correctly by all students were obviously insufficiently challenging; however these were based on misconceptions observed to be common among students in the mainstream laboratories. This anomaly could be due to the small sample size of the participant group.

Experiment 13

Mazur (1996) recommends piloting questions to ensure an appropriate level of difficulty. This was not possible; however before working with the participant group, the researcher assisted several hundred

students with the same experiments in the mainstream laboratories, thereby gaining insight into the most common misconceptions and the parts of the procedure that caused most difficulties. This experience informed the development of the concept questions, modified instructions and preparatory materials. Students' discussions provided insight into their thinking and confirmed conclusions drawn from concept question responses. For example, one student explained her reasoning for question 1:

“Doesn't air pressure increase as you go further down in water?”

This would be true if no sound wave was present, suggesting that she had not made the conceptual link between sound waves and variations in pressure.

One participant stated that discussion of a concept question had “clarified things a lot”, but was not able to apply this new knowledge when writing the conclusion. New information requires rehearsal in order to be incorporated into long-term memory, so although students may understand a new concept during a lab, this new knowledge will quickly be lost unless it is rehearsed. The second question was answered incorrectly by all participants so the demonstrator explained the correct answer and participants expressed satisfaction with their understanding of it. However, only 60% correctly answered a similar question in the results section and only 20% gave answers suggesting sound understanding, implying that the newly-acquired knowledge had not entered long-term memory. Questions for the first experiment appeared to be too difficult, based on Mazur's (1996) recommendations for writing concept questions.

Discussion of concept questions took significantly longer than anticipated and the third and final question was not discussed due to pressure of time. It was thought that this was caused by difficulties with apparatus; however pressure of time turned out to be a recurring problem for the participants during both modified and unmodified laboratories. The calculation section had not been modified to reduce cognitive load as we had focussed on reducing the split-attention effect in diagrams. Adding a worked example of the calculation and ensuring that all necessary formulas were supplied at the point of use, even if this meant repetition, would have reduced cognitive load. It should be noted that participants had not studied the topics before laboratories and were unfamiliar with the graphical methods used, so the intrinsic cognitive load was very high.

Findings from the first modified experiment and participant feedback were used to inform modification of the next two experiments. Cognitive Load Theory was used both for formatting diagrams and in providing worked examples for calculations to further reduce the cognitive load of the instructions. All formulae were presented at the point in the instructions where they are to be used, to reduce the cognitive load imposed by flicking through pages (Chandler & Sweller, 1991).

Experiment 18

The first concept question involved relating a graph to its equation. This concept depends critically on mathematical understanding: an area with which students consistently struggled. Although group discussion did result in an increase in the number of participants answering correctly, some groups did not arrive at the correct answer and one group expressed a desire to change their correct response to an incorrect one which had been chosen by another group. This was due to the influence of more confident participants who were seen by others as more knowledgeable. This suggests that group discussions guided by strong personalities may fail to result in improved understanding, and therefore that care needs to be taken when assigning students to groups. When the groups were asked to justify their choices they were unable to do so, and their misunderstanding was revealed. This underlines the importance of

requiring students and groups to justify and defend their choice of response, as this process should help to prevent group choices being based on personalities rather than conceptual understanding.

All participants answered question 2 correctly, so by Mazur's (1996) standards this question was not challenging enough. However, this question related to the same concept as the first question so it is unsurprising that, following extensive discussion of the concept, they were able to answer correctly. When a concept is particularly challenging it may be useful to include multiple concept questions to allow students to rehearse new knowledge gained through discussion. Further, answering correctly boosted the participants' morale; this in itself may justify its inclusion.

Experiment 21

The approach for the third modified experiment was altered based on findings from the previous two modified laboratories and feedback from the focus group, which immediately preceded it. A larger number of concept questions were included; some testing the same concept and all focussed on the experimental procedure. As one participant explained:

[what's important is] "knowing how to set up the experiment because what you're supposed to learn from the experiment is the concepts, so if you know [the procedure], you'll find out the concepts later on"

Participants were not directed to discuss their responses in groups because of the burden of time imposed by previous discussions; instead they recorded their results with the researcher who provided feedback and clarification. The two open-response and three multiple-choice questions were based on misconceptions expressed by students in the mainstream laboratories.

