Enhancing Student Learning and Conceptual Understanding of Electric Circuits

Author

David Smith B.Sc. (Hons)

Thesis submitted to Dublin City University for the degree of

Doctor of Philosophy

School of Physical Sciences
Centre for the Advancement of Science Teaching and Learning
Dublin City University

September 2009

Research Supervisor

Dr. Paul van Kampen

Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy is entirely my own work, that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: __________________________

(Candidate) ID No.: __________________________

Date: __________________________

To My Family

Table of Contents

Abstract

Enhancing Student Learning and Conceptual Understanding of Electric Circuits

David Smith

Dublin City University

Prior research has highlighted that students have many conceptual difficulties regarding electric circuits and that traditional teaching methods are not successful in overcoming these difficulties. In addressing this issue, this research project placed its primary focus on the development of research based and research validated curriculum which systematically promotes the development of a scientific model for electric circuits.

Over the last four years, the project focussed on developing and assessing two separate inquiry based electric circuits curricula. The first curriculum was implemented in an electric circuits module for pre-service science teachers and addressed the concept of voltage in a variety of contexts, including multiple batteries in multiple loops and RC circuits. This thesis details how the curriculum addressed the concept of voltage qualitatively and how it helped students resolve their difficulty in differentiating between voltage and current. The research also highlighted a number of newly identified difficulties pertaining to these topics.

The second curriculum was implemented in a lab-based module for non-physics undergraduates. The investigation of students' conceptual understanding of dc circuits along with the process of adapting inquiry based curriculum to an undergraduate laboratory setting is discussed. The comparison of pretest and post-test data in both modules has shown that through the use of this curriculum the majority of students have improved their conceptual understanding of many electric circuits concepts.

Acknowledgements

Over the past four years, many people have made contributions to my work but none as significant as that made by my supervisor, Dr. Paul van Kampen. From the very beginning of my post-graduate, Paul has given continual guidance and support and has been both a friend as well as a supervisor. I can say with confidence that this project would not have been completed without his input and his continuing effort to work tirelessly on providing direction to my project. I wish him the best over the coming years and hope that this is only the beginning of our collaboration both on a professional and social basis.

My post-graduate experience would not have been the same, if it wasn't shared with my undergraduate classmate, Tommy Wemyss. The tradition of spending countless nights studying for undergraduate exams continued during our post-graduate work and things always seemed easier working with a friend.

Many others from the School of Physical Sciences at DCU have been very helpful. I would like to thank Head of the School, Prof. John Costello, for his support throughout the project. A large amount of thanks must be paid to Mike Aughey, Conor Farrell and Paddy Browne for all their help and patience in the redevelopment of the first year undergraduate laboratories. I am also grateful to Eilish McLoughlin for all her help and encouragement in my transition to post-graduate level. Lisa Peyton, Des Lavelle, and Pat Wogan were always supportive when I asked for help.

I would like to acknowledge the support and advice provided by Conor Sullivan, James Lovatt, John McLoughlin and Lorraine McCormack. I am grateful to all the Science Education students who worked through the curriculum and being some of the most valuable critics.

I must thank the Irish Research Council for Science, Engineering and Technology for providing financial assistance over the large part of my project. Thanks also to the School of Physical Sciences for providing financial support in the latter stages of the project.

Much thanks must go towards Dr. Andrew Crouse, Prof. John Thompson, Roger Feeley, and the Physics Education Group at the University of Washington for putting their trust in my curriculum and offering invaluable feedback during its development.

I am forever indebted to my family and friends who have provided great support over the last four years. My parents, Patrick and Regina have provided unconditional support and always encouraged any direction which I chose to take. Thanks to my brothers Neil and Barry for their support and humour and to my sister Sinéad, for her friendship and for playing a huge guiding role throughout my entire education. To Edelle for being there to listen and for always providing encouragement when I needed it. Finally, a large thank you to my friends, Paddy, Tony, Peter, Eugene, Brian and Paul and many others for all the good times and for putting up with my student lifestyle for so long!

List of Conference Presentations

Oral Presentations

- GIREP International Conference 2008
  MPTL 13^{th} Workshop, August 18^{th} - 22^{nd}, Nicosia, Cyprus
  Teaching Electric Circuits in First Year Undergraduate Laboratories

- AAPT Winter Meeting 2009
  February 12^{th} - 16^{th} Chicago, USA
  Teaching Electric Circuits in First Year Undergraduate Laboratories

Workshops

- GIREP International Conference 2008
  MPTL 13^{th} Workshop, August 18^{th} - 22^{nd}, Nicosia, Cyprus
  Focusing First Year Undergraduate Physics Labs on Constructing Knowledge and Understanding Science

- The Physics Higher Education Conference 2006
  September 7^{th} - $8t^{h}$, Leicester, UK
  Teaching Electromagnetism Through Guided Enquiry

Poster Presentations

- SMEC 2008
  September 11^{th} - 12^{th}, Dublin, Ireland
  Teaching Electric Circuits in First Year Undergraduate Laboratories

- SMEC 2006
  September 18^{th} - 19^{th}, Dublin Ireland
  Teaching Electric Circuits through Guided Inquiry for pre-service teachers

- *IOP Spring Weekend 2006*
  April 8^{th} - 9^{th}, Donegal, Ireland
  Teaching Electric Circuits through Guided Inquiry for pre-service teachers

- IRCSET Symposium 2005
  November 17^{th}, Dublin, Ireland
  Teaching Electric Circuits through Guided Inquiry for pre-service teachers

List of Figures

List of Tables

Chapter 1

Introduction

Research on student understanding of electric circuits has taken place over a large number of years[1,2,3], most of which has involved students at primary and secondary level. The research at university level has largely involved students in introductory physics courses and pre-service science teachers. Out of this research two main instructional strategies have evolved. Both strategies separate the concepts of voltage, current and resistance. One deals with voltage as the primary concept; the other, current. The work presented here follows the latter strategy. It is largely influenced by the work carried out by the Physics Education Group at the University of Washington (UW). Both my work and that of UW follow a single iterative process whereby research, curriculum[†] development and instruction are carried out side by side[1]. Two separate inquiry based electric circuits curricula were developed using this cyclical process.

The first part of this thesis deals with the investigation of students' understanding of the concept of voltage and how the findings of this research guided curriculum development. The curriculum was implemented in an electric circuits module for pre-service teachers taking a degree in Science Education at Dublin City University (DCU). It is a revision and extension of the voltage curriculum published in Physics by Inquiry[4] (PbI) for pre-service teachers. The efficacy of the curriculum is discussed through the comparison of pretest and post-test data.

The electric circuits curriculum is divided out over a second year and third year module. The second year module focusses on the concepts of current and resistance. The published version of PbI[5] was used in this module. Analysis of pretest and post-

[†] The term curriculum refers to instructional or educational materials. The term module refers to a set of lectures or labs taken by students.

test data is discussed in Chapter 3 to serve as a prelude to the electric circuits module on voltage. The third year module focusses on voltage. Chapter 4 describes the changes that were made to the published PbI voltage curriculum. Extension of the PbI curriculum to incorporate multiple batteries in multiples loops and RC circuits is discussed in Chapters 5 and 6 respectively.

The second part of the thesis is concerned with the development of three electric circuits labs for first year non-physics undergraduates. Prior to this redevelopment, all students were given traditional 'cook book' style labs regardless of their background. The analysis of students' opinions of the labs revealed that the majority did not find the labs interesting, found the lab manual difficult to comprehend and felt that the labs did not reinforce lecture material. On the basis of these results, a new set of labs was developed to improve students' conceptual understanding and to increase their level of enjoyment. Discussion of the three labs on current, resistance and voltage is carried out in Chapters 7 and 8.

References

1. L. C. McDermott, P. S. Shaffer, *Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding,* Am. J. Phys. **60** (11), 994-1003, 1992. Also see companion article, L. C. McDermott, P. S. Shaffer, *Research as a guide for curriculum development: An example from introductory electricity. Part II: Design of instructional strategies,* Am. J. Phys. **60** (11), 1003-1013, 1992.
2. R. Cohen, B. Eylon and U. Ganiel, *Potential difference and current in simple electric circuits: A study of students concepts*, Am. J. Phys. **51** (5), 407-412, 1983.
3. See examples from R. Duit, W. Jung and C. v. Rhöneck (eds.), *Aspects of Understanding Electricity. Proceedings of an International Workshop*, Ludwisburg, IPN, Kiel, 1984.
4. L. C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry vol II*, 430 - 454, Wiley, New York 1996.
5. L. C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry vol II,* 383 - 429, Wiley, New York 1996.

Chapter 2

Research Context

The recognition of the limitations of traditional teaching methods is one of the key factors that motivates physics education research. Over the past number of decades, research in this area has highlighted these limitations and the need for the improvement of physics teaching[1,2,3]. Based on the experience of more than three decades across all topics typically covered in an introductory physics module, these limitations were summarised by McDermott in the following statements[4].

(1) Facility in solving standard quantitative problems is not an adequate criterion for functional understanding.
(2) A coherent conceptual framework is not typically an outcome of traditional instruction.
(3) Certain conceptual difficulties are not overcome by traditional instruction.
(4) Growth in reasoning ability does not usually result from traditional instruction.
(5) Connections among concepts, formal representations, and the real world are often lacking after traditional instruction.
(6) Teaching by telling is an ineffective mode of instruction for most students.

Even though these statements are often met with scepticism by those not familiar with results of physics education research, the evidence is overwhelming[5]. Hence, the purpose of this project is not to confirm these statements but to use them as a guide in the development of our curricula.

2.1 Research Methods

The principal research method used in this project is that of the comparison of written pretest and post-test data. By analysing students' responses to questions before and after instruction, the development of students' conceptual understanding can be quantified.

In both the module for pre-service teachers and the module for first year non-physics undergraduates, a pretest consisting of one or several questions is administered to every student, before each new topic is covered in class. The pretest questions are concept based, cannot be answered from memory, and students complete them individually. Each pretest is designed specifically to identify the primary misconceptions related to the relevant topic. The identification of these difficulties is a key process in the development of effective curriculum. Pretests also compel students to commit to a particular answer or line of reasoning. This helps students realise where they have conceptual difficulties.

The curriculum is designed to further elicit student problems, confront the students with their difficulties and help the students to resolve them[6]. The efficacy is measured by pretest / post-test comparison. In both the pre-service teacher module and the first year undergraduate laboratories, students took two post-tests. The first test was taken half way through their course; the second at the end. Each post-test contains a number of unseen questions. The questions are similar to, but different from the pretest questions and are generally more difficult. Post-tests are given as exams which count towards the students final grade.

2.2 Instructional Context

All DCU students who used the curriculum for pre-service teachers and for first year undergraduate laboratories have taken science at secondary level. In the Irish secondary school system, science is taught at both the Junior Certificate and Leaving Certificate level. Junior Certificate (JC) Science is taken in the first three years of secondary school, when students are typically aged between 12 and 15 years. The course covers the three sciences of Physics, Chemistry and Biology. Each science is covered theoretically in equal amounts over four 40 minute classes each week[7]. However, in practice the teacher's area of expertise tends to dominate the time dedicated to each science. Since most secondary school science teachers are biology majors[8], many students spend less than one third of the time on physics. In our experience, many JC science teachers have a poor understanding of physics concepts and possess many of the same misconceptions held by their students[†]. Many concepts are treated superficially, and little time is devoted to scientific reasoning. These shortcomings are compounded by the large amount of content in the JC syllabus[9], meaning that material is covered so quickly that rote learning is the most likely outcome. The situation is, for example, similar in the US[10].

The Leaving Certificate (LC) is taken after the Junior Certificate over the final two years of the students' secondary school education. In each LC science course, the student focusses on one science subject only, with most schools offering Physics, Chemistry and Biology. A small number also offer Geology and Agricultural Science. It is possible for students to take more than one LC science subject, which many of our science undergraduates have done. In the LC physics course, many of the topics addressed in the JC science course are covered for a second time, albeit in somewhat more detail. It must be noted that, as in JC science, the emphasis is on content rather than concepts.

The lack of conceptual development in the JC and LC courses is generally driven by the assessment of both courses. At the end of each course, students sit a terminal exam, which for the LC students serves as the passage into third level[‡]. Many of the exam questions focus on recall and the manipulation of simple formulae, with essentially no probing of conceptual understanding. This ripples its way back into the classroom, where many teachers solely prepare students for the exam and thus focus on rote learning and practising quantitative problems. This is not only true in

---

[†] For example, during the 2008 DCU Summer School for in-service JC teachers, only 1 of 13 teachers chose the correct arrangement of a battery, bulb and a single wire while 6 stated that a single bulb was brighter than a bulb connected in parallel across a single bulb circuit. See Section 3.3.1 for pretest question.

[‡] The third level system in Ireland includes Universities, Colleges and Institutes of Technology.

the Irish education system. For example, similar cases can also be found in the US[9] and in the EU[11].

In the Irish University system, teaching methods are not dissimilar to those at secondary level. Little emphasis is placed on conceptual development, particularly in large (~ 250) introductory science modules. Typically neither tutorials, end-of-chapter problem solving, nor laboratories taken by non-physics majors are tailored to students' backgrounds. As a result many students attain very little understanding of the subject. The only concession to their backgrounds, was that the module was algebra based, as opposed to the calculus based module given to physics majors.

2.3 Context for Traditional Pre-service Teacher Preparation

As described above, the education of many science teachers in Ireland involves little or no emphasis on conceptual development. Until the start of the 21st century, science teachers would typically have taken a traditional science course, followed by a teaching certification course. The latter course contains general science education and methodology modules, but no discipline specific modules focussed on conceptual development.

In the early years of the Science Education degree at DCU, aimed at pre-service teachers, education and science modules were taught concurrently, but with little overlap. McDermott *et al* point out that this separation can decrease the value of both types of instruction for teachers[12]. Lectures, tutorials and labs were all taught in the conventional teaching-by-telling, cook-book way. As a result, many beginning student teachers leave university with the perception that physics is a large body of information that needs to be memorised, and not as a process of inquiry in which both teachers and students can participate[12].

Since 2005, however a number of modules have been introduced that focus on conceptual development, and simultaneously address issues on teaching the material. This focus on pedagogical content knowledge[13] has been achieved by introducing two, and at times three, PbI modules.

2.4 Changes in Pre-service Teacher Preparation

The introduction of PbI curriculum in pre-service teacher modules creates an environment where inquiry and investigation are central and confronts students with the nature of their understanding. This method relates to the essence of scientific research, where students are allowed to reason the truths of scientific laws through experimentation and interpretation of accumulated data. The method moves the focus from rote learning to developing students' understanding. Its success lies in the incremental learning process where students proceed through the concepts step by step, and in doing so builds a consistent and well-reasoned model of a specific physics principle or concept[6].

This process necessitates changes in the method employed by the teacher or instructor. In PbI, the teacher replaces lecturing with questions that guide and motivate students to reason and think logically about the physical concepts they encounter. In the classroom this is done through a check-out process whereby students write their name on the board when they are ready for a check-out which is signalled at a specific point in the curriculum. During the check-out the instructor will look over students' work and then ask questions on the material, being very careful to listen to students' reasoning and use of language. If a student uses incorrect reasoning or still has some misconceptions about the material, the instructor uses semi-Socratic dialogue to guide the student to the correct conclusion. The working of students in pairs promotes collaborative learning and peer tutoring, allowing students to share ideas, discuss different solutions and ideally work towards constructing a model, which will explain their observations and predictions about various concepts.

In the PbI modules for pre-service teachers, students' complete a number of homework exercises. Generally upon the completion of each section, students are given a problem which they have to complete in their own time. Each homework problem addresses the concepts of its relative section and requires the use of qualitative reasoning. Students' answers are graded by the instructor, paying careful attention to the use of reasoning in students' answers. Students who do not provide an answer that is supported by well thought out reasoning and based on observations from the classroom, are asked to resubmit their homework. Each homework counts towards the students' final grade.

The reasons for specialised courses for pre-service teachers are well documented (see examples by McDermott *et al*[12,14]). In many topics, there is evidence that traditional courses in physics do not provide the kind of preparation necessary for effectively teaching physics or physical sciences[12]. The lack of preparation stems from the inadequacies in traditional instruction outlined in sections 2.2 and 2.3. The specialised PbI modules for pre-service teachers replace an emphasis on superficial content knowledge for the deep understanding of a topic. This process allows the pre-service teachers to confront each of the difficulties they may have associated with the topic, allowing them to attain a deeper understanding than they might expect of their students. Teachers also become familiar with difficulties that others might encounter in the study of a particular topic or concept. These objectives can only be achieved if sufficient time is given to work through a process of inquiry where teachers not only understand the concept but also the line of reasoning used in attaining such understanding. The use of these methods where students learn in the context in which it is to be implemented is more effective that separating instruction in science and instruction in education[12]. It is proposed that these methods will not only deepen their level of understanding of physics principles but also have significant effects on their approach to teaching and student learning.

2.5 Context for Change to First Year Undergraduate Laboratories

Prior to 2005, physics laboratories for non-physics undergraduates at DCU were carried out in a traditional setting. The large majority of labs were styled on 'cook-book' instructions and focussed on the verification of known formulae. Traditional laboratories were implemented on a rotational basis and variation in difficulty was not obvious. The labs were pitched at a level for students who had completed physics at higher secondary level, however we find that only 25% of non-physics undergraduates have this level of experience. Moreover, little emphasis was placed on conceptual understanding and development of transferable laboratory techniques.

Students also reported that laboratories were not enjoyable although many students had looked forward to carrying out physics practicals before taking the labs.

To tackle these issues, a complete overhaul of the undergraduate laboratories took place. This included curriculum development for three electric circuits laboratories. The rotational structure of the laboratories was replaced by a linear structure where the difficulty of labs was increased incrementally. By the time students tackled the electric circuits labs, they had developed many laboratory skills and had become acquainted with inquiry based labs. The electric circuits laboratories added an element of model building. They focussed on the concepts of current, resistance and voltage; each concept is dedicated a single laboratory. The development of students' conceptual understanding was a key part in the curriculum design in conjunction with promoting students perception of physics and enjoyment of physics practicals. A detailed discussion is given in Chapter 7.

2.6 Project Outline

The first part of this project concerns itself with the revision of the voltage curriculum published in PbI[15]. As part of the revision, a coherent plan was followed, the first step being the identification of misconceptions on the topic gathered from the literature. The curriculum was then designed to overcome these difficulties and implemented for the first time in 2006. During the implementation, close examination of the curriculum took place and the need for many immediate changes was identified. At the closing of the module, post-test results were analysed and compared to pretest data. The analysis identified areas where students had improved their conceptual understanding of the concept but also highlighted areas which they still found difficult. This process continued for two more years with further implementation at DCU. In 2009, the curriculum was used at the National Science Foundation Summer Institute in Physics and Physical Sciences for in-service K-12 teachers at the University of Washington, and also in a course for teachers at the University of Maine. Each implementation provided new insights to the successes and shortcomings of the curriculum.

The second part of the project deals with the design of curriculum for the first year undergraduate labs. The curriculum was implemented for the first time in February 2008. The labs were designed with the goal of improving students' conceptual understanding in an environment where they could enjoy the activity of the experiment. The labs began with the same conceptual structure as that outlined in Physics by Inquiry where current is treated as the primary concept followed by resistance and voltage. Each concept was dealt with in a single laboratory. After implementation in 2008, revisions took place and the labs were reintroduced in 2009. The labs were also taught in 2009 at Ithaca College, NY. The post-test results show that students improve their conceptual understanding and state that they both enjoyed and learned something from the labs.

2.7 Alternative Approaches

The introduction of current is significant to the Physics by Inquiry method as it is the primary concept on which the students build their model. By introducing current first, followed by resistance and then voltage, students can build their model from the least abstract concept. A disadvantage is that the cause for current is not addressed until later in the curriculum.

Others such as Psillos, Tiberghien, Cohen, and Rosenthal[16,17,18] look at presenting voltage as the primary concept. Their reasons to conduct research on this particular concept are very similar to those discussed before. They all express the range and severity of students' difficulties with the concept of voltage. Psillos *et al* find that students conceived that the volt indicates the quantity of something (e.g. 'current' or 'energy') and that the battery is the container of this something. The research also showed the difficulty in recognising that an ideal battery maintains a constant potential difference between its terminals.

In both methods, students are directed to the notion that the volt indication on a battery and voltmeter is related to the brightness of the bulb[16,19]. The differences lie in the introduction of the chemical reactions taking place within the battery and the concepts of energy storage and charge accumulation in the voltage based curriculum.

Psillos also dedicates a significant amount of time to investigating the physical size of batteries and the consequences on bulb brightness. Students conduct an experiment with two batteries of the same voltage but different size, connected to identical bulbs. They investigate the brightness of the bulb and the duration for which it is lit, coming to the conclusion that a bulb connected to differently sized batteries with the same volt indication lights to the same brightness but not for the same duration. Although this experiment addresses an issue that is not dealt with in the PbI voltage curriculum until much later, it may promote the concept of the battery being a "bottle" of current whereby the smaller battery has less current "stored" and therefore the current is used up faster.

The sequence of development is similar to that of UW in that they allocate the initial nine hours of teaching to the familiarisation with series and parallel connections of batteries and bulbs. This is then followed by three hours of teaching where the voltage concept is introduced and taught as a concept which is linked to a battery[16]. The similarities are extended to the content of the curriculum although there are some slight differences when the level of content is increased to introductory physics at university level.

Other common possibilities compare voltage and current to pressure and water flow. The water analogy often goes little deeper than the ad hoc observations that "voltage is just like pressure" and "in parallel circuits, it is just like a river splitting into two". Given that these observations do not constitute a model, and that many students do not have a deep conceptual understanding of pressure, we do not think that this analogy helps students' understanding. However, Schwedes and Dudeck[20] developed a complete analogical model whereby the battery was replaced by a double water column. The water level difference could be kept constant by an adjustable pump. This water level difference drives a flow of water through a set of tubes, which is monitored by a flow meter. By using clamps, the water flow can be adjusted.

Students investigate the set up and learn that, if they keep everything else constant, the only way they can keep the water flow constant is by adjusting the pump speed such that the water level difference remains constant. They also learn that different flow rates are achieved by maintaining different constant water level differences. Students learn that the pump does not determine the magnitude of the flow, but that it maintains the water level difference. The analogy here is complete: The pump is like the battery separating charges, the water level difference is like potential, the water flow is like current, tubing is like a (variable) resistor. This curriculum takes up twenty 90 minute classes, 13 of which are devoted to the water model and 7 to electric circuits.