Writing experimental conclusions

Participants identified writing conclusions as the second most significant recurring problem, after shortage of time. Although there are guidelines in the laboratory manual on writing conclusions, participants did not use them, and no student in the mainstream laboratories was observed using them. It is suggested that the cognitive load imposed by looking these up, interpreting and applying them involved makes them unusable. For the final modified experiment, participants were provided with a set of stimulus questions for the conclusions. Participants read these, asked for clarification with one of them and stated that they had found them helpful. Participants claimed that the experimental instructions did not usually include an aim and that this made writing conclusions more difficult:

"How are we supposed to conclude something when we don't know what we're aiming at?"

Two experimental aims were given in bullet-point format in the instructions for experiment 21; participants reported that they found this useful and would like to see this in all laboratories. However, all the experimental instructions begin with a statement of objectives. It was observed that students, both participants and nonparticipants, frequently asked for information already in the instructions. Therefore, it seems likely that by simply presenting the information in bullet-point format, the participants' attention was drawn to it.

Conclusions

The very small sample size means that for any difference in marks to be statistically significant, the effect would have to be large. As no statistically significant difference between marks for modified and non-modified laboratories was detected, any improvement was small. In order for students to learn

effectively, the total cognitive load of the task must not exceed a manageable level (Chandler & Sweller, 1991). It was apparent, both from direct observation of participants and from feedback during the focus group, that the cognitive load imposed by all the laboratories was extremely high:

“It’s frustrating: we don’t get time to think about all the concepts”
“We’re nearly always confused. That’s why we call for [the demonstrator]”.

As the semester progressed it became apparent that the participants experienced considerable cognitive overload during the majority of laboratories. It is suggested that the changes to format did not decrease net cognitive load enough to counteract the incorporation of Peer Instruction combined with the very high intrinsic cognitive load of the laboratories. Further, both direct observation during laboratories and focus group comments showed that participants resented being interrupted while they were working on an experiment and perceived the extra cognitive load imposed by peer instruction:

“They made everyone angry because we wanted to get our lab done which was being marked ... and they usually came at the most frustrating point in the experiment when we couldn’t get things to work, and we’ve got to take the time out and you can’t just stop in the middle of what you’re doing, while your brain is thinking of something else”.

Cox and Junkin III (2002) found significant benefit from incorporating peer instruction into their laboratories; our study has not replicated this. There are a number of possible reasons for this inconsistency. Cox and Junkin III’s participants may have had content covered in lectures prior to laboratories, and so would have been more familiar with concepts, reducing their cognitive load. Their laboratories may have run for three hours rather than our two: our participants identified time as their most significant recurring problem. Cox and Junkin III did not mention how many concept questions they incorporated and how many of these were actually discussed in groups: they may not have attempted discussion of more than one or two questions.

Even though the reformatting of the instructions failed to bring the participants’ cognitive load to manageable levels, it seems that the changes were a step in the right direction. Participants were not able to directly compare modified and unmodified instructions as they did not see both sets of instructions for any one experiment, but participants voiced a preference for format that corresponds to elements of CLT:

“A page of instructions does not help at all. You can’t take it all in at once”.
“Do it step by step – bullet points would be best”
“it’s not the experiment that takes a lot of time; it’s figuring out what you’re supposed to be looking at or writing down”
“Diagrams, not paragraphs [are clearer] It’s like – wow, there’s a big paragraph in front of me”.

Recommendations

CLT

Although this study did not set out explicitly to compare students’ performance using CLT-modified and unmodified instructions, participants voiced strong preference for the CLT format, particularly the replacement of paragraphs of text with labelled diagrams and the provision of worked examples. However, care must be taken in applying these principles because minimising cognitive load is not a trivial task. Additionally, if students received more thorough preparation during pre-laboratories, it might be possible to reduce the amount of material in the instructions correspondingly. This would in turn

reduce the cognitive load imposed by reading them and allow students more time to concentrate on carrying out the procedure.