In contrast to these alternative methods, we share the view held by UW that current should be treated before the concepts of resistance and voltage. The introduction of current as an initial concept helps promote model development whereby students can deal with one concept at a time, allowing them to fully understand the concept before being introduced to another. The research at UW has shown that the introduction of the concept of energy early in the curriculum causes complications, generally based on students' difficulty in distinguishing current from energy. Due to the difficulty students have with reconciling the dissipation of energy with the conservation of current, UW find it more effective for students to develop a consistent, conceptual framework from a single primary concept instead of from two concepts that they may not have fully separated[19]. Following from a review of the literature and familiarity with the curriculum development at UW, we have adopted their approach.

References

1. E. F. Redish and R. N. Steinberg, *Teaching Physics: Figuring out what works*, Phys. Today **52** (1), 24-30, 1999.
2. D. Hestenes, *Who needs physics education research?*, Am. J. Phys. **66**, 465-467, 1998.
3. F. Reif, *Milikan Lecture 1994: Understanding and teaching important scientific thought processes*, Am. J. Phys. **63**, 17-32, 1995.
4. L. C. McDermott, *Guest Comment: How we teach and how students learn - A mismatch?*, Am. J. Phys. **61** (4), 295-298, 1993.
5. L. C. McDermott, E. F. Redish, *Resource Letter: PER-1: Physics Education Research*, Am. J. Phys. **67** (9), 755-767, 1999.
6. L. C. McDermott, *Oersted Medal Lecture 2001: Physics Education Research—The Key to Student Learning,* Am. J. Phys. **69** (11), 1127, 2001.
7. *Junior Certificate Science - Guidelines for Teachers*, Department of Education and Science and NCCA, Ireland, online: http://www.education.ie/servlet/blobservlet/jc_science_guidelines.pdf?language=EN
8. *Report on the Task Force on the Physical Sciences*, Department of Education and Science, Ireland, online: http://www.education.ie/servlet/blobservlet/physical_sciences_report.pdf
9. *Junior Certificate Science Syllabus*, Department of Education and Science, Ireland, online: http://www.education.ie/servlet/blobservlet/jc_science_sy_rev.pdf?language=EN
10. L. C. McDermott, *Preparing K-12 teachers in physics: Insights from history, experience, and research*, Am. J. Phys. **74** (9) 2006.
11. M. Rocard, P. Csermely, D. Jorde, D. Lenzen, H. Walberg-Henriksson, V. Hemmo, (2007): *Science Education Now. A renewed pedagogy for the future of Europe*, European Commission. Online:http://ec.europa.eu/research/science-society/document_library/pdf_06/report-rocard-on-science-education_en.pdf
12. L. C. McDermott, P. S. Shaffer, C. Constantinou, *Preparing teachers to teach physics and physical science by inquiry,* Phys. Educ. **35** (6) 411-416, 2000.
13. L. S. Shulman, *Paradigms and research programs for the study of teaching*. In M. C Wittrock (Ed.), Handbook of research on teaching, 3-36, New York, Macmillan 1986.
14. L. C. McDermott, *A perspective on teacher preparation in physics and other sciences: The need for special science courses for teachers*, Am. J. Phys. **58** (8), 1990.
15. L. C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry vol II*, 430 - 454, Wiley, New York 1996.
16. D. Psillos, P. Koumaras, A. Tiberghien, *Voltage presented as a primary concept in an introductory teaching sequence on DC circuits* Int. J. Sci. Educ., Vol 10, No 1, 29-43, 1988.
17. R. Cohen, B. Eylon, U. Ganiel, *Potential difference and current in simple electric circuits: A study of students' concepts*, Am. J. Phys. **51** (5), 1983.
18. A. S. Rosenthal, C. Henderson, *Teaching about circuits at the introductory level: An emphasis on potential difference,* Am. J. Phys. **74** (4), 2006.
19. L. C. McDermott, P. S. Shaffer, *Research as a guide for curriculum development: An example from introductory electricity. Part II: Design of instructional strategies*, Am. J. Phys. **60** (11), 1003-1013, 1992.
20. H. Schwedes and W. G. Dudeck, *Teaching Electricity by Help of Water*. In Research in Science Education in Europe, edited by G. Weldord, J. Osborne, and P. Scott. The Falmers Press, London, 1996.

Part I

Curriculum for Pre-service Teacher Modules

Chapter 3

Research on Students' Understanding of Current and Resistance

3.1 Course Context

In this chapter I discuss in some detail the electric circuits module taken by all pre-service teachers one year prior to taking the electric circuits module on voltage. This discussion serves as an introduction to the development of curriculum on the concept of voltage and sheds some light on students' background knowledge.

The module was run over three years as part of the degree in Science Education at Dublin City University. Students worked through curriculum from Physics by Inquiry[1]. The choice of curriculum was supported by its documented success[2]. All pretest questions presented in this chapter were provided by UW. However, post-tests were designed at both DCU and at UW.

The first year of the module spanned a period of nine weeks with two, 2 hour laboratory sessions taking place each week. In the second and third year, the module was extended to 10 weeks with the number of classes reduced to a single, 3 hour laboratory session per week. The class contained on average 17 students tutored by two instructors.

Although the module covers a multitude of concepts, this chapter deals with only three of the main concepts introduced in the curriculum. These concepts are:

- Complete circuits
- Current and Resistance
- Equivalent resistance

The concepts are discussed simultaneously with pretest data that highlights the key misconceptions students have with a particular concept. This is followed by appropriate post-test data which shows the changes in students' conceptual understanding of the topic. The data highlights results which confirm findings of others while selected questions provide some new results. The chapter is concluded with a contrast of the concepts that students have made the most gains to those that they still find quite challenging.

3.2 Research Background

Research carried out by the Physics Education Group at the University of Washington has shown that serious misconceptions about electric circuits are common among students who have received formal instruction in the relevant curriculum[3]. Other research has shown that students from different cultural backgrounds and educational systems carry the same misconceptions, including students who have been taught theoretical and experimental physics for many years[4].

Very few schools and universities have acted upon these findings. This may result from students' ability to produce quantitative solutions to standard questions on exams. However the ability to answer quantitative problems is not an efficient measurement of conceptual understanding, as students who can solve standard quantitative problems find difficulty in answering simple qualitative questions on the same topic[3].

Due to the large range of difficulties encountered by students, McDermott and Shaffer have grouped them into three general categories[3]:

(1) an inability to apply formal concepts to electric circuits,

(2) an inability to use and interpret formal representations of an electric circuit and,

(3) an inability to reason qualitatively about the behaviour of an electric circuit.

This chapter focuses on a small number of sub-categories contained within the main categories detailed above. The first looks at students' belief that current is 'used up' in a circuit. This misconception is very common and is closely linked to the idea that the battery produces current and that circuit elements use up this current[3,5,6]. It is also common for students to express the notion that a battery is a bottle of current and when it has given all its current to the circuit, the battery is 'dead'.

The problem is often highlighted when students are asked to rank the brightness of two bulbs in series such as those shown in Figure 3.1. The most common incorrect answer is to rank bulb A brighter than bulb B based on the reasoning that bulb A uses up most of the current and bulb B gets the 'left over' current. It is also common for some students to rank bulb B brighter than bulb A, basing their reasoning on the direction of electron current.

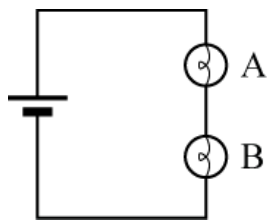


Figure 3.1: Two bulb series circuit.

These findings have also been confirmed by Shipstone *et al* where research carried out in five European countries showed that the notion that current is consumed remained very attractive to students even after instruction[7].

As stated above the idea that current is consumed is closely linked to the belief that the battery is a constant current source. This is possibly the most prominent misconception and one that is difficult to eradicate. The problem may arise from students' lack of understanding of resistance and its critical role in determining current[3]. For example, in reference to the circuits shown in Figure 3.2 a student made the following comment about how the presence of a bulb would affect the reading on the ammeter[3].

Student: *"I just don't see how I'd see that much difference whether the light bulb is there or not-isn't the current the same all of the time"*

Interviewer: *"What would you predict?"*

Student: *"That the ammeter would read the same in all three circuits"*

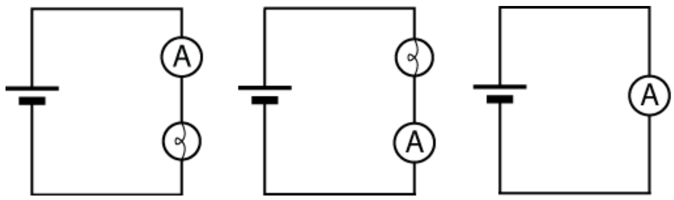


Figure 3.2: Circuit diagrams in which a student expressed that the current in all circuits is the same.

In the following sections a basic overview of the curriculum is given. The misconceptions described above and others are discussed in the context of students who have taken the electric circuits module on current and resistance at DCU.

Each section consists of three parts: (1) a description of the pretest and analysis, (2) a description of the relevant part of the curriculum and (3) a description of the post-test and analysis.

3.3 Complete Circuits

In the first section of the curriculum, students are introduced to complete circuits, conductors and insulators, short circuits and circuit diagrams. Through a sequence of experiments and exercises they form the initial rules of their model of electric circuits.

The concept of a complete circuit is a key part in the development of the students' model and it is dealt with as the first topic in the curriculum. The analysis of students' pretest results and experience in the laboratory shows that many students find this topic difficult in spite of having covered complete circuits on at least two previous occasions, once or twice at secondary level and again at university.

3.3.1 Complete Circuits: Pretest and Analysis

The pretest on complete circuits contains two questions. In the first pretest question, students encounter a number of single bulb circuit arrangements shown in Figure 3.3. They are asked to circle the arrangement in which they think the bulb will light. The only correct arrangement (labelled I) forms a complete circuit through the battery, wire and bulb. Arrangements A and E are the only other arrangements which include both battery terminals, while the others include a combination of only one battery terminal and one or two parts of the bulb.

Complete Circuits Pretest, Question 1

Circle the arrangement(s) at right in which the bulb will be lit. (Note: You may select more than one arrangement.) Explain your reasoning.

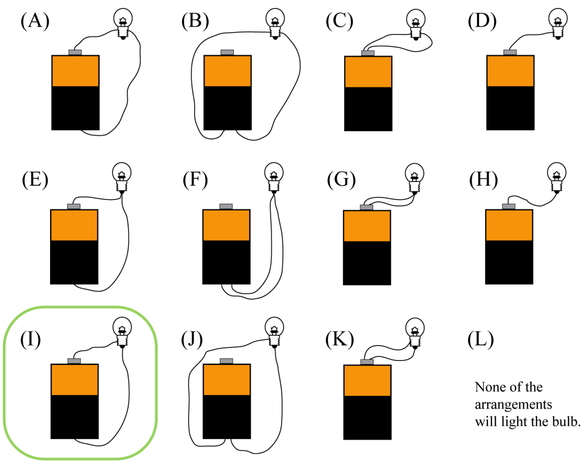
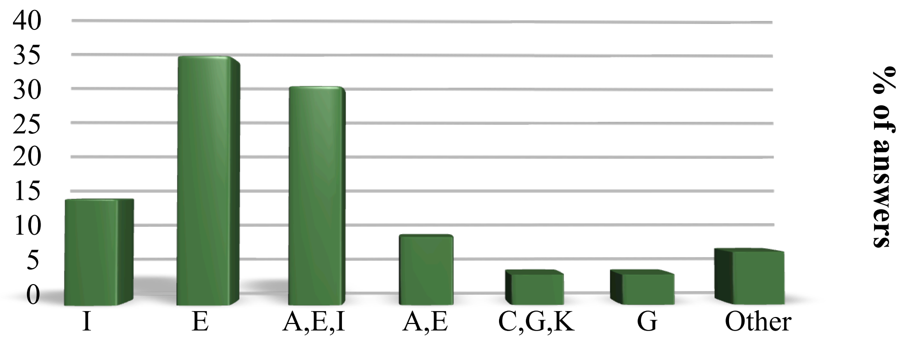


Figure 3.3: Eleven different arrangements a battery, wire(s) and a bulb.

The purpose of this pretest question is to investigate students' views on the requirements of a complete circuit. By asking students to explain their reasoning for choosing particular arrangements, any potential misuse of physics concepts is highlighted. The frequency of arrangement choices is presented in Figure 3.4.

Complete Circuits Pretest, Question 1 (N=54)



Chosen Arrangement(s)

Figure 3.4: Frequency of arrangement choices in Complete Circuits Pretest, Question 1.

Figure 3.4 shows that 30% of students chose all arrangements which included both battery terminals (A, E & I). A further ~35% chose arrangement E alone. Only ~15% chose the correct arrangement. The data shown in Figure 3.4 is strong evidence that many students only focussed on the terminals of the battery. This is supported by the analysis of the concepts referenced by students in their explanations. (The analysis of question 2 discussed below lends additional support and allows for a more clearer perspective.) The frequency of concepts that accompanied students' answers to the chosen arrangements in question 1 is shown in Figure 3.5.

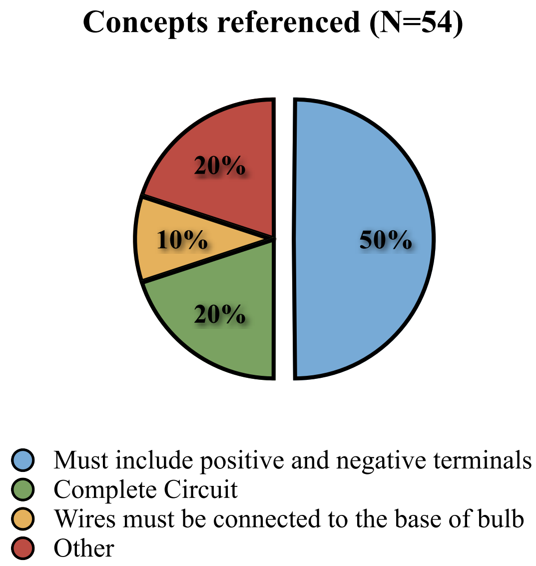


Figure 3.5: Frequency of concepts referenced by students in answer to Complete Circuits Pretest, Question 1.

Figure 3.5 shows that 50% of students made reference to the positive and negative terminals of the battery while 10% stated that the wires must touch the base of the bulb.

The arrangement in which the wires made contact with the bulb was assessed in more detail in question 2 of the pretest. Students were presented with three different bulb diagrams showing three possible arrangements of how the filament posts are connected to the base of the bulb. The bulb diagrams are shown in Figure 3.6.

Complete Circuits Pretest, Question 2

Circle the diagram(s) below that could represent the connections of the wires to the base of the light bulb used in question 1. (Note: You may select more than one diagram. If two or more diagrams are equivalent, state so explicitly. Explain your reasoning.

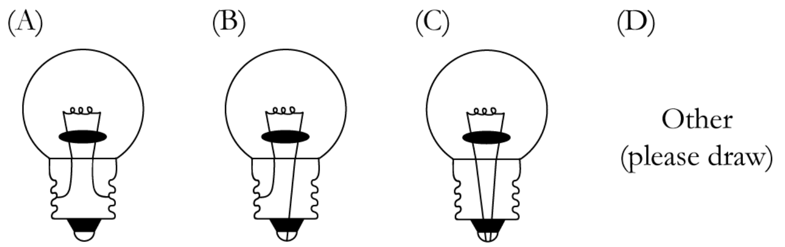


Figure 3.6: Possible connections inside a bulb.

The analysis of students' answers provided the data shown in Table 3.1.

Table 3.1: Chosen diagrams for Complete Circuits Pretest, Question 2.†

Bulb Diagram	% (N=54)
B	**15 (8)**
C	60 (33)
A	5 (4)
A, C	5 (4)
B, C	5 (2)
A, B, C	5 (2)
A, B	<5 (1)

The data in Table 3.1 suggests that students hold a strong opinion that the filament posts are connected to the metal tip of the bulb, as 60% of students chose diagram C as the only perceived correct arrangement. However, possibly the most revealing statistic regarding students' misconceptions is the correlation between the chosen circuit arrangement in question 1 and the chosen bulb diagram in question 2. Since both questions are undoubtedly related, it would be reasonable to assume that there would be a direct correlation between the answers to the questions.

† In all tables presented in this thesis, correct answers are presented in bold font. The data is presented in % values rounded to the nearest 5% and numbers are presented in parentheses.

Table 3.2 shows the correlations between the chosen circuit arrangements in question 1 and the chosen bulb diagrams in question 2 of the pretest. For example, students who chose arrangements A, E and I should logically select all three bulb diagrams, A, B and C. The data highlights that many students did not link the two questions and applied a different logic to answering each question. The values only represent the fraction of students who chose particular arrangements.

Table 3.2: Correlation between answers to Complete Circuits Pretest, Question 1 and Question 2.

Chosen Arrangements	**N (*N*=54)**	**Correct correlated bulb diagrams**	**Correct correlation %**	**Incorrect correlation %**
A, E, I	16	A, B, C	**10 (2)**	90 (14)
E	18	C	**95 (17)**	5 (1)
A, E	5	A, C	**20 (1)**	80 (4)
I	7	B	**100 (7)**	0 (0)
Other	8	Other	**60 (5)**	40 (3)

The analysis of this correlation suggests that students' primary focus is different in each question. In question 1 it seems that the primary focus involves the usage of both battery terminals while question 2 reveals the incorrect belief that both wires enter the base of the bulb. Table 3.1 shows that 15% of students chose two or more bulb diagrams which hints at a poor understanding of the bulb layout. It may also highlight that the focus on battery terminals is predominant. In the Irish context, one might think that diagram C is chosen because of students' experience with bayonet bulbs, which happen to place the bulb filament wires at the base, separated by an insulator. This type of bulb is more common in Ireland than the Edison screw format that is typically used in the United States.

3.3.2 Complete Circuits: Curriculum Discussion

Students begin their investigation of complete circuits by attempting to form an arrangement of a battery, a single wire and a bulb, that allows the bulb to light. This open investigation may be unusual to many students as previous laboratory experience is typically based on 'cook book' style instructions. When students have formed a successful arrangement, they are guided to investigate three other possible arrangements. Students are generally surprised at the comparison between their initial perception of the experiment and their experience. Many feel that the experiment is relatively simple before they start. However the manner in which students struggle through the experiment immediately confronts them with the difficulty of the concept. Similar results are reported independently by Evans and Fredette[8,9].

The experiment is followed by a number of related exercises. The most significant is the writing of an operational definition for a complete circuit. An operational definition for a complete circuit is a set of unambiguous instructions that describe the formation of a complete circuit[10,11]. Many, if not all students fail to write an acceptable operational definition on their first attempt. An inadequate example is shown below.

> *"Put a wire on the battery. Then put the bulb on the battery and connect the wire to the bulb"*

In a check-out, the instructor carefully examines each students' response. Students come to recognise any ambiguities in their operational definition. Upon revision, they form a concise number of instructions highlighting the sequential connection of the battery terminals, ends of the wire and the terminals of the bulb. A specific example is shown below.

> *"Place one end of a wire in contact with the bottom of the battery. Place the metal tip of the bulb on the top of the battery. Place the other end of the wire in contact with the metal casing of the bulb."*

On completion of this exercise, students investigate lighting a bulb with two wires and a battery which reinforces the fact that bulbs are not polar specific. This experiment concludes their investigations of complete circuits.

3.3.3 Complete Circuits: Post-Test and Analysis

In the first section of the curriculum and particularly in the first experiment, students grapple with their misconceptions and begin to understand the requirements for a complete electric circuit. To measure students' level of understanding of complete circuits, we present the following post-test question on their mid-term or final exam.

Complete Circuits Post-Test†

When a small fan is connected to a battery using two wires, as shown at right, it is observed that the blades of the fan rotate.
Suppose that the fan is now connected to two batteries using two wires as shown below.

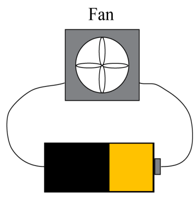


Figure 3.7: Fan connected to a single battery.

Will the blades of the fan rotate when the fan is connected to the two batteries as shown? Explain your reasoning."

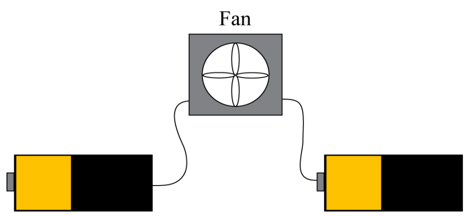


Figure 3.8: Fan connected to opposite terminals of two batteries.

It is hoped that students recognise that there is a break in the second circuit and thus state that the blades of the fan will not rotate. However, some students believe that since the fan is connected to a negative and positive terminal, the blades of the fan will rotate. The results for all years are shown in Table 3.3 where E1 refers to mid-term exam and E2 refers to final exam.

† This post-test question was developed by MacKenzie Stetzer (UW) with input from Paul van Kampen (DCU).

Table 3.3: Students' answers to Complete Circuits Post-Test.

Answer	2005 E1% (*N*=23)	2006 E2% (*N*=18)	2007 E1% (*N*=13)	Total % (*N*=54)
Blades won't rotate	**95 (22)**	**85 (15)**	**90 (12)**	**90 (49)**
Blades will rotate	5 (1)	15 (3)	10 (1)	10 (5)

It should be noted that students who provided the correct answer also provided correct reasoning, stating that the circuit in Figure 3.8 was incomplete or contained a gap. Examples are shown in Figure 3.9.

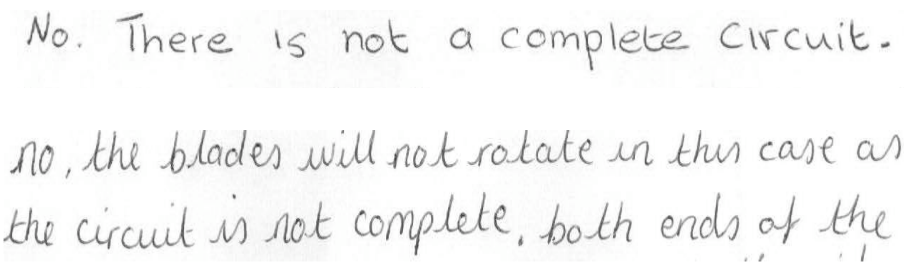


Figure 3.9: Examples of students' reasoning in answer to Complete Circuits Post-Test.

These results show that the large majority of students have improved their conceptual understanding of a complete circuit.

3.4 Current and Resistance

In section 2 of the PbI curriculum, students are introduced initially to the term 'flow' which is later defined as electric current. The use of non-technical terms is chosen for a number of reasons. There is evidence that students who insist on using technical terms rarely understand them and some students feel intimidated when discussions are flooded with terms and words that they don't understand. The use of non-technical terms allows students to progress through the material while they are still forming an understanding of the concepts. The use of technical terms are not introduced until students can use them correctly[8].

The curriculum does not concern itself with the nature of the 'flow' and students discover that the direction of 'flow' cannot be determined from classroom observations. Once students have been introduced to the concept, the following two assumptions are described in the narrative of the curriculum:

(1) There is a 'flow' around a circuit.

(2) Bulb brightness is an indicator of 'flow' where an increase in brightness indicates an increase in 'flow'.

It is important for students to understand that these are assumptions of the model since 'flow' or current cannot be observed, however they also need to recognise the importance of the assumptions in the formation of their model. As results show in the following section, the assumption that bulb brightness is an indicator of current comes intuitively, as the majority of students apply the assumption in answering questions to the pretest given prior to section 2.

3.4.1 Current and Resistance: Pretest and Analysis

To pretest students' understanding of current and resistance they are asked to rank the relative brightness of bulbs in the circuits shown in Figure 3.10. This pretest is carried out after students have worked through curriculum on complete circuits, conductors and insulators and short circuits, but before they are introduced to the concepts of current and resistance.

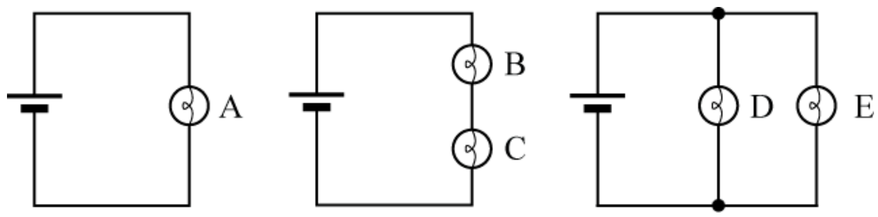


Figure 3.10: A single bulb circuit, a two bulb series circuit and a two bulb parallel circuit.

The analysis of students' rankings identified 14 individual rankings from 51 attempts. The most popular rankings are shown in Table 3.4.

Table 3.4: Bulb Rankings to Current and Resistance Pretest.

Ranking	**2005 % (*N* = 22)**	**2006 % (*N* = 17)**	**2007 % (*N* = 12)**	**Total % (*N* = 51)**
A=D=E>B=C	**5 (1)**	**25 (4)**	**0 (0)**	**10 (5)**
A=B=C>D=E	30 (6)	25 (4)	0 (0)	20 (10)
A>D=E>B=C	25 (5)	10 (2)	35 (4)	25 (11)
A>B=C>D=E	25 (4)	0 (0)	15 (2)	15 (6)
A>B=C>D>E	10 (2)	0 (0)	15 (2)	10 (4)

The results in Table 3.4 are consistent with the data gathered by UW, where they administered the test to more than 500 university students. Their data shows that approximately 10% of students in algebra-based courses and 15% of students in calculus-based courses are able to rank the bulbs correctly[3].

It is often difficult to extract meaningful information from rankings alone. A more telling perspective is obtained from the analysis of students' reasoning. The analysis of students' reasoning revealed a number of significant misconceptions that students have regarding simple electric circuits. We find that in the majority of answers, a combination of these misconceptions are used rather than a single one dominating over others. A list of the most common misconceptions is now presented:

1. **Brightness is related to the number of bulbs in the circuit**

   The analysis of students' results show that 65% ranked bulb A as the brightest bulb. Of the students who gave a specific reason, 40% reasoned on the basis that bulb A was the only bulb in the circuit. The remaining 60% stated that bulb A receives all the current (or some other quantity - see point 6). Further evidence for this misconception is provided when students state that bulbs B and C are dimmer than bulb A, since there are two bulbs in the circuit. This line of reasoning is similar to a 'sharing' (see point 4) or 'used up' model (see point 3) where students state that bulb A receives all the current and either all of the current or the left over current is shared among the rest of the bulbs.

2. Current through the battery doesn't change (Constant current model)

The idea that the current through the battery is always the same is one of the most significant misconceptions held by students. It leads students to rank bulbs A, B and C as equal in brightness, since both circuits contain a single loop. It also leads them to incorrectly believe that bulbs D and E will be dimmer than all other bulbs on the basis that an equal amount of current in the two bulb parallel circuit is split between the two bulbs, thus making them dimmer. Many of our students state that the current through the single bulb circuit and the two bulb series circuit is the same. This implies that students believe that the current through each battery is the same, although none of our students explicitly state so. Analysis shows that 15% of students apply a constant current model explicitly. Classroom discussions also confirm these findings. An example is shown in Figure 3.11:

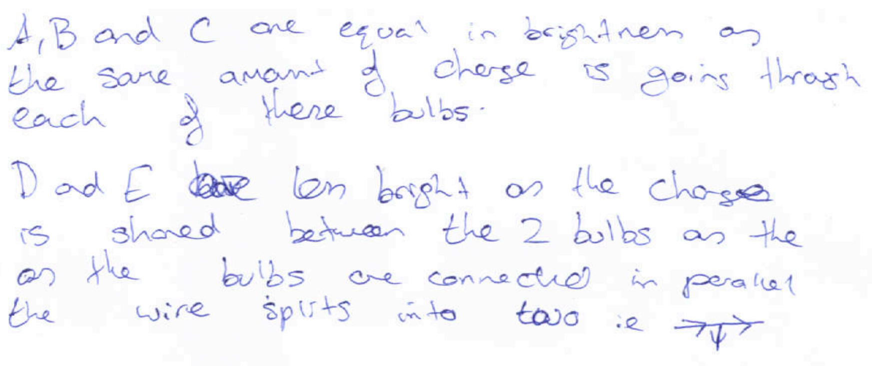

A, B and C are equal in brightness as the same amount of charge is going through each of these bulbs.
D and E ~~are~~ less bright as the charge is shared between the 2 bulbs as the as the bulbs are connected in parallel the wire splits into two ie

Figure 3.11: Example of a student's answer which is based on a constant current model.

3. Current is used up

Although the misconception that current is used up is well documented and persistent in the data shown later in Chapter 6, it is not particularly obvious in students' answers. This misconception can lead students to rank bulb B brighter than bulb C or vice versa on the basis that current is used up before it gets to the second bulb. However, when combined with the constant current model, students incorrectly reason that bulb A is brighter than bulbs B and C on the basis that all the current travels through bulb A while bulb B and bulb C use half of the current each. Analysis of students' answers show that 15% of students provided direct evidence that they were reasoning based on the misconception that current is used up. An example is shown in Figure 3.12:

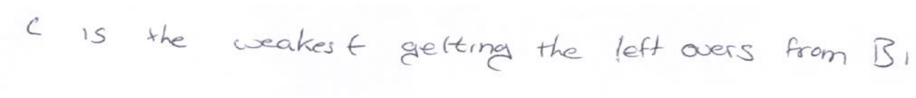


Figure 3.12: Example of a student's answer which is based on a current is 'used up' model.

4. Bulbs in series share current

When ranking the brightness of bulbs B and C, many students correctly rank the bulbs equal in brightness however they incorrectly reason on the basis that the bulbs 'share the current equally' or that it is 'split evenly between them'. It is often difficult to discriminate whether the students are applying a 'used up' model whereby they believe that the current is used up equally in each bulb, or they believe that each bulb somehow gets half the current from the battery. For example in a bipolar flow or clashing current model as proposed by Osborne[12]. An example is shown in Figure 3.13:

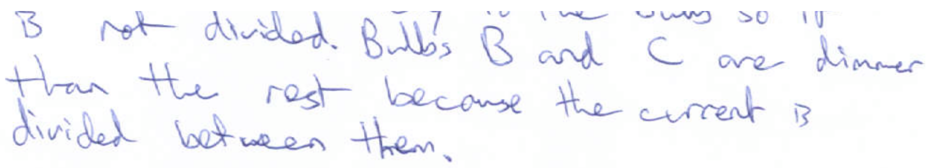


Figure 3.13: Example of a student's answer which is based on current being divided between bulbs in series.

5. Proximity to the battery / position of bulbs influences brightness

Some students believe that the circuit diagram represents the physical layout of the circuit and that the distance of a bulb to the battery affects its brightness. This leads some students to rank bulb D brighter than bulb E since it is closer to the battery. This error also clearly highlights students' lack of understanding of circuit diagrams. An example of a student's answer is shown in Figure 3.14:

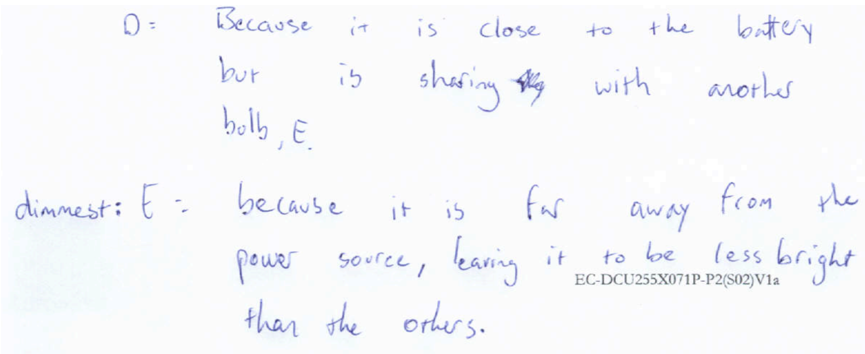


Figure 3.14: Example of a student's answer which is based on the misconception that a bulb's proximity to the battery affects its brightness.

6. Related physics concepts are not differentiated

It is very common for students to use a mix of concepts in their explanations. In this particular pretest, students use multiple terms such as power and voltage as if describing current. Examples are shown in Figure 3.15.

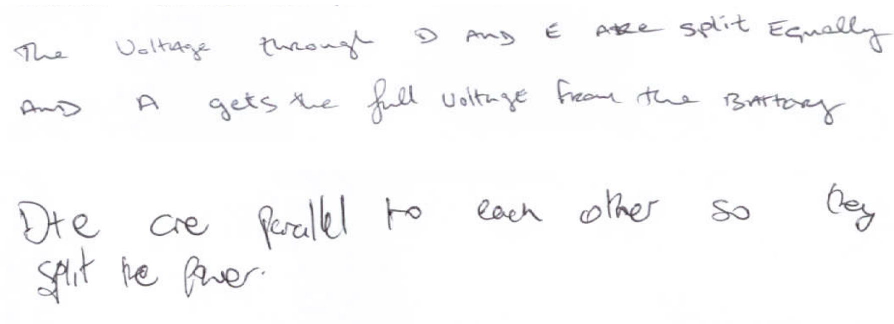


Figure 3.15: Two examples of students' answers that highlight the inability to differentiate related physics concepts.

Other examples highlight the students' inability to separate the concepts of current, energy and conductivity. For additional evidence see McDermott and Shaffer[2].

From a global perspective it seems that on this pretest many students implicitly apply a constant current model as evidenced by 25% of students who rank A=B=C>D=E. About 60% rank bulb A as the brightest and then apply a constant current model. It appears that for these students the belief that bulb A is the brightest (since it is the only bulb in the circuit) overrides any other reasoning. The constant current model leads them to rank bulbs B and C greater in brightness than bulbs D and E on the basis that the same amount of current is split between bulbs D and E.

3.4.2 Current and Resistance: Curriculum Discussion

After students have been introduced to the concept of current they continue their investigation by comparing the brightness of two bulbs in series to the brightness of a bulb in a single bulb circuit. Students notice that the two bulbs in series are dimmer than a single bulb and equal in brightness to each other. When explaining their observations, many students use incorrect models such as those explained earlier. To overcome these difficulties, students are guided to reason on the basis of their observations and assumptions of current flow to form a model which states that the current through a single bulb circuit is greater than that through a two bulb series circuit.

To reinforce the concept that the current through the battery can change and to also further their investigation, they investigate the two bulb parallel circuit shown in Figure 3.16.

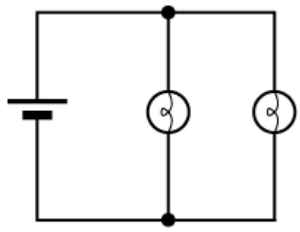


Figure 3.16: Two bulb parallel circuit.

Students notice that the two parallel bulbs are equal in brightness to each other and also equal in brightness to a bulb in a single bulb circuit. They allows them to infer that the current through each of the bulbs is the same and also equal to the current through a bulb in a single bulb circuit. By examining the layout of the parallel circuit they infer that the current through the battery must split between each of the bulbs in the circuit. Since the current through each branch is equal to the current through a single bulb circuit, this leads them to the conclusion that the current through a battery in a two bulb parallel circuit is greater than the current through a battery in a single bulb circuit.

The concept of resistance is introduced through the investigation of series circuits in section 3 of the PbI curriculum[13]. Students observe that adding bulbs in series to a single bulb circuit causes the bulb to become dimmer. Students can infer that the current has decreased in this case. On the basis of these observations, students are guided to think of an extra bulb in series as an additional obstacle or resistance to the current. This forms the basis of the rule that adding bulbs in series to a circuit increases resistance.

The addition of bulbs in parallel and the effect on resistance is carried out in a similar fashion. Students add a bulb in parallel across a bulb connected in a two bulb series circuit to form the circuit in Figure 3.17.

Bulb A receives all current through the battery and students are encouraged to think of bulb A as an indicator bulb. Students observe that bulb A becomes brighter on the addition of bulb C to the circuit.

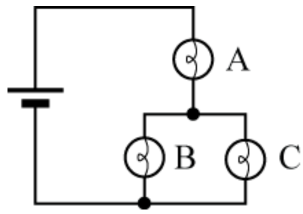


Figure 3.17: Circuit diagram of a two bulb parallel network in series with a single bulb.

This leads students to infer that the current through bulb A, and therefore the current through the battery, has increased. To be consistent with series circuits, students reason that the resistance must have decreased. This leads to the rule that adding a bulb in parallel decreases the resistance of the circuit. Many students find this hard to accept as many incorrectly believe that resistance is somewhat proportional to the number of bulbs in a circuit, where an increase in the number of bulbs causes an increase in resistance.

Through the remaining exercises and experiments in section 3 of the PbI curriculum, students discover rules for independent and dependent parallel branches. As a single part of a larger exercise, students observe that making changes to one branch in Figure 3.18 does not affect the brightness of the bulbs in the other branches. These branches are therefore said to be independent.

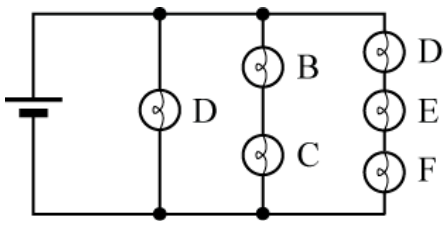


Figure 3.18: Circuit diagram with three independent parallel branches.

The treatment of dependent parallel branches is carried out in a similar manner. Students first predict how the brightness of bulb A and bulb B changes when bulb E is removed from the circuit in Figure 3.19.

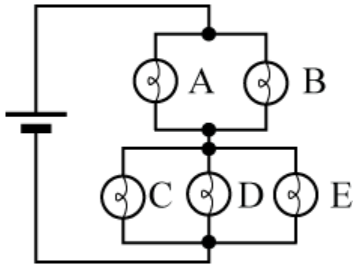


Figure 3.19: Circuit diagram with dependent parallel branches.

Many students predict that bulb A and B remain the same by applying a false generalisation of the addition of bulbs in parallel across a battery. However they should recognise that the removal of bulb E would cause an increase in resistance. Consequently the current through the battery decreases and hence bulbs A and B get dimmer. We often observe that when a new concept is introduced, students initially try to fit this in with their previous knowledge in an inconsistent way.

Students are not asked to predict what happens to the brightness of bulbs C and D since their current and resistance model will not allow them to make this prediction. They are however explicitly asked to take note of any change in brightness of bulbs C and D. The observation that the brightness of bulbs C and D get dimmer shows that the branches C, D and E are dependent on each other. By recognising that these parallel branches are not connected across the battery, students can differentiate between independent and dependent branches. This distinction allows students to see that they made an invalid generalisation when they assumed all bulbs in parallel are independent.

In the final exercise of section 3 students discover the limitations of the current model. Students are asked to predict the change in brightness of bulb B when bulb C is removed from the circuit in Figure 3.20. The experiment is also accompanied by a student conversation.

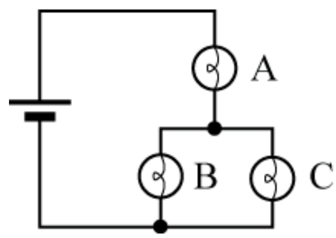


Figure 3.20: Circuit diagram used for highlighting the limitations of the current model.

The function of student conversations in the PbI curriculum is to address possible lines of reasoning on a particular concept. For many of the conversations, students are asked whether they agree or disagree with a particular statement or in some cases identify a correct or incorrect line of reasoning. By asking students to commit to a particular statement, the instructor can recognise students' thoughts on the concept. This is both useful for identifying underlying misconceptions and to also highlight the development of students' understanding. The student conversation that accompanies the exercise detailed above is shown in Figure 3.21.

Student 1: *"Unscrewing bulb C removes a path for the current. Thus the resistance of the circuit increases and the current through the battery and the remaining bulbs decreases. So bulb A and bulb B would dim."*

Student 2: *"I agree that bulb A will dim, but I disagree about bulb B. Before you unscrew bulb C, only part of the current through bulb A goes through bulb B. Afterward, all of the current through bulb A goes through bulb B. So bulb B should get brighter."*

Figure 3.21: Extract from PbI curriculum highlighting the use of a student conversation.

On the first attempt, some students answer without hesitation and state that bulb B gets brighter since it is no longer sharing current with bulb C; a common line of reasoning seen in pretest answers and used by student 2 in Figure 3.21. In the check-out following the exercise, instructors guide students through the correct reasoning. They are asked to consider the current through the battery before and after the removal of bulb C. Students reason that the current through the circuit is less after bulb C is removed based on current and resistance reasoning. They recognise that before bulb C is removed, bulb B receives half of more current while without bulb C it receives all of less current. These two values cannot be compared unless it is known whether upon adding bulb C the current doubles, more than doubles or less than doubles.

3.4.3 Current and Resistance: Post-Test and Analysis

Since the conceptual development of current and resistance forms the foundation of the curriculum, the post-test data on these concepts is quite extensive. In this section, we discuss some of the post-test data.

Current and Resistance Post-Test 1

The first question to be discussed is shown overleaf and was given in the final exam of each year. As with all our post-tests, students have not seen this particular example. At this stage they must reason their answers based solely on current and resistance.

Current and Resistance Post-Test 1†

Rank the bulbs according to brightness. Explain your reasoning. If you cannot determine a complete ranking, explain why not.

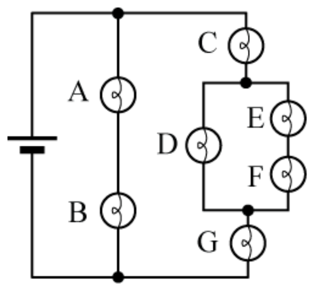


Figure 3.22: Circuit diagram used for Current and Resistance Post-Test 1.

The analysis of the students' rankings provided the data shown in Table 3.5.

Table 3.5: Rankings for Current and Resistance Post-Test 1.‡

Bulb ranking	2005 % (*N*=23)	2006 % (*N*=18)	2007 % (*N*=14)	Total % (*N*=55)
A=B>C=G>D>E=F	**85 (20)**	**40 (7)**	**55 (8)**	**65 (35)**
C=G>A=B>D>E=F	5 (1)	15 (3)	15 (2)	10 (6)
C=G>D>E=FXA=B	0 (0)	10 (2)	0 (0)	5 (2)
Other	10 (2)	35 (6)	30 (4)	20 (12)

Similar to the pretest results, a clearer picture is attained when the partial rankings are analysed. These are shown in Table 3.6.

† This question was developed at UW.

‡ In presenting students' rankings, an X is used when students stated that bulbs cannot be ranked, a ? is used where students do not explicitly provide a ranking.

Table 3.6: Partial rankings for Current and Resistance Post-Test 1.

Individual Rankings	2005 % (*N*=23)	2006 % (*N*=18)	2007 % (*N*=14)	Total % (*N*=55)
A=B > C=G	**95 (22)**	**55 (10)**	**55 (8)**	**75 (40)**
C=G > D	**95 (22)**	**90 (16)**	**80 (11)**	**90 (49)**
D > E=F	**95 (22)**	**90 (16)**	**85 (12)**	**90 (50)**
C=G > A=B	5 (1)	40 (7)	30 (4)	20 (12)

The analysis of students' answers shows how the curriculum has both addressed some of the students' difficulties and also developed some of the key concepts in understanding electric circuits. These are detailed below:

1. **Resolving student difficulties**

   The analysis of student's answers highlights that many have resolved the difficulties identified in the pretest analysis discussed previously. The belief the current is used up seems to have been eradicated with all students ranking bulb C equal in brightness to bulb G. All students state that the current through bulb C is equal to that through bulb G, or that all the current goes through bulb C, splits at the first node and recombines at the second, to go through bulb G. Students also rank bulbs A and B equal in brightness and do the same for bulbs E and F. Students no longer fail to differentiate between related physics concepts and their answers show large improvements in the use of appropriate and unambiguous scientific language. The belief that the proximity of a bulb to a battery affects its brightness is not present in students' explanations.

2. **Independent Parallel Branches**

   Students recognise that the circuit contains two parallel branches connected across the battery. The branches can therefore be treated independently. In an answer to a question, not analysed in detail here, the majority of students state that the brightness of bulb A is unaffected when bulb E is removed on the basis that it is connected in an independent parallel branch.

3. Comparison of resistance

The curriculum looks to develop students' ability to identify how bulbs are connected within each branch and use that information to compare the relative resistance of the branches. The only difference between the two branches is the connection between bulbs A and B and bulbs C and G. In the left branch there is a direct connection or wire between bulbs A and B, however bulbs C and G are connected in series with a parallel network. Therefore students can conclude that the left branch is less resistive than the right branch. (The independence of the two branches is implicit in this reasoning.) Therefore the current in the left branch is greater, and bulbs A and B are brighter than C and G. The results shown in Table 3.6 show that the majority of the 2005 class recognised this line of reasoning. Tables 3.5 and 3.6 show that most of students who make this ranking go on to make a successful complete ranking. However the class of 2006 and 2007 did significantly worse, with only 55% of both classes recognising that the left hand branch was less resistive than the right hand branch. Suggested reasons for this difference include an additional six hours of instruction in the 2005 module as students received two 2 hour classes for nine weeks rather than a single three hour class for 10 weeks which was carried out in 2006 and 2007. The separation of classes into two shorter classes where focus on the concepts was more intense may also been a contributing factor. Also, for the 2005 module, 23 students were tutored by three instructors while the 18 students in the 2006 class and the 14 students in the 2007 class were tutored by two instructors.