Peer instruction

Given that high cognitive load is likely to be a common problem in laboratories, activities such as peer instruction that increase cognitive load should be avoided during the experimental procedure, even if intended to contribute to learning. However, observation revealed that misconceptions were common, so including concept questions in laboratories has value. If students complete a laboratory without having misconceptions challenged they are likely to misinterpret their data in order to make it fit their misconception, and fail to benefit from the laboratory.

Incorporation of concept questions and demonstrator feedback before students begin the experimental procedure is suggested for effectively uncovering misconceptions without imposing excess cognitive load during laboratories. Should these questions contribute to the laboratory mark, and if so how should they be marked? Participants indicated during the focus group that when their workload is high, they do not expend effort on activities that do not attract subject marks. If marks were only given for a correct answer, students would be more likely to collaborate to find the correct answer. This could have the undesired consequence of some weaker or less motivated students copying the answer without trying to understand it. However, if marks were awarded for participation, ie: for any answer whether correct or not, then less motivated students would be likely to submit any answer in order to be able to move on. However, submission of an incorrect answer would mean discussion with the demonstrator and less time to complete the experiment. More research will be required in order to determine the best method for administering these concept questions. As stated before, students need to rehearse new knowledge. This could be achieved by having students summarise their reasons for changing their answer to a concept question, although again this would require time.

As described above, peer instruction failed to result in improved understanding when participants were unduly influenced by more confident individuals. In order to minimise this risk, care needs to be taken when assigning students to groups: it is suggested that more confident students be grouped together and less confident individuals grouped together. It is also important that peer instruction activities follow the format described by Mazur (1996) and that groups are required to justify and defend their choice of response with reference to relevant scientific principles.

Writing experimental conclusions

To reduce the cognitive load imposed by looking up the conclusion-writing guidelines, stimulus questions can be provided to help students write their conclusions. These can include both generic advice about summarising results, discussing sources of error and suggesting improvements; and suggestions relevant to specific experiments. Students could be directed to discuss these questions in groups: this would be unlikely to impose an additional burden of time because participants spent a significant amount of relatively unproductive time on writing conclusions. As noted previously, students need to rehearse new knowledge before they can use it; therefore repetition of new concepts and scaffolding to help students apply them are recommended.

Long-term retention of new knowledge

One key aim of this study was to enrich the learning experience of pre-service teachers. However, participants said they did not generally think about the experiments after leaving the laboratory. Reasons for this include the fact that they are not subsequently assessed on their understanding of experiments but

there is compelling evidence that cognitive overload is hindering participants' ability to retain and transfer understanding into long-term memory:

“As soon as I leave I forget everything we did. It's because we have such a short amount of time, we rush through it all and get out and it's like “what just happened?”

According to Cognitive Load Theory, information cannot be transferred into long-term memory unless rehearsed (Sweller, 1994). Therefore, in addition to further reducing cognitive load during the laboratories, content should be revisited after the laboratories. This could take the form of an online post-lab either after each lab or at the conclusion of a module, or during time set aside at the start of the following laboratory.