4. Splitting of current in parallel networks

In addition to the recognition that the current splits unevenly between the left and right branch, a large number of students correctly applied the same reasoning to the parallel network in the right branch. They recognised that the branch consisting of the series network of bulbs E and F is more resistant than the branch consisting of bulb D. They seem to understand that the current splits unevenly between these branches, with more than half flowing through bulb D and less than half through bulbs E and F, therefore allowing them to rank the bulbs correctly.

The results shown in Table 3.5 were taken with a sense of achievement. After the implementation of the curriculum, a large number of students have overcome the misconceptions evident in the pretest shown earlier. Additional analysis that confirms these results is shown in the discussion of a post-test question given in the 2005 and 2007 mid-term exam.

Current and Resistance Post-Test 2

In the 2005 and 2007 mid-term exam, students were presented with the question shown below. It was known that students would find this question difficult since a complete ranking was not possible based on current and resistance only, similar to the circuit of Figure 3.20. However it was hoped that students would make the following predictions:

- Bulb A = brightest bulb in the circuit
- Bulb C = Second brightest bulb in the circuit
- Bulb B and D are equal in brightness
- Bulb E and F are equal in brightness
- Bulb C is brighter than bulbs E and F

Current and Resistance Post-Test 2†

Rank the bulbs in the diagram to the right in terms of their brightness. Explain your reasoning.

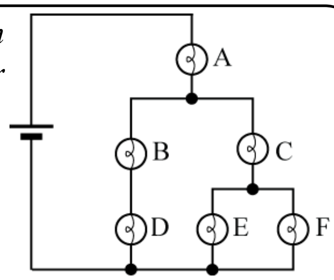


Figure 3.23: Circuit diagram for Current and Resistance Post-Test 2.

The analysis of students' rankings showed that 5% of each class group recognised that a complete ranking was not possible. The results for the categories above were excellent. This is illustrated in Figure 3.24.

† This question was developed at UW.

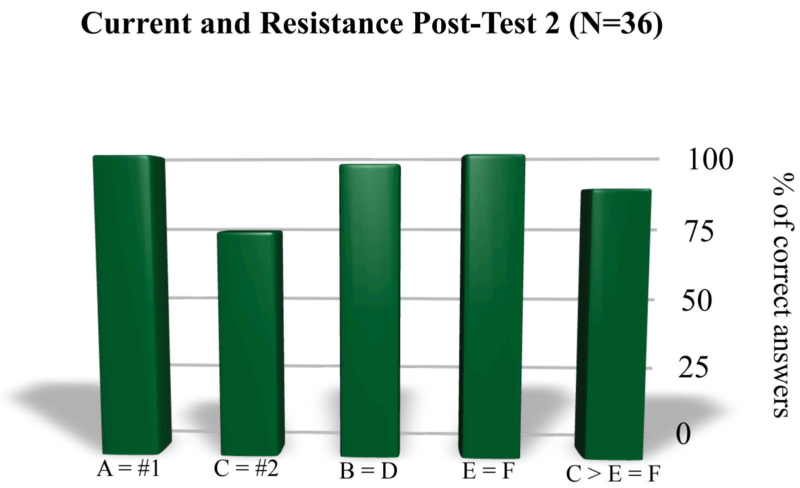


Figure 3.24: Partial analysis of Current and Resistance Post-Test 2.

This was a considerable achievement and marked success in the first six weeks of the course.

Current and Resistance Post-Test 3

As the two previous examples have shown, many of the post-test questions focus on the ranking of the relative brightness of bulbs contained within a circuit. However, I also wanted to analyse students' ability to transfer their understanding to type of question they had not seen before. This was done by asking students to interpret a set of predictions for an unknown circuit and to use the predictions to draw the circuit diagram. The question which students were given in shown below.

Current and Resistance Post-Test 3†

For a circuit with one battery and five bulbs labelled (A-E), a student can make the following predictions:

(1) *All bulbs light*
(2) *Unscrewing bulb E does not affect any of the other bulbs*
(3) *If a wire is connected across bulb A, the brightness of bulbs B, C and D increases.*
(4) *Unscrewing bulb C (leaving the socket in the circuit) causes bulb D to go out.*
(5) *If bulb B is unscrewed the other bulbs still glow although not necessarily with the same brightness.*

Draw a circuit diagram for which these predictions are true. Make sure you label you diagram appropriately and explain your reasoning.

† This question was developed at DCU.

Given the information in the question, I expect students to use the following reasoning for each prediction.

1. **All bulbs light**

   Students should infer that all bulbs are connected to the battery in complete loops and that no short circuits exist.
2. **Unscrewing bulb E does not affect any of the other bulbs**

   Students should recognise that bulb E must be in an independent parallel branch, i.e. connected directly across the battery, in order for this to be true.
3. **If a wire is connected across bulb A, the brightness of bulbs B, C and D increases**

   Students should recognise that if a wire is placed across bulb A, the bulb is shorted out and the resistance of the circuit is reduced. Since the brightness of bulbs B, C and D increases when this occurs, bulb A must be in series with a network containing bulbs B, C and D.
4. **Unscrewing bulb C (leaving the socket in the circuit) causes bulb D to go out**

   Since the removal of bulb C causes bulb D to go out, these two bulbs are arranged in series. No inference can be made about bulb B.
5. **If bulb B is unscrewed the other bulbs still glow although not necessarily with the same brightness**

   This prediction implies that bulb B is placed in a parallel branch. Since the shorting of bulb A affects its brightness, it cannot be connected across the battery. If bulb B were connected in series with bulb C and D, these would go out. Hence bulb B must be connected in parallel to the series network of bulbs C and D.

Using the above reasoning, the circuit diagram shown in Figure 3.25 can be drawn. The analysis shows that 45% of students provided the correct circuit diagram. A further 25% provided diagrams which had one bulb out of place while the remaining 30% had two or more mistakes.

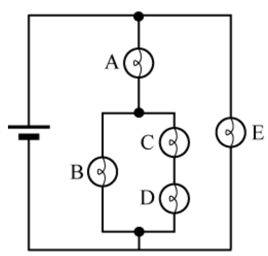


Figure 3.25: Correct circuit diagram for Current and Resistance Post-Test 3.

The circuit diagrams with one mistake are shown in Figure 3.26.

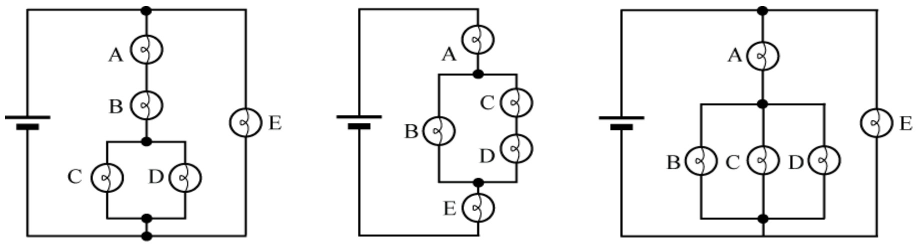


Figure 3.26: Incorrect circuit diagrams drawn by students in response to Current and Resistance Post-Test 3.

The circuit on the left has placed bulb B in series with bulb A which disagrees with prediction 5, as the removal of bulb B in this case, would cause bulbs A, C and D to go out. The middle circuit places bulb E in series with bulb A and with the parallel network of bulb B, C and D. This contradicts prediction 2 as unscrewing bulb E would cause all other bulbs to go out. Finally, the circuit at right places bulb C in parallel with bulb D rather than in series. Prediction 4 states that unscrewing bulb C causes bulb D to go out. As drawn in the circuit at right in Figure 3.26, bulb D would remain lit upon the removal of bulb C. The analysis of students' circuit diagrams provided the data shown in Table 3.7.

Table 3.7: Analysis of circuit diagrams for Current and Resistance Post-Test 3.

Category	2006 % (*N*=18)	2007 % (*N*=14)	Total % (*N*=32)
All bulbs light: No shorts, open switches	**65 (12)**	**95 (13)**	**80 (80)**
Bulb E is in parallel to all other bulbs	**45 (8)**	**100 (14)**	**70 (22)**
Bulb A in series to bulbs B, C, D	**70 (13)**	**70 (10)**	**70 (23)**
Bulbs C and D in series	**50 (9)**	**80 (11)**	**65 (20)**
Bulb B in a parallel branch to [CD]	**65 (12)**	**65 (9)**	**65 (21)**
Other	10 (2)	0 (0)	5 (2)

Considering that this was an unseen type of question, the results show that many students have formed a coherent model for electric circuits by displaying an ability to 'work backwards' from a set of predictions to form the circuit in question.

3.5 Equivalent Resistance

In sections 1 through 4 of the PbI curriculum, the qualitative development of current and resistance is covered comprehensively while in sections 5 and 6 students begin to add a quantitative structure to their model. This should not be unfamiliar to students as it forms a large part of traditional instruction of electric circuits both at second and tertiary level.

3.5.1 Equivalent Resistance: Pretest and Analysis

The pretest which was carried out over the three years examined students' understanding of two key concepts.

- Equivalent resistance of a series and parallel network of linear resistors.
- Equivalent resistance of a series network of bulbs.

The equivalent resistance of a series network of linear resistors is a topic typically covered in first year introductory physics modules and many end-of-chapter problems are based on it. Understanding of the equivalent resistance of bulbs may be inferred from the study of the I-V relationship of a filament bulb that is carried out as part of secondary school and first year university curriculum. However we find that no student makes this inference. To test students' ability in understanding these concepts, they were given the pretest consisting of several related questions.

Equivalent Resistance Pretest 1, Question 1

Two ammeters, a bulb, and a 35-cm piece of nichrome wire are connected as shown at right. The ammeters have the same reading.

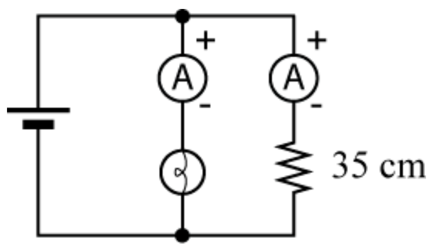


Figure 3.27: Parallel circuit of a bulb and 35 cm piece of nichrome wire.

Is the resistance of the bulb greater than, less than, or equal to the resistance of the nichrome wire? Explain your reasoning.

The analysis shows that students do not find this question difficult, as all students in all three years answered the question correctly by stating that the resistance of the bulb is equal to the resistance of the nichrome wire in Figure 3.27. This is not unexpected as the students have gained a comprehensive understanding of the relationship between current and resistance in sections 1-4, making it relatively straightforward to recognise that if the current through each branch is equal, then the resistance of each branch must be equal.

The second question of the pretest investigates students' understanding of the equivalent resistance of a series network of two pieces of nichrome wire.

Equivalent Resistance Pretest 1, Question 2

In the circuit shown at right, is the reading of ammeter 1 greater than, less than, or equal to the reading of ammeter 2? Explain your reasoning.

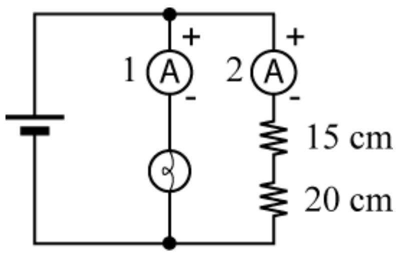


Figure 3.28: Parallel circuit containing a single bulb in parallel with a series network of two pieces of nichrome wire.

Similar to question 1, students do not find it difficult to answer this question correctly as only one student in the three years provided an incorrect answer, stating that the reading of ammeter 1 is greater than ammeter 2. The reasoning used is shown below:

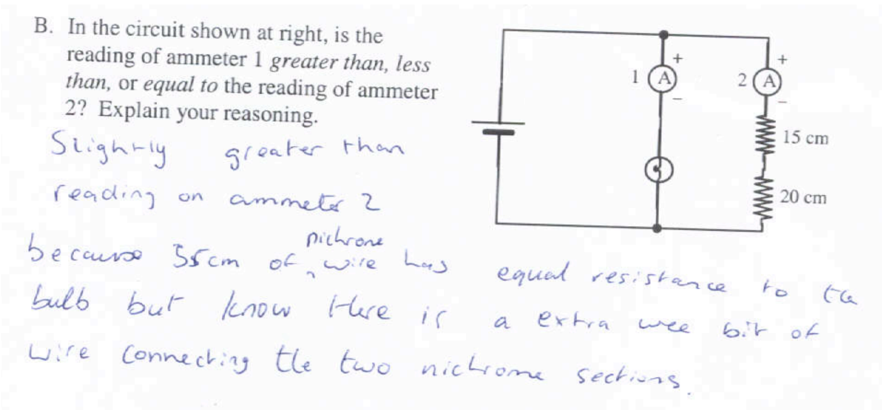


Figure 3.29: Example of a student's answer in response to Equivalent Resistance Pretest 1, Question 2.

For the last question of the pretest, students are faced with the following question.

Equivalent Resistance Pretest 1, Question 3

In the circuit shown at right, is the reading of ammeter 1 greater than, less than, or equal to the reading of ammeter 2? Explain your reasoning.

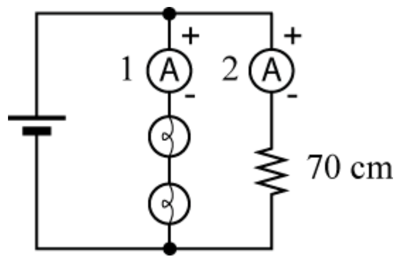


Figure 3.30: Parallel circuit containing a network of two bulbs in series and a 70 cm piece of nichrome wire.

In the circuit shown in Figure 3.30, a second bulb has been added in series with the first bulb and the 15 cm and 20 cm pieces of nichrome have been replaced by a 70 cm piece of nichrome. Although the resistance of the branch containing the nichrome wire has doubled in comparison to the circuits shown in Figure 3.27 and 3.28, the resistance of the branch containing the bulbs has not. Since the bulbs are now dimmer than a single bulb, their individual resistance is less than the resistance of a single bulb and thus their combined resistance is less than double the individual resistance, thus less than 70 cm. Therefore the reading on ammeter 1 is greater than the reading on ammeter 2. The analysis of the pretest answers shows that students are unable to apply this reasoning with 85% of students stating that the ammeter readings will stay the same.

Three of the five students who answered the question correctly did not provide an answer to the question, while one student stated that the reading of ammeter 1 is less than that of ammeter 2 and the other said it is greater. Students' reasons are shown in Figure 3.31 and Figure 3.32 respectively .

Ammeter 1< Ammeter 2

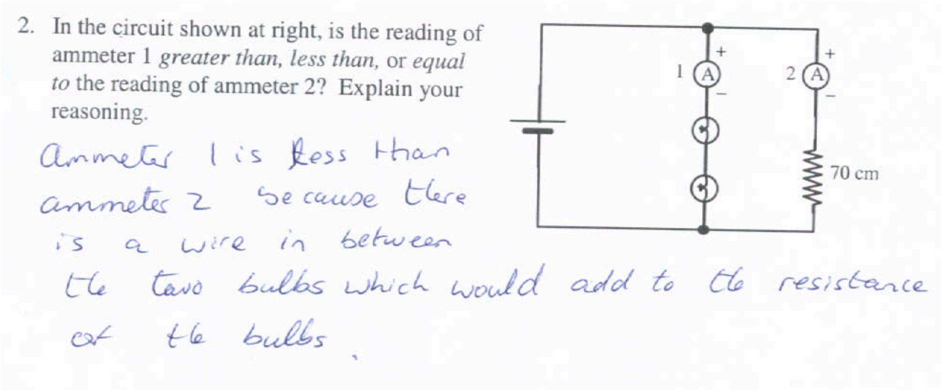


Figure 3.31: Example of a student's answer in response to Equivalent Resistance Pretest 1, Question 3.

Ammeter 1 > Ammeter 2

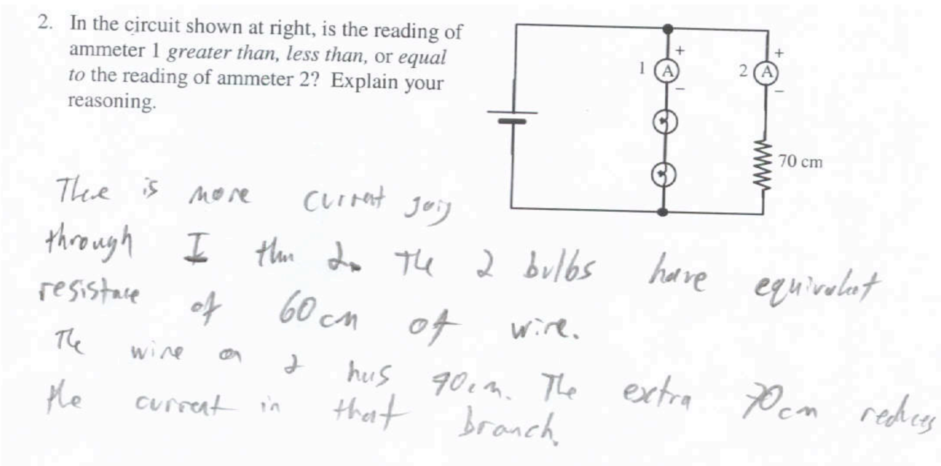


Figure 3.32: Example of a student's answer in response to Equivalent Resistance Pretest 1, Question 3.

Although the second student has provided a correct answer, it is difficult to establish how they determined the equivalent resistance value of 60 cm for the series network of bulbs.

3.5.2 Equivalent Resistance: Curriculum Discussion

One of the most significant aspects of this section of the curriculum is the development of rules for the equivalent resistance of a number of pieces of nichrome wire placed in series and in parallel.

Students carry out their investigation by placing two branches across a battery, one containing a network consisting of a number of pieces of nichrome wire in various arrangements, and another containing a single piece of nichrome wire.

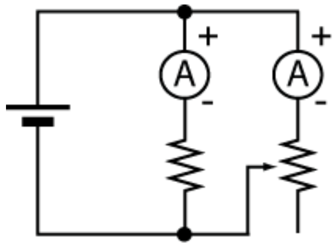


Figure 3.33: Circuit used in determining the equivalent resistance of pieces of nichrome wire.

Both branches also contain an ammeter as shown in Figure 3.33. By adjusting the length of the nichrome wire in the right branch until the ammeters read the same value, students can experimentally determine the equivalent resistance of the arrangement of the pieces of nichrome wire in the left branch. This allows them to determine that the equivalent resistance of *n* pieces of nichrome wire connected in series is equal to the sum of their lengths. They also discover that the arrangement of *n* pieces of nichrome wire, of equal length, connected in parallel has the equivalent resistance of *1* piece / *n*. What is different to other electric circuits curricula is that resistance is expressed in units of centimetres of nichrome wire.

At the conclusion of the section, students carry out a significant investigation on the equivalent resistance of a bulb. Using the same experimental set-up as previously described, students determine the equivalent resistance of networks consisting of a single bulb, two bulbs in series and three bulbs in series. Students find that the resistance of a two bulb series network is less than twice the resistance of a single bulb. This allows them to find that the resistance of a bulb decreases as the current through it decreases and vice versa.

3.5.3 Equivalent Resistance: Post-Test and Analysis

The post-test for this concept consisted of a number of different questions, two of which are analysed here. The first question, which was given on the final exam of the 2006 module, is shown overleaf.

Equivalent Resistance Post-Test 1†

Suppose you were provided with five pieces of nichrome wire, all of which have a length of 60 cm. Show how you could create a set-up which has an equivalent resistance of the four values given below. In each set-up you may use any number of pieces of nichrome wire (up to five), but you must use their full length; e.g., in (iii) you may not attach a clip at one end of a nichrome wire and another at 36 cm from that end.

(i) 180 cm (ii) 80 cm (iii) 36 cm (iv) 24 cm

It was expected that most students could complete the first two set-ups since the arrangement of wires is not too complicated. The correct circuits and indicative reasoning, are shown diagrammatically in Figure 3.34.

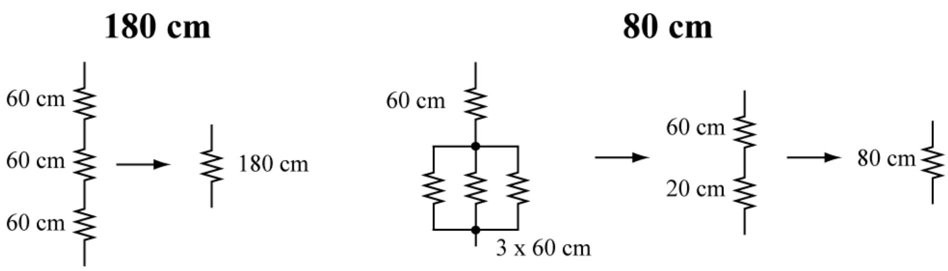


Figure 3.34: Correct circuit arrangements for two of the tasks in Equivalent Resistance: Post-Test 1.

The results for these set-ups are shown below in Table 3.8.

Table 3.8: Some results for Equivalent Resistance Post-Test 1.

	180 cm			80 cm		
	2006 E2 % (*N*=18)	**2007 E2 % (*N*=14)**	**Total % (*N*=32)**	**2006 E2 % (*N*=18)**	**2007 E2 % (*N*=14)**	**Total % (*N*=32)**
Correct set-up	**90 (16)**	**95 (13)**	**90 (29)**	**75 (13)**	**100 (14)**	**85 (27)**
Incorrect set-up	10 (2)	5 (1)	10 (3)	15 (3)	0 (0)	10 (3)
Almost correct	0 (0)	0 (0)	0 (0)	10 (2)	0 (0)	5 (2)

As expected, a large number of students drew the correct arrangements for the 180 cm and 80 cm arrangements. However, the results for the remaining two arrangements were quite poor, which is understandable considering the complexity

† This question was developed at DCU.

of the question. Again, the correct circuits and indicative reasoning for the 36 cm and 24 cm arrangements are shown in Figure 3.35.

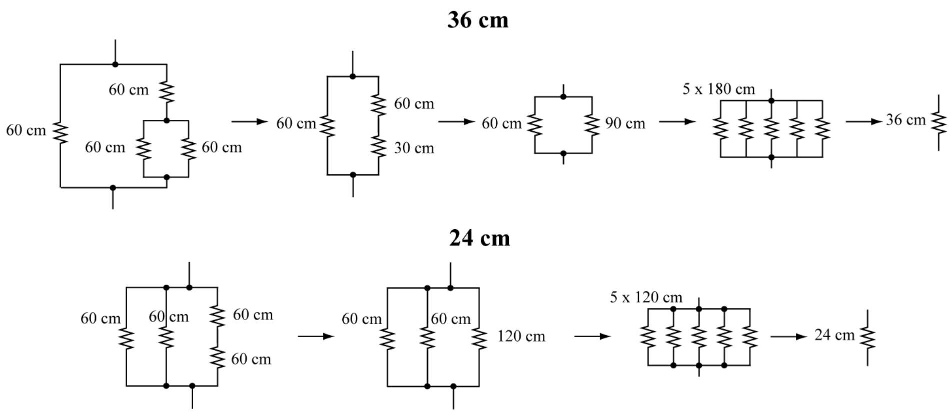


Figure 3.35: Correct circuit arrangements for two of the tasks in Equivalent Resistance Post-Test 1.

Student's answers to these two arrangements are shown in Table 3.9.

Table 3.9: Some results for Equivalent Resistance Post-Test 1.

	36 cm			24 cm		
	2006 E2 % (*N*=18)	**2007 E2 % (*N*=14)**	**Total % (*N*=32)**	**2006 E2 % (*N*=18)**	**2007 E2 % (*N*=14)**	**Total % (*N*=32)**
Correct set-up	**15 (3)**	**0 (0)**	**10 (3)**	**25 (4)**	**15 (2)**	**20 (6)**
Incorrect set-up	70 (13)	20 (3)	50 (16)	55 (10)	20 (3)	40 (13)
Correct set-up >5 pieces	5 (1)	15 (2)	10 (3)	5 (1)	5 (1)	5 (2)
No answer	5 (1)	65 (9)	30 (10)	15 (3)	55 (8)	35 (11)

It was not surprising to see that the majority of students could not answer this question correctly. The unsatisfactory results may be linked to students' lack of experience with such questions. The exercise which addresses this concept is the second last exercise in the curriculum on current and resistance. In some cases, students do not reach this exercise and in most cases, it is rushed through with little time spent on understanding the concepts.

The second question that was analysed examined students' understanding of the relationship between a bulb's resistance and the current through the bulb. The first part of the question is shown below.

Equivalent Resistance Post-Test 2, Question 1†

In the following problem, the resistors, R_i, are identical pieces of nichrome wire of length L. The bulbs, B_i, are identical.
It is observed that when one of the resistors ***or*** *one of the bulbs is connected to a battery as shown at right, the current through the battery is equal to i_o.*

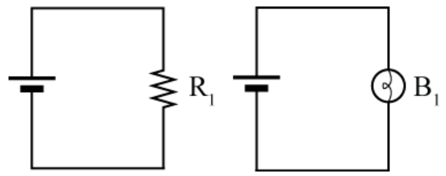


Figure 3.36: A single resistor circuit and a single bulb circuit.

Two resistors and two bulbs are each connected to batteries as shown at right.
Is the current through R_2 greater than, less than, or equal to that through B_2? Explain.

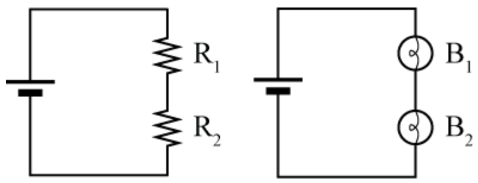


Figure 3.37: A two resistor series circuit and a two bulb series circuit.

This question is identical in context to the third question of the equivalent resistance pretest, which is discussed in detail on page 44. The first piece of information given in the question highlights that the resistance of the bulb is equal to the resistance of the nichrome wire. This is true as the current through the battery is equal for both cases. However when a second bulb is added the equivalent resistance of the network of bulbs does not double, unlike the equivalent resistance of the two resistors in series. This causes the current through B_2 to be greater than that through R_2. However as the analysis in Table 3.10 shows, many students found this task difficult as most failed to apply the idea that the resistance of a bulb changes with changes in current through the bulb.

† This question was developed at UW.

Table 3.10: Results of Equivalent Resistance Post-Test 2, Question 1.

Question 1	% (N=23)
Less than	**25 (6)**
Greater than	15 (4)
Equal to	50 (12)
Not possible	5 (1)

The second question of the post-test again dealt with the ability of students to calculate the equivalent resistance of an arrangement of nichrome wires in series and in parallel. The question is shown below.

Equivalent Resistance Post-Test 2, Question 2

In Circuit 1 at right, each resistor is a 15 cm piece of nichrome wire. The equivalent resistance of bulb B_1 in Circuit 1 is 35 cm of nichrome wire.

What is the equivalent resistance (in cm of nichrome wire) of the arrangement of circuit elements B_1, R_1, R_2, and R_3 in Circuit 1? Explain.

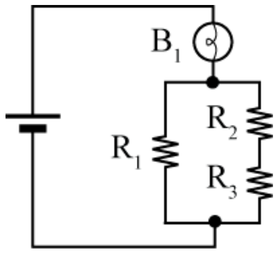


Figure 3.38: A single bulb in series with a parallel network of linear resistors.

The results are shown in Table 3.11.

Table 3.11: Results of Equivalent Resistance Post-Test 2, Question 2.

Question 2	% (N=23)
45 cm	**50 (12)**
40 cm	20 (5)
65 cm	5 (1)
Not answered	5 (1)
0.2	5 (1)
10 cm /not possible	10 (2)
50 cm	5 (1)

The arrangement of the resistors in Figure 3.38 is quite similar to the correct arrangement for 80 cm of nichrome wire in Figure 3.34. In that question, we find that 75% of the 2006 and 100% of the 2007 class could draw the correct arrangement. However in this question we find that only 50% of students can determine the equivalent resistance of the circuit. An additional 20% treated the parallel network of resistors equal to three 15 cm pieces in parallel, thus determining the equivalent resistance of the network as 5 cm and the overall resistance as 40 cm. Once again we find that in one context students seem to have a solid grasp of a concept. When it is transferred to a different context their original difficulties reappear.

3.6 Conclusion

In this chapter, the development of students' understanding of current and resistance was discussed. At first, the primary misconceptions held by students were revealed in the pretest analysis. The majority of these misconceptions were consistent with those documented in the literature. We found that the majority of students apply a constant current model when asked to rank the relative brightness of bulbs in three different circuits. In doing so, they reveal a belief that the current through a battery is always the same regardless of what elements are connected to the battery. In a large number of cases we found that this misconception was overruled by the belief that a single bulb is brighter than any bulb in a two bulb-circuit.

Other misconceptions such as the belief that the proximity of the bulb to the battery influences brightness and the inability to differentiate related concepts, were also prevalent. To further probe the misconception that the proximity to the battery influences brightness, and to examine students' understanding of circuit diagrams, changing the circuits diagrams in Figure 3.10 to look like those in Figure 3.39 has been proposed.

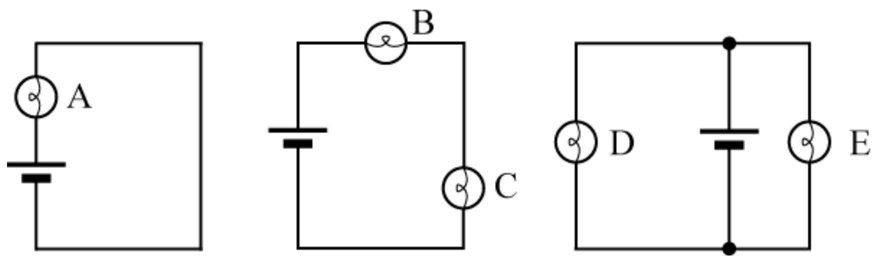


Figure 3.39: Proposed circuit diagrams for a single bulb circuit, a two bulb series circuit and a two bulb parallel circuit.

After eliciting students' misconceptions from the pretest analysis, a discussion of how the curriculum tackled these issues took place. The discussion outlined how the PbI curriculum allows students to work through a process of inquiry where difficulties with the concepts can be resolved. The concepts of complete circuits, conductors and insulators and short circuits are covered in the first section. Students discover that a sequential arrangement of circuit elements, in which a complete conductive pathway is formed, is necessary. On completion of the opening section, they are introduced to the concept of current. They are encouraged to think of a 'round trip' model and discover that the amount of current through the battery can change, depending on the arrangement of elements which it is connected to. This naturally paves the way for the introduction of resistance and to associate resistance with bulbs and nichrome wires.

Based on observations of bulb brightness, students find that the resistance of a circuit increases when a bulb is added in series, but decreases when a bulb is added in parallel. Rules for independent and dependent parallel branches are also discovered.

In the closing sections of the PbI curriculum on current and resistance, students discover experimentally the equivalent resistance of *n* pieces of nichrome wire arranged in series and in parallel. In the final section they discover that a bulb's resistance is dependent on the current through the bulb, where an increase in current causes an increase in resistance.

The post-test data discussed in this chapter highlighted areas where students conceptual understanding has improved. After instruction, 90% of students recognised an incomplete circuit.

Even if completely correct analysis of complex circuits remains difficult, the majority of students correctly ranked bulbs connected in series and parallel networks.

The students still find some concepts difficult, particularly the concept of equivalent resistance and the dependence of a bulb's resistance on the current through it. Time constraints may contribute to relatively poor post-test results.

References

1. L. C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry vol II*, 383 - 429, (Wiley, New York 1996)
2. L. C. McDermott, P. S. Shaffer, *Research as a guide for curriculum development: An example from introductory electricity. Part II: Design of instructional strategies*, Am. J. Phys. **60** (11), 1003-1013, 1992.
3. L. C. McDermott, P. S. Shaffer, *Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding*, Am. J. Phys. **60** (11), 994-1003, 1992.
4. D. Psillos, P. Koumaras, A. Tiberghien, *Voltage presented as a primary concept in an introductory teaching sequence on DC circuits,* Int. J. Sci. Ed., Vol 10, No 1, 29-43, 1988.
5. P. V. Engelhardt, R. J. Beichner, *Students' understanding of direct current resistive electrical circuits,* Am. J. Phys. **72** (1) 2004.
6. D. M. Shipstone, (1985). 'Electricity in simple circuits' In R Driver, E Guesne & A Tiberghien (Eds.), *Children's ideas in science,* (pp. 291-316). Milton Keynes: Open University Press.
7. D. M. Shipstone, C. v. Rhöneck, W. Jung, C Karrqvist, J. J. Duphin, S. Johsua, P. Licht, *A study of students' understanding of electricity in five European countries,* Int. J. Sci. Ed., Vol 10, No 3, 303-316, 1988.
8. J. Evans, *Teaching Electricity with Batteries and Bulbs*, Phys. Teach. **16**, 15, 1978.
9. N. Fredette, J. Lochhead, *Student conceptions of simple circuits*, Phys. Teach, 1980.
10. A. B. Arons, *Teaching Introductory Physics*, Wiley, New York, 1997.
11. C. Nicolaou, C. P. Constantinou, *Obstacles to the development of conceptual understanding in observational astronomy: The case of spatial reasoning difficulties encountered by pre-service teachers*, First International Girep Seminar, 2001.
12. R. J. Osborne, *Towards modifying children's ideas about electric current*, Journal of Research in Science and Technological Education **1**, 73-82, 1983.
13. L. C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry vol II*, 397 - 405, Wiley, New York 1996.

Chapter 4

Development of Voltage Curriculum

4.1 Introduction

The development of inquiry based curriculum on the concept of voltage and the topics of multiple batteries in multiple loops and RC circuits was one of the primary objectives of my research project. This chapter discusses the development of curriculum for the concept of voltage.

The curriculum builds upon the published current and resistance curriculum in Physics by Inquiry[1], which was discussed in the previous chapter. While many of the experiments and exercises from the published voltage curriculum[2] have been retained, it was agreed early in the development stages that a new approach was required. It was felt that the published curriculum did not emphasise the conceptual understanding of voltage to the same depth as the concepts of current and resistance. Fellow Physics by Inquiry instructors agreed with this opinion.

The new approach was mainly concerned with introducing the concept of voltage qualitatively. It has been introduced, without the use of a voltmeter, in terms of current and resistance. The curriculum allows students to differentiate clearly between voltage and current. By introducing voltage in terms of current and resistance, students discover that both concepts are different and above all discover that the battery is a voltage provider and not a current provider.

In the following pages, I discuss the published PbI voltage curriculum in some detail and comment on the reasons why I felt it needed to be redeveloped. This is followed by a discussion of the latest version of the curriculum from a global perspective, which is intertwined with pretest and post-test results. The data from the most recent edition is compared, where possible, to the data from the 2006 and 2007 modules. The report concludes with a discussion of the successes of the curriculum and the areas which need to be further developed.

4.2 The Published Curriculum

In reviewing the reasons for which I redeveloped the published voltage curriculum, it is important to note that my concern was mainly with the sequence of experiments, the early focus on quantitative data, and the lessened emphasis on conceptual development, rather than the individual purpose of each experiment and exercise. Many of the published experiments and exercises function efficiently and have been retained or modified slightly. Over the course of this section, I discuss some of these matters in detail.

The concept of voltage is dedicated two sections, 7 and 8, in the published PbI curriculum. Section 7 focusses on the effect of adding batteries to a circuit along with forming rules for voltages across circuit elements in series and circuit elements in parallel. Section 8 is mainly focussed on the application of Kirchhoff's loop rule to series circuits which contain parallel networks.

The opening two experiments of section 7 guide students to investigate how the addition of a battery to a circuit affects the current through the circuit. The first of these experiments instructs students to compare the brightness of bulbs in a single bulb circuit, a two-battery-two-bulb series circuit and a three-battery-three-bulb series circuit as shown in Figure 4.1.

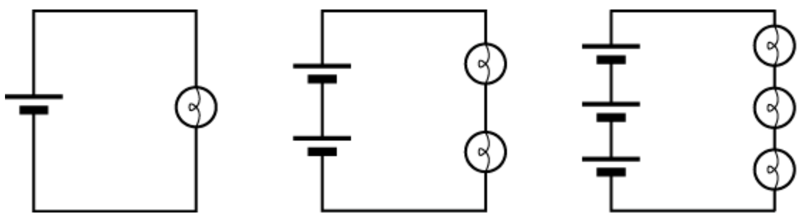


Figure 4.1: A single bulb circuit, a two battery-two-bulb series circuit and a three-battery-three-bulb series circuit.

They observe that the addition of a battery in series increases the brightness of bulbs in the circuit thus inferring that the current through the circuit has increased. Furthermore, they observe that the addition of bulbs in series reduces the current. On the basis of this experiment, a narrative encourages the students to think of the battery as the agent that pushes or drives the current through the circuit, since when the resistance of the circuit increases, the number of batteries must be increased in order for the current to remain the same.

The combination of the first experiment followed by the narrative is uncharacteristic of the inquiry based material. Although narrative is essential in parts of the curriculum to summarise ideas, I feel that students' understanding could be probed further such as to infer the change in resistance based on their understanding of series circuits and equivalent resistance.

Students are then introduced to the voltmeter. Relationships between voltages and between voltage and resistance are developed based on quantitative measurements. By contrast, the concepts of current and resistance are treated quantitatively in section 5 of the published curriculum, only after students have carried out four qualitative sections on the concepts.

The issue of applying an analogy to the concept of voltage was a topic of much discussion during the three years of development. Although there can be significant value in the use of analogies[3,4], the concept of drive or push is not satisfactory in describing the voltage across a bulb or piece of nichrome wire. Applying the analogy to a bulb or piece of nichrome wire, students may infer that the bulb or piece of nichrome wire drives or pushes the current through the circuit. This is obviously not ideal, however a satisfactory alternative is difficult to attain; as concepts like electric field and line integrals are not known to the intended audience. It could be argued that the analogy of resistance with an obstacle is equally flawed. For example, it is not intuitively clear, that when two obstacles are placed in parallel, the resistance they offer would be less than the individual resistance[5].

The experiments which follow this introduction in the published PbI curriculum have seen very little further development. The development of the voltage curriculum focusses mainly a new introduction of the concept. The development process is discussed over the following sections.

4.3 New Curriculum: A Global Perspective

The writing of new curriculum proved a difficult task as the concept of voltage is quite abstract and difficult to link seamlessly with the current and resistance model described in Chapter 3. Where possible, I wanted the students to investigate as freely as possible the concept of voltage, its use in modelling circuits, and its relationship with current and resistance, while avoiding the pitfall of making Ohm's Law seem like a fundamental law of physics. Without the explicit use of an analogy for voltage, I wanted students to develop a set of rules for their model that would allow them to make accurate predictions on more complicated circuits or those in which the current model failed. The curriculum has undergone many changes over the past number of years. I focus firstly on the most recent version and explain the sequential development of the concepts.

4.4 Multiple Batteries

The opening section of the new curriculum consists of two parts. The first part deals with the addition of a second battery to a single loop circuit while the second part deals with finding a relationship for voltage in terms of current and resistance.

In the opening experiments, I wanted to immediately guide students towards a particular line of reasoning. In sections 1-6 of the published PbI curriculum, students based their reasoning on bulb brightness with no explicit focus on the function of the battery. Therefore I wanted students to shift their focus to the battery and see how adding batteries could affect the brightness of bulbs in a circuit. In the initial stages of development I was not fully aware of the misconceptions attached to the concept of multiple batteries in single loops, but analysis of the first pretest broadened my scope and clearly highlighted some key difficulties students have with this section of the curriculum.

4.4.1 Multiple Batteries in Series: Pretest and Analysis

In the 2006 module, students were given the following pretest question which focusses on connecting batteries in series and connecting batteries in opposite orientation in a single loop. It examines students' understanding of how the addition of batteries in series with each other, affects bulb brightness. It also implicitly addresses students' understanding of series and parallel circuits.

Multiple Batteries in Series Pretest 1, Question 1

Rank the six bulbs (A-F) in order of brightness, from brightest to dimmest. Explain your reasoning. Note: Battery 8 is connected in opposite orientation.

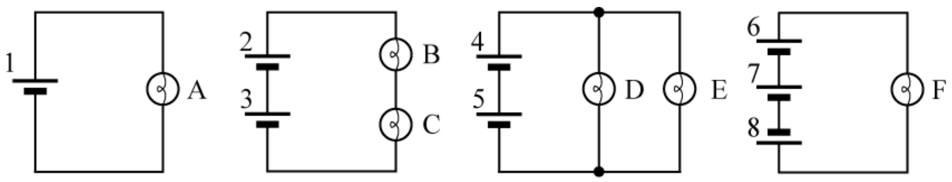


Figure 4.2: Circuit diagrams presented in Multiple Batteries in Series Pretest 1, Question 1.

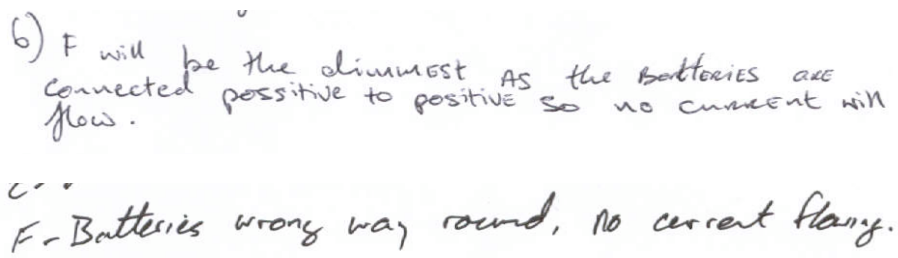
Like many other questions involving a large number of bulbs, the students returned a multitude of answers, in this case, 13 individual rankings from a total of 18 for the bulbs shown in Figure 4.2. Since it is difficult to interpret students' understanding from the individual rankings, I have analysed the data to highlight partial rankings as shown in Table 4.1.

Table 4.1: Partial rankings to Multiple Batteries in Series Pretest 1, Question 1.

Ranking	% (*N*=18)
Correct ranking	**5 (1)**
Bulb D = Bulb E	**95 (17)**
Bulb B = Bulb C	**95 (17)**
D = E > B = C	**85 (15)**
Bulb D & E brightest	**45 (8)**
Bulb A = Bulb B	**15 (3)**
Bulb A = Bulb F	**0 (0)**
Bulb F doesn't light	60 (10)

The data shown in Table 4.1 highlights that most students have little difficulty in making individual rankings based on their understanding of current and resistance as illustrated in the case of the circuits containing bulbs B and C and bulbs D and E in Figure 4.2. Both circuits contain two batteries in series, so students can liken the case to the comparison of the brightness of two bulbs in series to two bulbs in parallel. They completed this task successfully as 85% ranked bulbs D and E brighter than bulbs B and C. They also correctly rank bulbs in series (bulbs B and C) and bulbs in parallel (bulbs D and E) equal to each other respectively. Moreover, their reasoning is correct. This aspect of the question serves as a post-test, nine months after the current and resistance module, and high retention is observed.

However, the rankings which require an understanding of voltage and the affects of adding batteries to a circuit, were done quite poorly. The most common incorrect answer was to state that bulb F doesn't light due to the opposite orientation connection of battery 8. Two representative answers are shown in Figure 4.3.


6) F will be the dimmest As the Batteries are connected possitive to positive so no current will flow.

F - Batteries wrong way round, no current flowing.

Figure 4.3: Examples of students' answers in response in Multiple Batteries in Series Pretest 1, Question 1.

The results in Table 4.1 show that only 15% of students recognised that bulb A was equal in brightness to bulb B and as a consequence of the previous misconception regarding bulb F, no student stated that bulb A was equal in brightness to bulb F. The analysis of students' reasoning also revealed that no student referred to the concept of voltage in explaining their reasoning to this question. This highlights that students have either some understanding of voltage but are uncomfortable in applying it in modelling circuits, or very little to no understanding of the concept and therefore rely on their understanding of current and resistance. These misconceptions were probed further in the second part to the first question.

Multiple Batteries in Series Pretest 1, Question 2

Rank the eight batteries (1-8) in order of the current through them, from greatest to least. Explain your reasoning.

Since only one student gave the correct answer to the previous question, it was not expected that many students would provide the correct ranking of the current through the batteries, as the two questions are related. This was shown to be true as the analysis of students' answers revealed that no student provided the correct ranking. It must also be noted that seven students did not make an appropriate ranking and repeated the same ranking for bulb brightness. The correlation between the two answers is shown in Table 4.2.

Table 4.2: Correlation between answers to Multiple Batteries in Series Pretest 1, Question 1 and Question 2.