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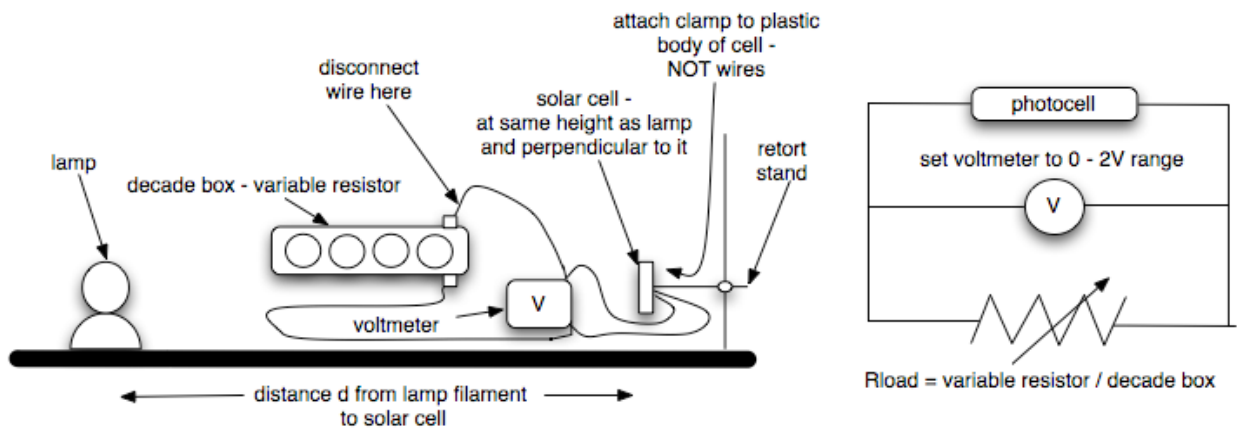
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Appendix 1 - Application of Cognitive Load Theory in Experiment 18

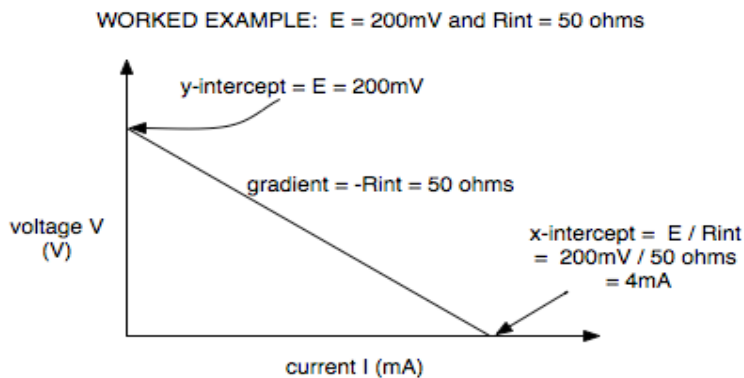
The following section of the laboratory manual illustrates the principles of integrating information onto diagrams, and the provision of worked examples for calculations.

Experimental instructions

1. Place the lamp in the middle of the bench. Clamp the solar cell to the retort stand on one side of the bench facing the cell. The cell should be at the same height as the lamp filament and perpendicular to it. Clamp the photocell by its plastic case, not by the wires. The set-up is shown below:



2. On the graph of V versus I , draw in the line you would expect for a simple-model power supply where:
 $E = 300\text{mV}$ and $R_{\text{int}} = 100$ ohms. Here is a worked example to help you:



Appendix 2 – Concept questions

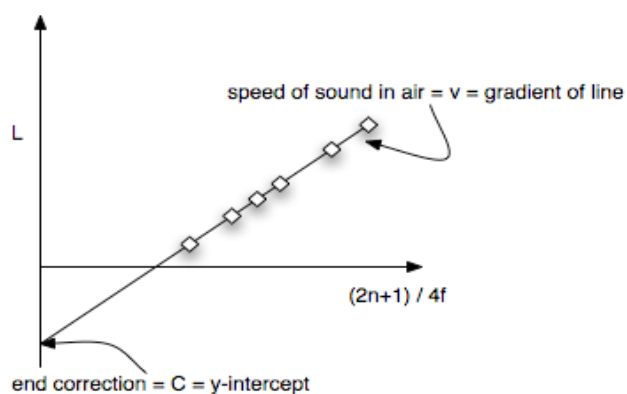
Experiment 13

Concept question 1:

At the point in the tube where the air column meets the water, the air pressure is:

- A at a maximum
- B at a minimum
- C varying between maximum and minimum values
- D constant

Concept question 2:



The data points from the two tuning forks will lie:

- A on the same line
- B on two parallel lines
- C on two lines that are not parallel but intersect
- D on two lines which are not parallel and which do not intersect