Bulb Ranking	**N**	**Battery Ranking**	**Correct Correlation %**	**Incorrect Correlation %**
Bulb F doesn't light	11	No current through batteries 6, 7 and 8	**90 (10)**	10 (1)
Bulb A = B = C	3	Batteries 1=2=3	**65 (2)**	35 (1)
Bulb A > B = C	13	Battery 1>2=3	**40 (5)**	60 (8)
Bulbs D & E brightest	8	Batteries 4 & 5 greatest	**65 (5)**	40 (3)

The analysis of the correlation between answers to question 1 and question 2, showed that five of the eight students who correctly ranked bulbs D and E to be brightest made a correct correlation for the currents through batteries 4 and 5. The analysis also highlighted some contradictory correlations. For example, a student who ranked bulb A brighter than bulb B, ranked the current through batteries 2 and 3 higher than that through battery 1. The correlation between the bulb ranking A > B=C and the battery ranking of battery 1 > 2=3 was also done poorly with only 40% providing the correct correlation. Only two of the eight students who provided an incorrect correlation provided a complete ranking of the batteries, the other six students provided incomplete rankings or repeated their bulb ranking.

In the 2007 and 2008 module, students were given a different pretest, but the questions addressed the same issues. The question is shown below.

Multiple Batteries in Series Pretest 2

Rank the five bulbs (A-E) in order of brightness, from brightest to dimmest in the circuits below. Explain your reasoning.
Note: In circuit 1 and circuit 3, a battery is connected in a different orientation.

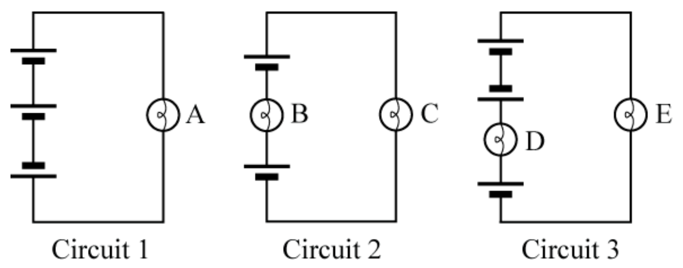


Figure 4.4: Circuit diagrams used in Multiple Batteries in Series Pretest 2.

The analysis showed that only one student in both years ranked the bulbs correctly, but the student's answer did contain some misconceptions. The analysis of the most common incorrect answers is shown in Table 4.3.

Table 4.3: Common incorrect answers for Multiple Batteries in Series Pretest 2.

Misconceptions	**% (*N*=30)**
Bulb A won't light	55 (16)
Bulb D won't light	45 (14)
Bulb E won't light	35 (11)
Bulb C > Bulb B	10 (3)
Bulb E > Bulb D	10 (3)

It is interesting to note that 10% of students abandon the idea that the current is the same at every point in a single loop when they rank bulb C brighter than bulb B, and rank bulb E brighter than bulb D. The analysis also shows that a large number of students state that the bulbs, connected in circuits with batteries in opposite orientation, don't light. This is consistent with the analysis of the 2006 data.

4.4.2 Connecting Batteries in Parallel: Pretest and Analysis

Since the opening experiments of the new curriculum also addressed the concept of adding batteries in parallel†, this concept was addressed in the first pretest. Once again the pretest for the 2006 module, which is shown below, differed slightly from the pretest in 2007 and 2008.

Connecting Batteries in Parallel Pretest 1

Rank the four bulbs (A-D) in order of brightness, from brightest to dimmest. Explain your reasoning.

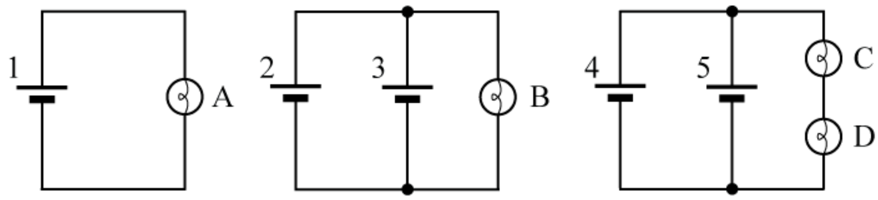


Figure 4.5: Circuit diagrams presented in Connecting Batteries in Parallel Pretest 1.

Students provided the rankings shown in Table 4.4.

Table 4.4: Rankings for Connecting Batteries in Parallel Pretest 1.

Ranking	% (N=18)	Ranking	% (N=18)
A=B>C=D	**30 (5)**	A>B>C>D	5 (1)
B>A>C=D	35 (6)	B=C=D>A	5 (1)
B>A>C>D	5 (1)	B>A=C=D	5 (1)
A>B>C=D	15 (3)		

Of the five students (30%) who ranked the bulbs correctly, three did not provide a reason for why they ranked bulbs A and B brightest. The other two gave incomplete statements as shown in Figure 4.6:

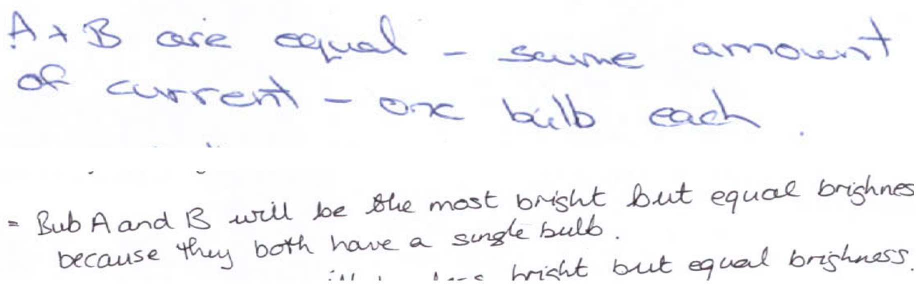


Figure 4.6: Examples of students' answers which ranked bulb A and bulb B as the brightest bulbs in Connecting Batteries in Parallel Pretest 1.

† This applies to the curriculum implemented at DCU in 2008. During revisions, the topic of adding batteries in parallel was moved to section 9.

The data in Table 4.4 shows that seven students ranked bulb B brighter than bulb A. The analysis of students' answers highlight that many of them based their reasoning on the misconception that the battery supplies current to the circuit. This leads them to believe that bulb B is brighter than bulb A since it is supplied current from two batteries rather than one. These results are similar to those documented by Licht[6]. Two representative answers are shown in Figure 4.7:

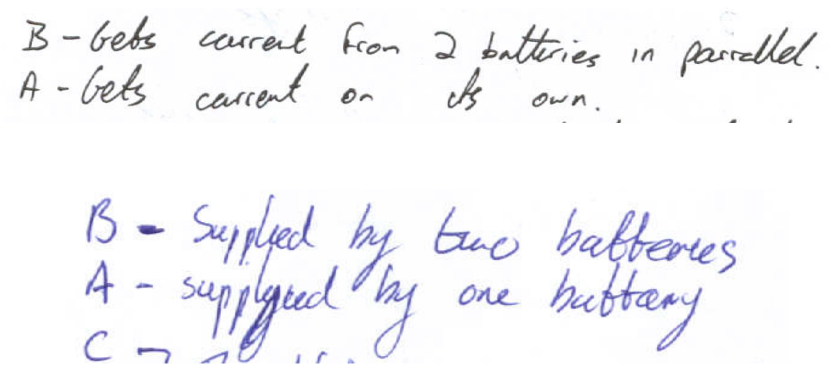


Figure 4.7: Examples of students' answers, which reveal a belief that a battery supplies current.

In the second question of the same pretest, students were also asked to rank the current through batteries 1-5 in the circuits shown in Figure 4.5. The rankings are shown in Table 4.5.

Table 4.5: Students' battery rankings in response to Connecting Batteries in Parallel Pretest 1.

Ranking	% (N=18)	Ranking	%. (N=18)
1>2=3>4=5	**15 (3)**	3=5>2=4>1	10 (2)
1=2=3=4=5	10 (2)	3=5>1=2=4	5 (1)
1=3=5>2=4	5 (1)	4=5>2=3>1	5 (1)
1=3=5>4>2	5 (1)	4>2>1>5>3	5 (1)
1?2?3>4=5	5 (1)	D>C>B>A	5 (1)
2=3>1>4=5	5 (1)	1=3	5 (1)
2=3>4=5>1	5 (1)	A>B>4=5	5 (1)

The results shown in Table 4.5 reveal 14 rankings for the current through the batteries. This highlights that many students do not correlate their bulb brightness ranking with the ranking of the currents through the batteries, since Table 4.4 only shows 7 bulb brightness rankings. The five students who correctly ranked the brightness of the bulbs in Figure 4.5 (A=B>C=D), gave five separate rankings for the current through the batteries. None of these rankings were consistent with their bulb ranking.

The corresponding rankings for the most popular incorrect bulb ranking (B>C>A=D) were slightly different. Three separate rankings for the current through the batteries were provided, two of which were correct. Despite having ranked bulb B brighter than bulb A, these two students still ranked the current through battery 1 greater than the current through battery 2 and 3. Although it is possible for this to be case, the students' answers do not reveal a deep understanding.

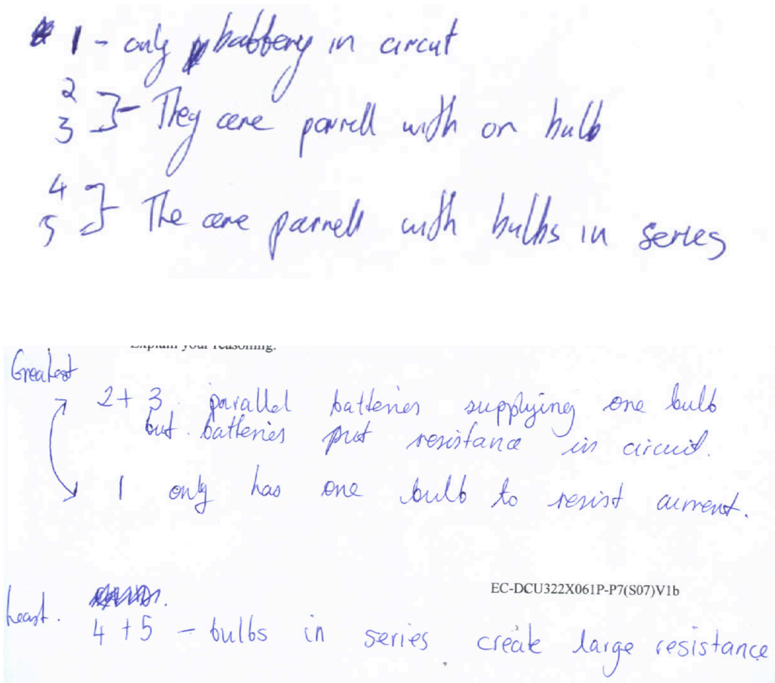


Figure 4.8: Examples of students' answers in response to Connecting Batteries in Parallel Pretest 1.

Inconsistencies were also shown as only three of the six students who ranked bulbs C and D as the dimmest, ranked the current through batteries 4 and 5 as the least. The analysis also shows that a third of the class ranked the current through batteries 2 and 3 or batteries 4 and 5 different to each other. This implies that these students do not recognise the symmetry in the connections.

As stated earlier, the pretest for the 2007 and 2008 modules differed slightly from the 2006 pretest. However it still addressed the issues of adding a second battery in series and in parallel to a single bulb circuit. The results were again varied with several different rankings provided. No additional misconceptions or findings were revealed from the analysis.

Considering the data which has been presented over the last number of pages, a number of misconceptions come to the fore. These are listed below:

- In the pretest on multiple batteries in single loops, the analysis revealed that a large number of students believe that bulbs, connected in circuits with batteries in opposite orientation, don't light. The analysis of students' answers show that they either state that no current flows in these circuits or that they are incomplete.
- In both the pretest for multiple batteries in singles loops and the pretest on connecting batteries in parallel, many students referred to the misconception that the battery supplies current. This has also been shown in pretests on the concepts of current and resistance and is well documented[7,8,9]. In the context of circuits containing more than one battery, this misconception is extended to the belief that the currents supplied by each battery are added, leading to an increased in bulb brightness.
- It was also evident from students' answers, that many relied on current and resistance reasoning only. This is not a misconception, but rather highlights the students' lack of understanding and confidence in reasoning based on the concept of voltage. Several studies have shown that students even at a quite advanced level, treat current as the primary concept, while voltage is regarded as a consequence of current and not as its cause [10].

These findings provide justification of the development of curriculum that guides students to investigate how adding batteries to a circuit affects bulb brightness. The next section discusses how the latest curriculum tackles students' beliefs and guides them to overcome their misconceptions.

4.4.3 Multiple Batteries: Curriculum Discussion

In the opening two experiments of the new curriculum, students grapple with the misconceptions shown previously by immediately adding a second battery to a single bulb circuit. As with the development of current and resistance, students first investigate the addition of batteries in series. They observe that the bulb brightness increases. Rather than allowing them to make a conclusion based on one observation, we ask them to carry out the same procedure on three additional circuits to test if the same observations hold true. Of course on the addition of the second battery in series, they notice that all bulbs attached to the circuit increase in brightness. From this observation students derive a rule like:

> *"When I add a second battery in series to another battery, the brightness of all bulbs in the circuit increases."*

Students then investigate how adding batteries in parallel affects bulb brightness. (The results in Table 4.4 and 4.5 show that students have considerable difficulty in predicting how the addition of a battery in parallel affects bulb brightness.)

They notice that the addition of a battery in parallel does not affect any of the bulbs in the circuit, thus allowing them to form another rule.

> *"When I add a second battery in parallel to another battery, the brightness of all bulbs in the circuit remain the same."*

At first glance the new curriculum appears to begin in a similar manner to that of the published curriculum (see section 4.2). In both curricula, students investigate the effects of adding a second battery to the circuit. The difference lies in the purpose of each experiment. In the new version, the experiments are designed to guide students to form the initial rules of their model. Their observations are not meant to support the analogy of push or drive, though this option is open to the individual instructor.

Following the addition of batteries in series and in parallel, students continue with three more experiments dedicated to adding batteries in opposite orientation in single loop circuits. They investigate if the order in which batteries and bulbs are connected affects bulb brightness. These three experiments help students tackle their misconceptions of the circuits shown in Figure 4.2.

By working through each of these experiments, students discover that when a battery is added in opposite orientation, it effectively cancels a battery already connected in the circuit. In addition to this, they discover that the order in which elements are placed in series does not affect the current through the circuit. Reasoning is based on current still.

4.4.4 Multiple Batteries: Post-Test and Analysis

Throughout the first half of the new section 7, students have gained a significant understanding of a number of concepts. The post-tests on this topic were carried out in the 2007 and 2008 mid-term exams in the aim to examine the improvement in students' understanding of the affects of adding batteries to a circuit. In the 2007 mid-term exam students were given the following problem.

Multiple Batteries Post-Test, Question 1

Rank the current through all the labeled components (batteries and bulbs) from greatest to least with both switches open. Explain your reasoning.

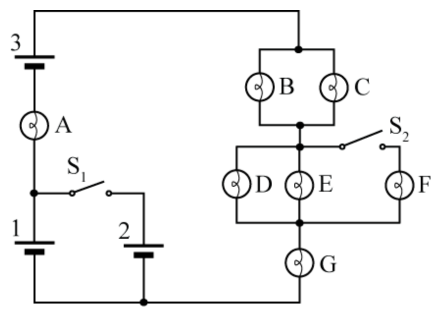


Figure 4.9: Circuit presented in Multiple Batteries Post-Test, Question 1.

It may be noticed that the question doesn't explicitly address the concept of adding batteries in opposite orientation. This was addressed in a homework problem at the end of section 7 and features in the curriculum on multiple batteries in multiple loops.

The intention of the post-test question was to address students' understanding of the affects of connecting batteries in parallel and how the order in which elements are connected affects bulb brightness. It also addressed concepts of current and resistance. In answering the question, some students ranked the current through the bulbs separately from their ranking of the current through the batteries. This consequently made it difficult to assess students' understanding. The analysis of students' answers provided the data shown in Table 4.6.

Table 4.6: Rankings for Multiple Batteries Post-Test, Question 1.

Ranking	% (*N*=17)
1=3=A=G>B=C=D=E>2=F	**55 (9)**
1=3>2 and A=G>B=C=D=E>F	20 (3)
A=G>B=C=D=E, 1& 2 don't work	5 (1)
1=2=3=A=G>B=C=D=E	5 (1)
1=3>2 and A>G>D=E=B=C>F	5 (1)
A>G>B=C=D=E	5 (1)
1=3>A=G>B=C=D=E	5 (1)

The data in Table 4.6 above shows that 55% of students answered the question correctly while a further 20% provided separate correct rankings of the current through the batteries and the current through the bulbs. Of the remaining answers, 15% ranked the current through the bulbs correctly. The results were satisfactory. However a number of students still struggled with some of the concepts. The analysis shows that 10% of students ranked bulb A brighter than bulb G although the bulbs are connected in series. This misconception was also prevalent in the multiple batteries in single loops pretest.

In the second part to the question, students were asked to comment on whether the brightness of bulb D would increase, decrease or remain the same when switch 1 was closed. The purpose of the question is to probe students' understanding of connecting batteries in parallel and their ability to transfer this understanding to a more difficult context. The students' answers are shown Table 4.7.

Table 4.7: Students' answers in response to Multiple Batteries Post-Test, Question 2.

Answer	% (*N*=17)	Correct Reasoning %	Incorrect reasoning %
Bulb D remains the same brightness	**90 (15)**	**85 (13)**	**15 (2)**
Bulb D increases in brightness	10 (2)		100 (2)

Students answered this question very well by recognising that the addition of battery 3 in parallel to battery 2, doesn't affect the current through the circuit. This gave some insight to the effectiveness of the curriculum in relation to this concept.

Although students excelled in this question, they very much struggled when asked to rank the current through all components when switch 1 was closed, even though it is directly related to the previous question. The results are shown in Table 4.8.

Table 4.8: Rankings to Multiple Batteries Post-Test, Question 3.

Ranking	% (*N*=17)
3=A=G>B=C=D=E=1=2>F	**25 (4)**
3>1=2,A=G>B=C=D=E	5 (1)
1=2=3,A=G>B=C=D=E>F	5 (1)
1=2=3>A=G>B=C=D=E	5 (1)
1=3=A=G>B=C=D=E>2=F	10 (2)
1=2=3=A=G>B=C=D=E>F	5 (1)
1=2=A=G>B=C=D=E	5 (1)
A=G>D=E=B=C	20 (3)
A>G>B=C=D=E>F	5 (1)
Other	10 (2)

As can be seen in Table 4.7 previously, 15 of the 17 students correctly stated that the brightness of bulb D would not change when switch 1 was closed, therefore implying that the current through the circuit had not changed. By analysing the circuit in Figure 4.9, it was hoped that students would recognise that the current must split between batteries 1 and 2. They would therefore rank the current through batteries 1 and 2 equal to that through bulbs B-E and less than battery 3. However, the results in Table 4.8 show that only five students ranked battery 3 greater than batteries 1 and 2 which were ranked equal to each other.

For the 2008 post-test the students were given a very similar circuit and asked similar questions. The analysis showed similar results to those discussed previously.

4.5 Voltage as a Product of Current and Resistance

In the second half of section 7, the curriculum takes a much different approach to the concept of voltage. Students are guided to recognise that the product of current through a circuit (single loop) and the resistance of a circuit always provides a constant regardless of the elements connected in the circuit. They also see that this product is proportional to the number of batteries connected to the circuit. The product is then given the name "voltage". Clearly there is a serious danger that students may confuse the equation V=IR with Ohm's law, which looks the same. This is discussed later in the curriculum.

To achieve this aim, students collect current and resistance data from two types of circuit; one consisting of bulbs and the other consisting of nichrome wire. The number of bulbs, length of nichrome wire and the number of batteries connected in series, varies in each circuit. The sequence of circuits presented in the curriculum has changed a number of times over the course of the development. In the 2008 curriculum, students begin by measuring the current through a circuit containing a single battery connected to an 80 cm piece of nichrome wire. Students vary the length of the nichrome wire to gather data for four different values of current and resistance.

This is followed by an experiment where students measure the current through a single bulb circuit, a two-bulb series circuit and a three-bulb series circuit, all connected to a single battery. Students determine the equivalent resistance (in cm of nichrome wire) of each network. In previous years we asked students to analyse their data in an attempt to form a relationship between current and resistance. It was hoped that they would recognise that the product of these two quantities is approximately constant. However, classroom experience showed that students could not do this spontaneously. To combat this we added an exercise which provided hypothetical data collected by a student in a similar experiment. This data is shown as it appears in the curriculum in Table 4.9.

Table 4.9: Extract from voltage curriculum of an experiment yielding hypothetical current and resistance data.

single battery circuit	
length of nichrome wire (cm)	**ammeter reading (mA)**
60	200
40	300
30	400
20	600

With the idealised data in Table 4.9, most students recognised that the product of the two values is a constant. A few students still struggled to see this and only managed to note that when the length of nichrome wire was increased, the current values decreased. In the checkout following the exercise, these students are guided through the process until they can interpret the data. On the completion of this exercise students check if the same pattern holds for their data in the previous circuits containing bulbs and nichrome wire, and see that (within ~ 5%) it is so.

Once students have discovered that the product of current and resistance yields a constant, they repeat the same experiments after adding a second battery in series to the circuits. Students recognise that the product of current and resistance is now approximately double the value of the product obtained from the single battery circuits.

The conclusions we hope students draw from these experiments are listed below:

- The resistance of the circuits was changed by varying the length of nichrome wire and by adding bulbs in series. This changed the current through the circuit.

- Regardless of the resistance of the circuit or the elements connected in the circuit, the product of current and resistance provided a constant value.
- The product for a two-battery circuit is twice that of a single battery circuit.
- Since the battery is the only element that did not change, the product is likely to be related to the battery.

Guiding students to associate voltage with the battery, and that it remains constant as long as the number of batteries remains constant was one of the key objectives of the curriculum. To help students see the significance of their data we asked them to comment on the following student statements.

> ***Student 1:*** *From my observations I can conclude that when I add a second battery in series the current always doubles.*
>
> ***Student 2:*** *After examining circuits in which a second battery was added in series, I conclude that the voltage always doubles."*

At first glance many students would like to agree with both students. Some students may still have the model that the battery acts like a bottle of current. In that model two batteries supply twice the amount of current. Others may use Ohm's law incorrectly. However, when students analyse their data for the bulb circuits they recognise that the current did not double when a second battery was added. Even though the voltage doubles in all circuits. This is a key idea in helping convince students that voltage is a concept associated with the battery, and in helping rule out the idea that the battery provides current to the circuit.

4.6 Kirchhoff's Loop Rule: Pretest and Analysis

In the pretest on measuring voltage we wanted to examine students' ability to rank the voltage across a number of bulbs connected in different circuits. Millar and Beh express this ability as one part of an understanding of voltage[11]. The post-test is carried out after students have completed section 7 of the new curriculum. They have not yet been introduced to the voltmeter.

Kirchhoff's Loop Rule Pretest

(1) Compare the voltage across bulb A to bulb B. Explain.
(2) Compare the voltage across bulb B to bulb C. Explain.
(3) Compare the voltage across bulb D to bulb E. Explain.
(4) Compare the voltage across bulb A to bulb E. Explain.

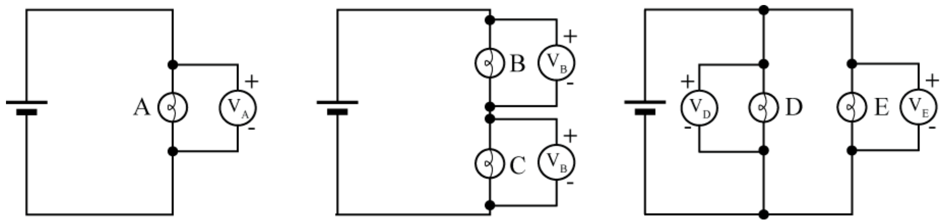


Figure 4.10: Circuits presented in Kirchhoff's Loop Rule Pretest.

The first question asked students to compare the voltage across bulb A (V_A) to the voltage across bulb B (V_B). Although students have seen that when the voltage across a bulb is increased, its brightness increases, they do not intuitively reason on the basis that brightness is an indicator of voltage. Since students have extensive experience with the circuits in Figure 4.1, this would allow them to rank the voltmeters correctly. However, as the results in Table 4.10 show, most students do not see this line of reasoning.

Table 4.10: Students' answers in response to Kirchoff's Loop Rule Pretest, Question 1.

Answer	% (N=11)
$V_A > V_B$	**25 (3)**
$V_A = V_B$	75 (8)

The reason that the majority of students have concluded that the voltage across bulb A is equal to the voltage across bulb B stems from their analysis of voltage in the previous section. Students had just discovered that the product of current and resistance is a constant related to the number of batteries. Many students carried this concept with them and apply the same logic unsuccessfully. Two representative answers are shown in Figure 4.11:

i. Compare the reading of V_A to V_B. Explain your reasoning.

$V_A \gneqq V_B$ Bulbs B+C are in series which increases the resistance ∴ decreases the current. when multiplied they will give the same Voltage as VA as both batteries identical

i. Compare the reading of V_A to V_B. Explain your reasoning.

Voltage on both V_A and V_B are the same as the voltage stays the same if the amount of batteries stay the same.

Figure 4.11: Examples of students' answers in response to Kirchhoff's Loop Rule Pretest, Question 1.

When asked to compare the voltage across bulb B and bulb C all students stated that the two voltages would be equal for a variety of reasons. Some state that the voltages are equal since they are in series; others make reference to the product of current and resistance.

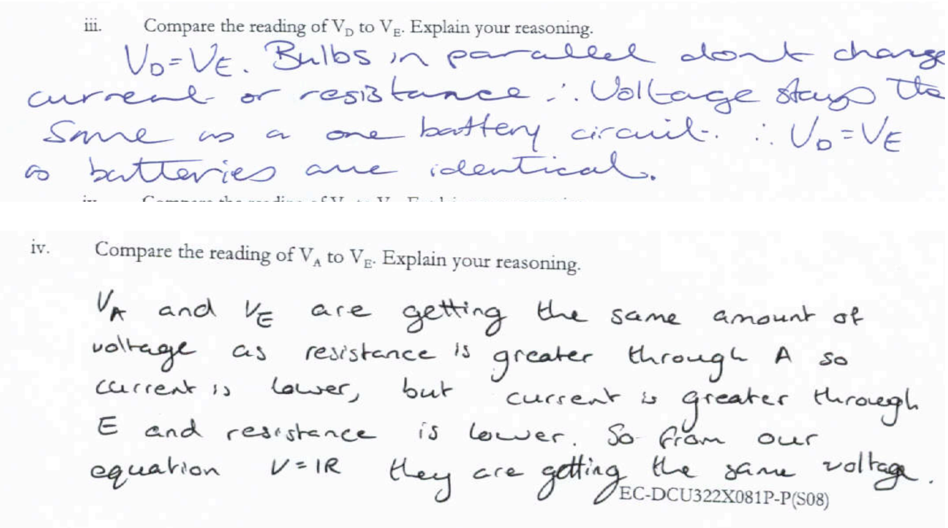
> *"I think all the voltages will be the same as the relationship between current and resistance will end up giving a constant voltage for all as there is only a single battery in each circuit"*

ii. Compare the reading of V_B to V_C. Explain your reasoning.

V_B + V_c will be the same
They are in series with eachother
B + C will have same brightness

Figure 4.12: Examples of a student's answer in response to Kirchhoff's Loop Rule Pretest, Question 2.

When asked to compare V_D to V_E and V_A to V_E all students stated that these voltages would be equal. Of course these are correct rankings. However, when one analyses students' responses, it becomes apparent that many students cannot differentiate at this stage between the voltage across a battery and the voltage across a bulb. Two examples of students' answers are shown in Figure 4.13:



iii. Compare the reading of V_D to V_E. Explain your reasoning.

$V_D = V_E$. Bulbs in parallel don't change current or resistance ∴ Voltage stays the same as a one battery circuit. ∴ $V_D = V_E$ as batteries are identical.

iv. Compare the reading of V_A to V_E. Explain your reasoning.

V_A and V_E are getting the same amount of voltage as resistance is greater through A so current is lower, but current is greater through E and resistance is lower. So from our equation $V = IR$ they are getting the same voltage.

EC-DCU322X081P-P(S08)

Figure 4.13: Examples of students' answers in response to Kirchhoff's Loop Rule Pretest, Question 3 and 4.

4.7 Kirchhoff's Loop Rule: Curriculum Discussion

In the second section of the new curriculum, many of the experiments from the published section 7 and some of key experiments from section 8 are retained. Often they are re-ordered, modified slightly, and interspersed with new experiments and exercises.

Students are first focussed on the method of taking voltmeter measurements. They also investigate how to connect a voltmeter without significantly affecting the circuit. Students then systematically work through a number of experiments which help them form the following rules:

- The voltage across the battery is equal to the sum of the voltages across elements connected in series.
- When the resistance across a network in series with another network is increased, the voltage across this network increases also, while the voltage across the other network decreases.
- The voltage across parallel branches connected across the battery is always equal to the battery voltage, regardless of the relative resistance of each branch.

Once students have formed these rules they investigate and discover Kirchhoff's loop rule by examining the circuit shown in Figure 4.14. As students measure the voltage across each circuit element they conclude that the sum of the voltages across bulb 1 and bulb 2 or bulb 1 and the nichrome wire is equal to the sum of the voltages across the batteries, thus forming Kirchhoff's loop rule.

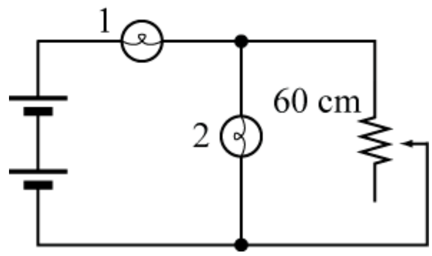


Figure 4.14: Circuit used to investigate Kirchhoff's loop rule.

By changing the length of nichrome wire in Figure 4.14 they notice that as its length is increased the voltage across the piece of nichrome wire and bulb 2 increase (and remain equal to each other) while the voltage across bulb 1 decreases. This is analogous to a series circuit if bulb 2 and the piece of nichrome wire are treated as a single circuit element.

On completion of this experiment students finally discover how the voltage model overcomes the limitations of the current model when they revisit the circuit of Figure 3.20, shown again in Figure 4.15.

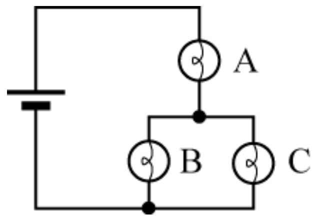


Figure 4.15: Two bulb parallel network in series with a single bulb.

As discussed in Chapter 3, students discovered that their current model had certain limitations since it could not predict what would happen to bulb B when bulb C was added in parallel across it as shown in Figure 4.15. Without quantitative data the students could not make a valid comparison of the current through bulb B before and after bulb C was added as it receives all of a smaller amount of current beforehand and half of a greater amount of current afterwards. Equipped with the voltage model, students can reason that beforehand the voltage across bulb B is $^1/_2V_0$, since it has the same resistance as bulb A and they are connected in series. When bulb C is added, the resistance of the [BC] network is less than the resistance of bulb A, thus the voltage across bulb B is less than $^1/_2V_0$. Therefore bulb B decreases in brightness when bulb C is added in parallel across it.

The ability for students to model circuits on their voltage model was tested in a number of post-test questions. Two of these questions are selected for discussion.

4.8 Kirchhoff's Loop Rule: Post-Test and Analysis

For the post-test to section 8 we asked a similar question to the Kirchhoff's lop rule pretest where students had to rank the readings on the voltmeters connected in the circuits in Figure 4.16.

Kirchhoff's Loop Rule Post-Test 1

In the circuits shown below, R_1 has a greater resistance than R_2 and all batteries and voltmeters are ideal and identical.
Rank the readings of V1-V7 from greatest to least.

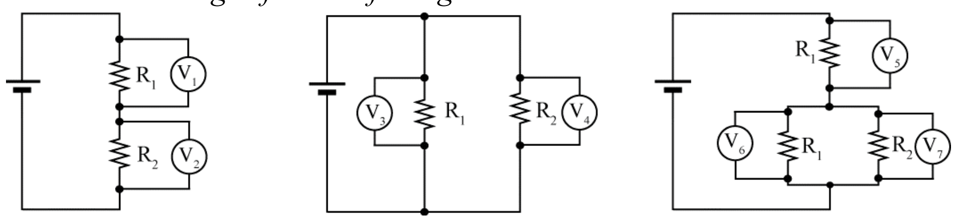


Figure 4.16: Circuits presented in Kirchhoff's Loop Rule Post-Test 1.

The analysis of complete correct answers and partial rankings provided the data shown in Table 4.11.

Table 4.11: Student's answers in response to Kirchhoff's Loop Rule Post-Test 1.

Answers	% (N=31)
Correct Ranking	**25 (8)**
$V_1 > V_2$	**80 (25)**
$V_3 = V_4$	**75 (23)**
$V_6 = V_7$	**70 (22)**
$V_5 > V_6$	**70 (22)**

Although only a small percentage of students provide a complete and correct ranking for the circuit, a large number of students made the correct ranking for voltages within each individual circuit. In the left circuit, 80% of students recognised that since the resistance of R_1 is greater than R_2, the voltage across R_1 is greater than that across R_2. Almost all of these students differentiated between voltages across elements connected in series and parallel, by correctly stating that the voltage across

R_1 and R_2 was equal in the middle circuit, since they are connected across the battery. Similar results were seen in the ranking of the voltages across R_1 and R_2 connected in parallel in the right circuit. Where students struggled was the recognition that the readings of V_1 and V_5 were different.

In another post-test question, we wanted to examine students' ability to recognise the limitations of the current model and how the voltage model overcomes these limitations. Students were presented with the same post-test question given in PbI module on current and resistant which was discussed previously in Chapter 3. Now equipped with the voltage model, it is possible for students to give a complete ranking.

Kirchhoff's Loop Rule Post-Test 2

Rank the bulbs A-F in order of decreasing brightness. Explain your reasoning. State whether you used a voltage model, a current model, or both. If you cannot determine a complete ranking, explain why not.

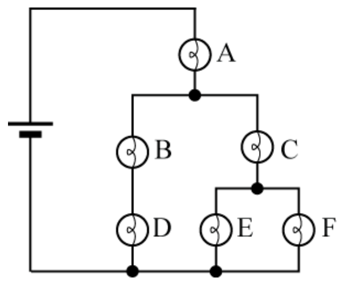
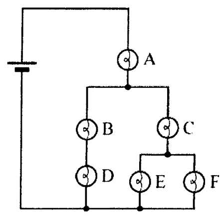


Figure 4.17: Circuit presented in Kirchhoff's Loop Rule Post-Test 2.

Of the 17 students who answered the question, nine provided the correct ranking of A>C>B=D>E=F. Of the nine students, five provided complete reasoning. Two of the students used the current model incorrectly while two others used the voltage model but did not give a complete answer. An example of a complete answer is shown in Figure 4.18.

2. [20pts total] The bulbs in the circuit shown are identical, as are the batteries.

   A. [8 pts] Rank the bulbs A-F in order of decreasing brightness. Explain your reasoning. State whether you used a *voltage model,* a *current model,* or *both.*
   If you cannot determine a complete ranking, explain why not.



In this case current can't be used to rank the brightness of all the bulbs.
Using the model we can determine that A will be brightest as all the current flows through it and that C will be next brightest because when current splits more will go through that branch (less resistance). However, we can't determine if B and D will be brighter or dimmer than E and F using current as it is a situation of B and D getting all of less and E and F getting half of more.

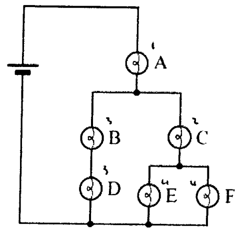
However, we can use voltage to rank all of the bulbs. A will be brightest as it has more resistance than the parallel part and therefore there is more voltage across it.
The voltage across each of the ~~[illegible]~~ branches in the parallel part is equal. Because B and D are in series the each have ½ the voltage across them. In the second branch C has the most resistance and will therefore get more than ½ the voltage and that means E and F have to get less than ½.
This means that after A, C will be next brightest, B and D will be of equal brightness and the next brightest and E and F will be of equal brightness and will be the dimmest.

Figure 4.18: An example of a complete correct answer to Kirchhoff's Loop Rule Post-Test 2.

The reasoning displayed in Figure 4.18 is essentially ideal and highlights a very competent understanding of the concepts.

Students who failed to use the voltage model relied on current and resistance reasoning only. Although students ranked bulb C brighter than bulb B, they fell into the trap of ranking bulbs E and F dimmer than bulbs B and D on the basis that the current is split between bulb E and F. This line of reasoning is shown in the third and fourth paragraphs of a student's answer in Figure 4.19.

2. [20pts total] The bulbs in the circuit shown are identical, as are the batteries.



A. [8 pts] Rank the bulbs A-F in order of decreasing brightness. Explain your reasoning. State whether you used a *voltage model,* a *current model,* or *both.*
If you cannot determine a complete ranking, explain why not.

In this circuit we can see that bulb A will be the brightest as all the current will flow through it.
Bulb C will be dimmer than A but brighter than the other bulbs as it is in series to a parallel circuit. The parallel circuit in series with C reduces resistance along that branch. Bulb C gets most of the current after it splits.
~~(Bulbs)~~ Bulbs B and D will be next dimmest as they are in series but the each get all of the current along their branch.
Bulbs E and F will be the dimmest bulbs of all as all the current that flows through C is split between them.

1) Bulb A gets 100% of the current
2) Bulb C gets more than 50%.
3) Bulbs B+B gets less than 50%.
4) Bulbs E+F get more than 50% divide between them.

For this circuit I used a ~~ck~~ current model.

15th November 2007 3 EC-DCU322X071P-E1(Q2,S7b).doc

Figure 4.19: An example of an incorrect student answer to Kirchhoff's Loop Rule Post-Test 2.

In the 2008 mid-term exam, we asked a similar question which addresses students' understanding of the voltage model and its ability to overcome the limitations of the current model. The question given on the exam was generally given as a homework question. In order to address the same issues in the homework problem, the question discussed previously was given.

Kirchoff's Loop Rule Post-Test 3, Question 1

Rank the relative brightness of the bulbs within the circuit shown at right. Explain your reasoning. State whether you used the current model or voltage model or both to decide the ranking.

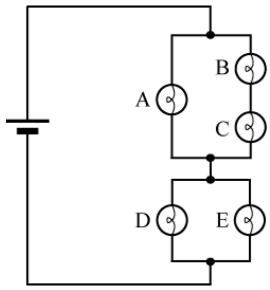


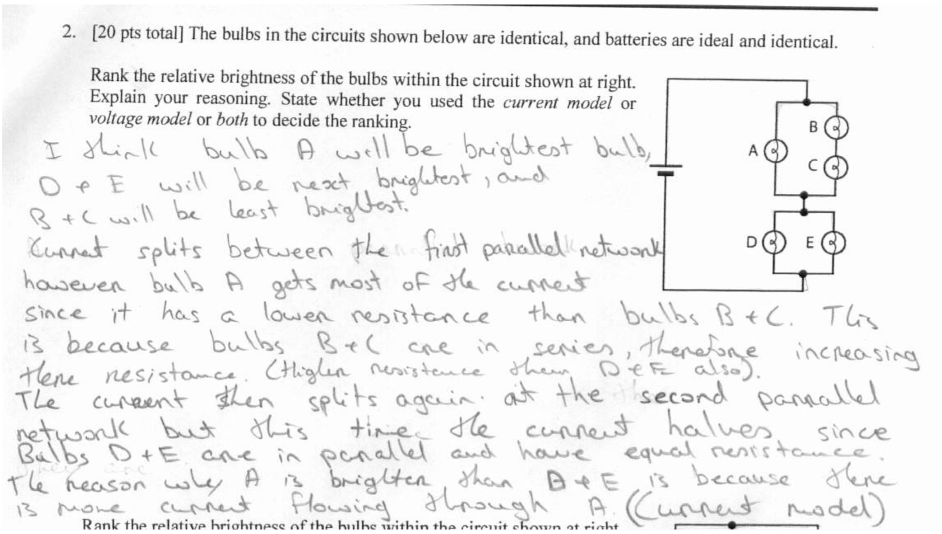
Figure 4.20: Circuit presented in Kirchhoff's Loop Rule Post-Test 3.

For this particular circuit students need to think in terms of current, since reasoning based on voltage cannot rank the relative brightness of bulbs B and C relative to bulbs D and E. (Bulbs B and C receive half of more than $^1/_2V_0$ while bulbs D and E receive less than $^1/_2V_0$) Reasoning on the basis of current and resistance, students can infer that the current splits unequally between the branches of the [ABC] network due to the difference in resistance of each branch. This leads them to reason that bulb A receives more than $^1/_2 i_0$ and bulbs B and C receive less than $^1/_2 i_0$. Since the branches containing bulbs D and E are equal in resistance, students can infer that each bulb receives $^1/_2 i_0$. This leads to a complete raking of bulbs A>D=E>B=C. The results are shown in Table 4.12 below.

Table 4.12: Rankings to Kirchhoff's Loop Rule Post-Test 3, Question 1.

Ranking	% (*N*=14)
A>D=E>B=C	**65 (9)**
A=D=E>B=C	30 (4)
A>B=C>D=E	5 (1)

Of the nine students who returned the correct ranking, five had complete and correct reasoning. A sample of a correct and complete answer is shown in Figure 4.21:



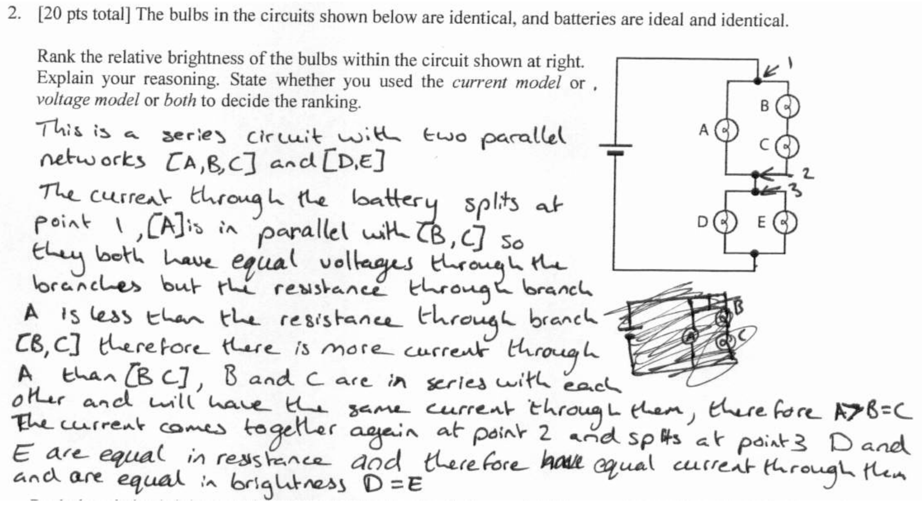
2. [20 pts total] The bulbs in the circuits shown below are identical, and batteries are ideal and identical.

Rank the relative brightness of the bulbs within the circuit shown at right. Explain your reasoning. State whether you used the *current model* or *voltage model* or *both* to decide the ranking.

I think bulb A will be brightest bulb, D + E will be next brightest, and B + C will be least brightest. Current splits between the first parallel network however bulb A gets most of the current since it has a lower resistance than bulbs B + C. This is because bulbs B + C are in series, therefore increasing there resistance. (Higher resistance then D + E also). The current then splits again at the second parallel network but this time the current halves since Bulbs D + E are in parallel and have equal resistance. The reason why A is brighter than D + E is because there is more current flowing through A. (Current model)

Figure 4.21: An example of a complete correct answer to Kirchhoff's Loop Rule Post-Test 3, Question 1.

A sample of a student's answer who correctly ranked the bulbs but uses ambiguous language when describing voltage and resistance is shown in Figure 4.22:



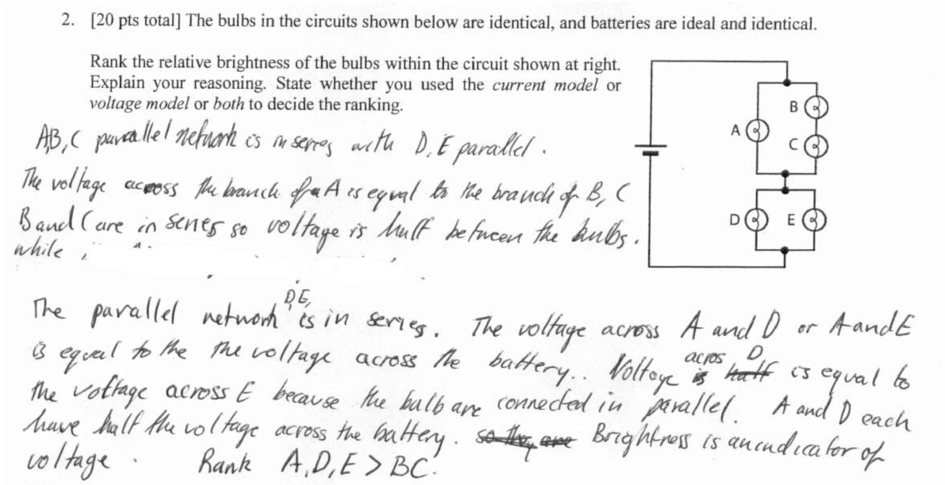
2. [20 pts total] The bulbs in the circuits shown below are identical, and batteries are ideal and identical.