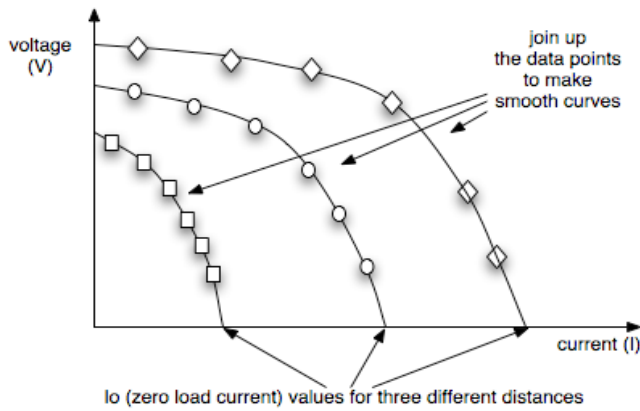
Concept question 3

The nodes for the higher frequency tuning fork will occur:

- A closer together than those for the lower-frequency tuning fork
- B further apart than those for the lower-frequency tuning fork
- C the same distances apart as the lower frequency tuning fork, but all closer to the top of the tube
- D the same distances apart as the lower frequency tuning fork, but all further from the top of the tube

Experiment 18

Question 1



The gradient of the graphs of V (on the y-axis) against I (on the x-axis) is the:

- A EMF of the source, E
- B the load resistance, R_{load}
- C the internal resistance, R_{int}
- D the power, P supplied to the load

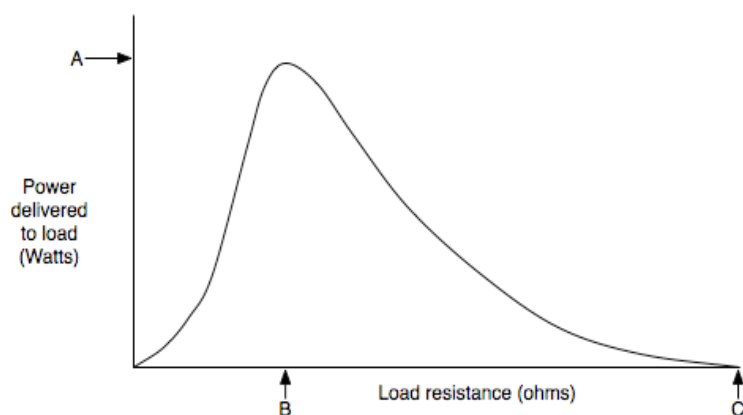
Question 2

For the simple model for internal resistance, with $V = E - IR_{\text{int}}$, a graph of V (on the y-axis) against I (on the x-axis) would have:

- A a straight line
- B a constant gradient
- C a y-intercept of R_{int}
- D both A and B
- E both B and C

Question 3

The following graph shows power plotted against load resistance for a power supply connected to a load resistance.

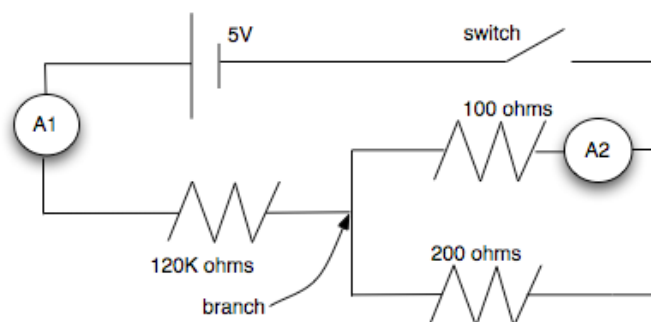


The internal resistance of the power supply is:

- A B C D can't be determined from this graph

Experiment 21

Questions 1 and 2 refer to the following diagram:



Question 1

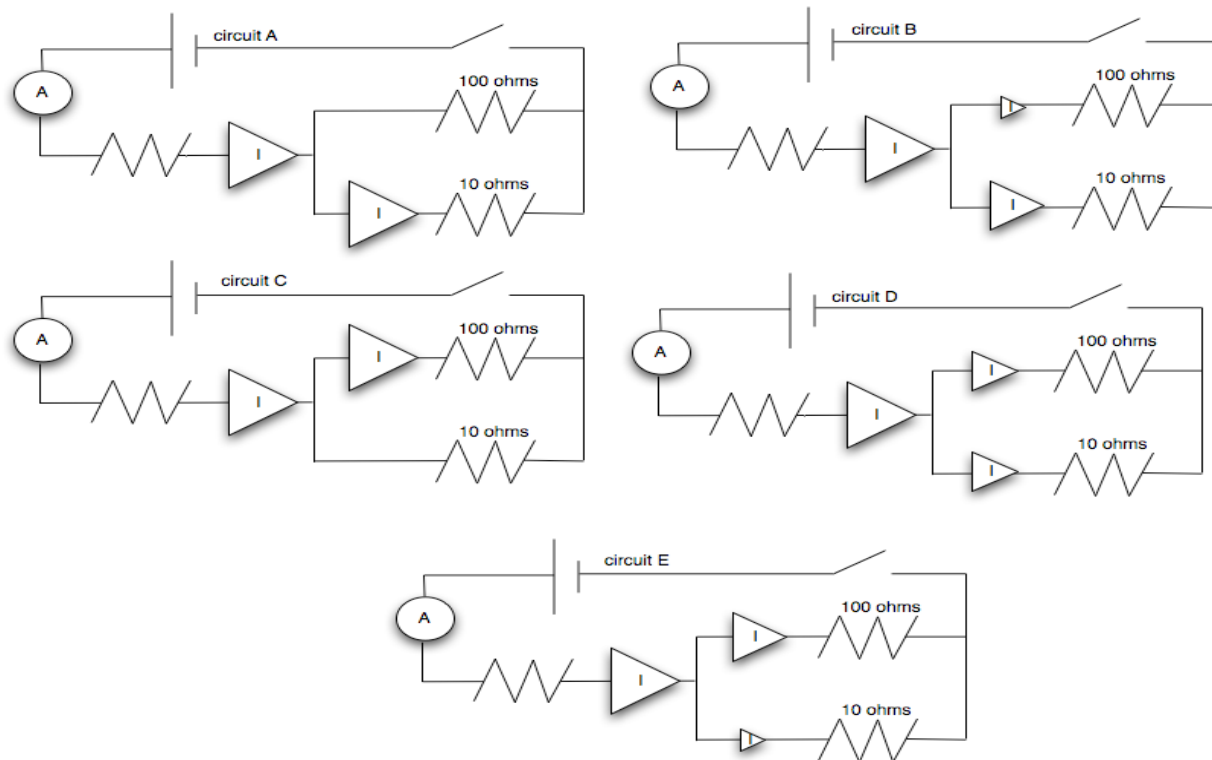
Which resistors do you need to consider when calculating the current in A1?

Question 2

What does the current do when it comes to the branch?

Question 3

Which of the following circuits best shows where the current (represented by arrows) goes when it meets the parallel section of the circuit?

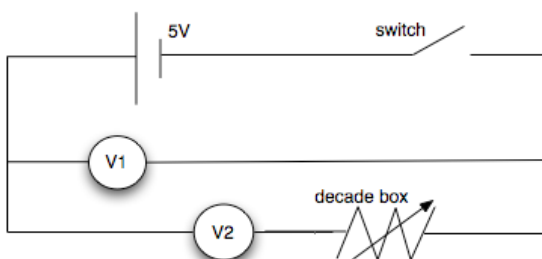


Question 4

When the resistance of the decade box equals the internal resistance of the ammeter:

- A A2 will read the same as A1
- B A2 will read twice A1
- C A2 will read half A1
- D A2 will read zero

Question 5



When the resistance of the decade box equals the internal resistance of the voltmeter V2:

- | | | | |
|---|------------------------|---|----------------------|
| A | V2 will equal V1 | C | V2 will read zero |
| B | V2 will read double V1 | D | V2 will read half V1 |