Rank the relative brightness of the bulbs within the circuit shown at right. Explain your reasoning. State whether you used the *current model* or *voltage model* or *both* to decide the ranking.

This is a series circuit with two parallel networks [A,B,C] and [D,E]. The current through the battery splits at point 1, [A] is in parallel with [B,C] so they both have equal voltages through the branches but the resistance through branch A is less than the resistance through branch [B,C] therefore there is more current through A than [B C], B and C are in series with each other and will have the same current through them, therefore A>B=C. The current comes together again at point 2 and splits at point 3 D and E are equal in resistance and therefore have equal current through them and are equal in brightness D = E

Figure 4.22: An example of a student's answer to Kirchhoff's Loop Rule Post-Test 3, Question 1.

As can be seen in Table 4.12, four students ranked bulbs A, D and E equal in brightness. This can result from an inability to recognise that the current splits at nodes according to the resistance of the branches. The sample of a students' answer shown in Figure 4.23 highlights a second misconception regarding Kirchhoff's loop rule. The equation of $V_{bat} = V_A + V_D$ leads this student to believe that the voltage is split equally across bulb A and bulb D thus giving them the same brightness.


2. [20 pts total] The bulbs in the circuits shown below are identical, and batteries are ideal and identical.

Rank the relative brightness of the bulbs within the circuit shown at right. Explain your reasoning. State whether you used the *current model* or *voltage model* or *both* to decide the ranking.

A,B,C parallel network is in series with D, E parallel.
The voltage across the branch of A is equal to the branch of B, C
B and C are in series so voltage is half between the bulbs.
while

The parallel network D,E, is in series. The voltage across A and D or A and E is equal to the the voltage across the battery.. Voltage across D ~~is half~~ is equal to the voltage across E because the bulb are connected in parallel. A and D each have half the voltage across the battery. ~~so they are~~ Brightness is an indicator of voltage. Rank A, D, E > BC.

Figure 4.23: An example of an incorrect answer to Kirchhoff's Loop Rule Post-Test 3, Question 1.

In the second part of the question, students had to rank the brightness of bulbs in the left circuit in Figure 4.24.

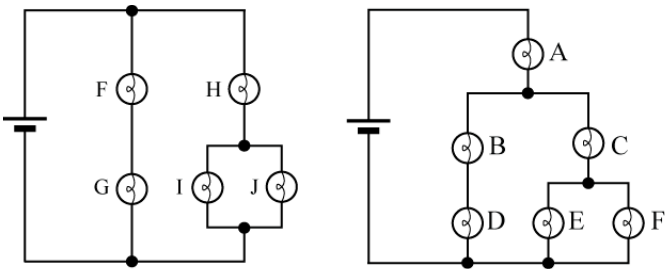


Figure 4.24: Circuits presented in Kirchhoffs Loop Rule Post-Test 1 and 3.

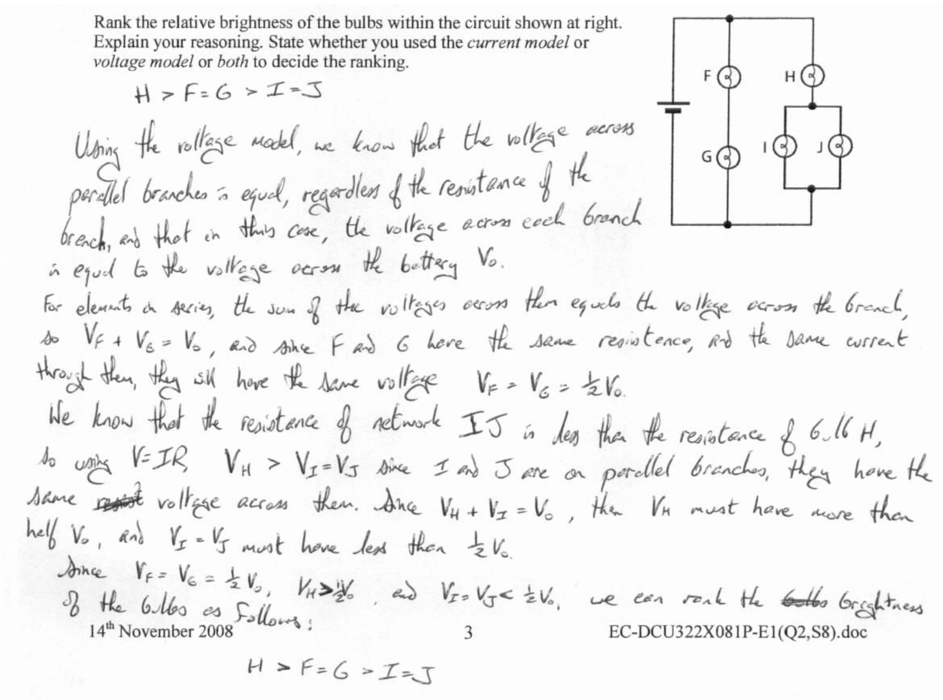
The right circuit shown in Figure 4.24 was given to students as part of a homework problem in the same year. It is the same circuit that was given in Kirchoff's loop rule post-test 1 discussed previously. A close look at the right circuit shows that it is identical to the left circuit upon the removal of bulb A. The similarities of the circuit connections require students to use the same voltage reasoning as that outlined for the Kirchoff's loop rule post-test question 1, as the current model does not allow the relative ranking of bulbs F and G to bulbs H and I in the left circuit of Figure 4.24.

The students' answers are shown in Table 4.13.

Table 4.13: Rankings to Kirchhoff's Loop Rule Post-Test 3, Question 2.

Ranking	% (N=14)
H>F=G>I=J	**80 (11)**
F=G>H>I=J	5 (1)
H>I=J>F=G	15 (2)

Of the 11 students who ranked the bulbs correctly, only four students provided complete and correct reasoning. An example of a correct answer is shown in Figure 4.25.


Rank the relative brightness of the bulbs within the circuit shown at right. Explain your reasoning. State whether you used the *current model* or *voltage model* or *both* to decide the ranking.

H > F = G > I = J

Using the voltage model, we know that the voltage across parallel branches is equal, regardless of the resistance of the branch, and that in this case, the voltage across each branch is equal to the voltage across the battery V_0.

For elements in series, the sum of the voltages across them equals the voltage across the branch, so $V_F + V_G = V_0$, and since F and G have the same resistance, and the same current through them, they still have the same voltage $V_F = V_G = \frac{1}{2}V_0$.

We know that the resistance of network IJ is less than the resistance of bulb H, so using $V=IR$, $V_H > V_I = V_J$ since I and J are on parallel branches, they have the same ~~current~~ voltage across them. Since $V_H + V_I = V_0$, then V_H must have more than half V_0, and $V_I = V_J$ must have less than $\frac{1}{2}V_0$.

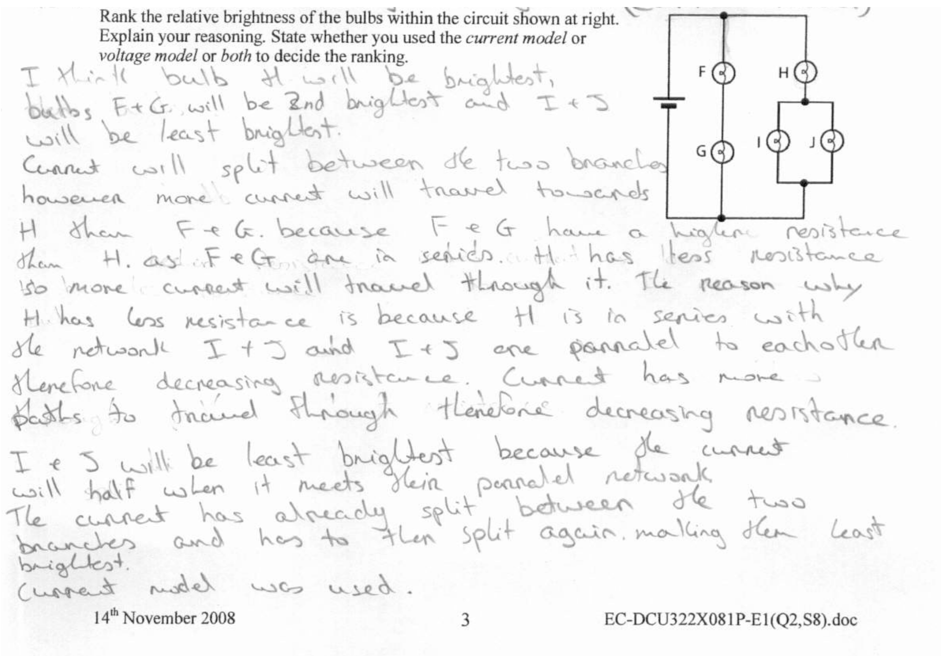
Since $V_F = V_G = \frac{1}{2}V_0$, $V_H > \frac{1}{2}V_0$, and $V_I = V_J < \frac{1}{2}V_0$, we can rank the ~~bulbs~~ brightness of the bulbs as follows:

H > F = G > I = J

14th November 2008 3 EC-DCU322X081P-E1(Q2,S8).doc

Figure 4.25: An example of a complete correct answer to Kirchhoffs Loop Rule Post-Test 3, Question 2.

As with the previous question, some students based their answers on current and resistance reasoning only. An example is shown in Figure 4.26.


Rank the relative brightness of the bulbs within the circuit shown at right. Explain your reasoning. State whether you used the *current model* or *voltage model* or *both* to decide the ranking.

I think bulb H will be brightest, bulbs F+G will be 2nd brightest and I+J will be least brightest.
Current will split between the two branches however more current will travel towards H than F+G. because F+G have a higher resistance than H. as F+G are in series. H has less resistance so more current will travel through it. The reason why H has less resistance is because H is in series with the network I+J and I+J are parralel to eachother therefore decreasing resistance. Current has more paths to travel through therefore decreasing resistance.
I+J will be least brightest because the current will half when it meets their parralel network The current has already split between the two branches and has to then split again, making them least brightest.
Current model was used.

14th November 2008 3 EC-DCU322X081P-E1(Q2,S8).doc

Figure 4.26: An example of an incorrect answer to Kirchhoffs Loop Rule Post-Test 3, Question 2.

The results to the post-test questions on the application of Kirchhoff's loop rule were showed an improvement in students' ability to model circuits based on the concept of voltage. In both years, we find that 30% of students have a competent understanding of the concept of voltage. The remaining percentage seem to have a grasp of some of the concepts but find it quite difficult to apply them in a difficult context. Possible solutions to further improve students' understanding are discussed further in the conclusion to the chapter.

4.9 Original Curriculum Discussion

The curriculum which was implemented in the 2008 electric circuits module is largely influenced by the original redevelopment of the published curriculum which was carried out in 2006. Although many changes were made to the 2006 curriculum, the overall ethos remained as the foundation for subsequent revisions. In this section, I detail the thoughts behind some of the experiments in the original version and discuss the problems which were encountered and why certain aspects needed to be redeveloped or omitted.

At the beginning of writing the new curriculum I focussed on the following question: "Has the student covered all the concepts necessary to progress to this new concept?" Since I was developing curriculum for voltage and would introduce multiple battery circuits, I first wanted to change students' focus from bulb brightness to the role of the battery and to investigate all the possible concepts in reference to single battery circuits.

In addressing single battery circuits, I wanted students to form the following two conclusions in the opening experiment.

- The battery must be included in the circuit in order for bulbs to light
- The current through the battery can change

As it turned out, we found that the focus was placed on the battery too soon. The experiment also unintentionally raised some issues which were difficult to address at this stage of the curriculum, such as: what flow is already there, or is the battery a current bottle?

When students had completed the opening experiment they added a second battery to the circuit. Rather than instructing students on how to add the second battery which was done in the 2007 and 2008 curriculum, we allowed students to add the second battery as they wish which was intended to promote the investigative nature of the lab. The four possible solutions are shown in Figure 4.27:

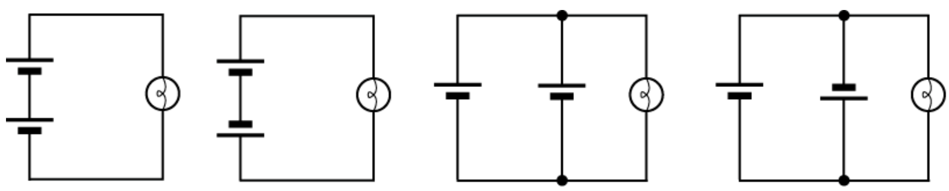


Figure 4.27: Possible solutions for adding a second battery to a single bulb circuit.

The students were asked to concentrate on the battery connection which causes the brightness of bulb A to increase which is intended to guide the students towards defining a series connection of two batteries.

It is at this stage where it became difficult to guide students to develop a well-reasoned and consistent model for voltage as it was difficult to answer the following question.

> "Why does the brightness of bulb A increase when I connect a second battery in series?"

This particular problem is partly solved through investigating whether the addition of batteries cause a decrease in resistance and therefore cause the current to increase. The first experiment asks students to observe the bulb brightness of a single bulb when a second and then a third battery are added in series to the circuit. Students observe that bulb brightness increases, however since they have investigated the non-linear characteristics of the bulb they conclude that as the bulbs becomes brighter, the bulb's resistance increases and therefore the resistance of the circuit increases.

The second experiment guides students to investigate the circuits shown in Figure 4.28.

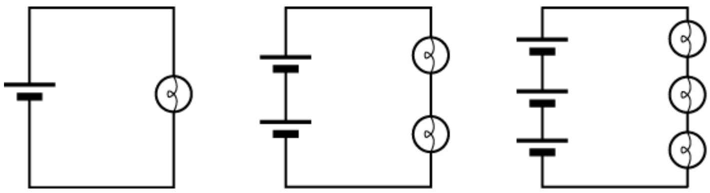


Figure 4.28: A single bulb circuit, a two battery-two-bulb series circuit and a three-battery-three-bulb series circuit.

In all circuits, students observe that the bulbs have equal brightness, therefore the same current, hence each bulb has equal resistance. Since the bulbs are connected in series the resistance of circuit 3 is greater than circuit 1.

Students are guided to realise that in both experiments, the resistance of the circuits increased. However, in the first experiment the current increased and in the second experiment the current remained the same. This conflicts with their model for current and resistance, and suggests that adding batteries in series does not decrease the resistance of the circuit.

Now that students have investigated this concept they are still left with the question, why the brightness of bulb A increases when a second battery is connected in series. The curriculum tackles this by instructing students to gather data for a number of current and resistance readings in a single battery circuit and a two battery circuit in which nichrome wire creates the resistance. Students tabulate this data and calculate the product of current and resistance for each reading. They then compare all the readings for the single battery circuit to each other and compare these to the readings for the two-battery circuit. This leads students to the conclusion that the product of current and resistance remains the same for each circuit, and doubles when the number of batteries doubles. This suggests that a particular property of the circuit remains constant. Since both the current and resistance are changing, the property is likely to be connected with the battery. Further evidence for this is that the product for current and resistance for the two battery circuit is twice that of the single battery circuit.

To strengthen this idea the students carry out the same investigation, but change the resistive element from nichrome wire to bulbs. If this experiment yields similar results from with a non-linear element, this would add some weight and consistency to the idea. When students have tabulated the data they notice that the product of current and resistance is the same for circuits with nichrome wire as it is for bulb circuits. This solidifies the idea that the product of current and resistance is related to the battery. At this juncture, voltage is introduced as the name of the product of current and resistance, which is associated voltage. On completion of these investigations the curriculum continues in a similar fashion to the Physics by Inquiry curriculum for the remaining sections, before the module addresses the new topics of multiple batteries in multiple loops and RC circuits.

4.10 Further developments

While revisions were taking place to the curriculum in November 2008, I felt that an additional section to the voltage curriculum would help improve students' understanding of voltage. The motivation for the additional section arose from the recognition of the importance of section 4 of the published PbI current and resistance curriculum.

In short, the curriculum for current and resistance comprises of six sections. As discussed in chapter 3, students are introduced to the concepts of complete circuits, current and resistance and equivalent resistance. After the concepts of current and resistance are covered students complete a section devoted entirely to helping students reinforce the concepts covered previously, before they discover equivalent resistance. Section 4 consists of a number of experiments and exercises which allow the student to become competent in applying their model to a number of unseen circuits, consisting of series and parallel networks. Students become comfortable in recognising series and parallel connections and their affects on bulb brightness.

In the new voltage curriculum, I have noticed that many of the new concepts are only addressed on one occasion. This is possibly a source of difficulty, as we find that for many concepts, it takes more than one experiment or exercise to gain an in-depth understanding. Other than homework problems which are only completed after each section, students do not get a chance to apply their voltage model. Equally as important, they do not get a chance to discuss their answers with fellow students and instructors. This process is a key part in developing students' understanding. Therefore I feel that an additional section which allows students to extensively practice the use of their voltage model and become more comfortable with the concept, is needed.

4.11 Conclusion

Prior research has shown that students find the concept of voltage very difficult to understand and many fail to differentiate it from the concept of current. This results in an overlap of misconceptions, where documented misconceptions for the concept of current are also prevalent for the concept of voltage. I have tackled these issues by helpin students develop a conceptual understanding of voltage in the context of current and resistance. By allowing students to discover that the product of current and resistance yields a constant related to the number of batteries, which is later defined as voltage, students discover that the concept of voltage is related to the battery. This process leads to two significant conclusions: (1) students discover that the voltage and not current is associated with the battery; this helps students resolve the incorrect belief that a battery supplies current. (2) By developing the concept of voltage in conjunction with the concepts of current and resistance, students can differentiate between current and voltage, which is an ability that many students lack before and after traditional instruction. These views on the effectiveness of the curriculum were shared by a fellow instructor of the curriculum at UW who stated:

> *"The greatest praise I have for this curriculum is this: I never heard any of the six participants say the word "voltage" when "current" was intended, or vice versa. I believe this to be remarkable because in other settings I have always had a significant fraction of students who mix up the two terms (or worse, the two concepts). Similarly, I heard very few instances of "the voltage through such-and-such" when voltage was truly the concept being discussed, and this construction vanished by approximately the end of §8. I think this curriculum was a huge success in this regard, and I believe much of it is due to voltage being introduced long after participants are comfortable with current."*[12]

In the investigation of specific student difficulties on the effects of adding a battery to a single loop circuit, a number of misconceptions were revealed. The most common misconception was the belief that bulbs, connected in circuits with batteries in opposite orientation, don't light. In addition, many students still believed that the battery supplies current. This leads them to state that when two batteries are connected in a circuit, the currents supplied by each battery are additive. I also noted that the majority of students did not reason on the basis of voltage, and relied largely on their understanding of current and resistance. It is likely that this is due to the students' comprehensive study of the concepts of current and resistance discussed in Chapter 3. It was difficult to determine whether students had some understanding of the concept of voltage and were uncomfortable in applying its use in modelling circuits, or had little or no understanding of the concept and were unable to reason on its basis.

The post-test on adding batteries to single loop circuits focussed on the effects of connecting batteries in parallel. The results show that most students resolved their misconceptions identified in the pretest analysis and improved their conceptual understanding of this topic. Further questioning in a homework problem showed that students also overcame their misconceptions regarding the connection of batteries in series and in opposite orientation in single loop circuits. The combination of these results highlighted the effectiveness of curriculum.

Pretest questions on Kirchhoff's loop rule were answered poorly. Many students relied solely on their understanding of the voltage across a battery to rank voltages across a number of bulbs in three different circuits. The analysis of the answers revealed that no student referred to prior knowledge on the topic, although it had been covered in a first year introductory physics course taken by students.

The post-test results on the application of Kirchhoff's loop rule showed that a third of each cohort gained a functional understanding of how circuits can be modelled on the concept of voltage. Others displayed a partial understanding but still found it difficult to recognise the use of voltage in modelling circuits. Suggested developments to the curriculum include an additional section which allows students to become comfortable in modelling circuits based on their voltage model and to facilitate time so students can discuss specific difficulties with instructors.

I think further research on the curriculum with revision to include the extra section discussed previously would greatly enhance the effectiveness of the curriculum. With these revisions, I feel that the completeness of the curriculum that we wish to achieve, can be attained.

References

1. L. C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry vol II*, 383 - 429, Wiley, New York, 1996.
2. L. C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry vol II*, 429 - 454, Wiley, New York, 1996.
3. R. Paatz, J. Ryder, H. Schwedes, P. Scott, *A case study analysing the process of analogy-based learning in a teaching unit about simple electric circuits*, Int. J. Sci. Educ. 26 (9), 1065-1081 2004.
4. D. Heywood, J. Parker, *Confronting the analogy: primary teachers exploring the usefulness of analogies in the teaching and learning of electricity*, Int. J. Sci. Educ. 19 (8), 869-885, 1997.
5. R. Cohen, B. Eylon, U. Ganiel, *Potential Difference and Current in Simple Electric Circuits: A study of students' concepts*, Am. J. Phys. **51** (5) 1983.
6. P. Licht, *Concept Development in Electricity: A Strategy and Some Preliminary Results. Communication to the International Symposium on Physics Teaching*, Brussels, 1985.
7. D. M. Shipstone, (1985). 'Electricity in simple circuits' In R Driver, E Guesne & A Tiberghien (Eds.), *Children's ideas in science* (pp. 291-316). Milton Keynes: Open University Press.
8. D. M. Shipstone, C. v. Rhöneck, W. Jung, C Karrqvist, J. J. Duphin, S. Johsua, P. Licht, *A study of students' understanding of electricity in five European countries,* Int. J. Sci. Ed., Vol 10, No 3, 303-316, 1988.
9. L. C. McDermott, P. S. Shaffer, *Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding*, Am. J. Phys. **60** (11), 994-1003, 1992, P. V. Engelhardt, R. J. Beichner, *Students' understanding of direct current resistive electrical circuits,* Am. J. Phys. **72** (1) 2004.
10. D. M. Shipstone, *A study of children's understanding of electricity in simple DC circuits*, Int. J. Sci. Educ. **6** (2) 185-198, 1984.
11. R. Millar, K. L. Beh, *Students' Understanding of voltage in simple parallel circuits*, Int. J. Sci. Educ. **15**, 129-138, 1993.
12. Private communication with Benjamin Pratt, University of Washington.

Chapter 5

Multiple Batteries in Multiple Loops

The section of the curriculum dedicated to multiple batteries in multiple loops is the penultimate section in the module given to third year pre-service teachers and covers possibly the most complex circuits students encounter. Although the section relies on many concepts which have been previously introduced, new concepts such as potential and potential difference come to the fore. Over the course of a number of experiments and exercises the curriculum progresses systematically from a review of multiple batteries in single loops and connecting batteries in parallel, to investigating how the addition of a network of bulbs and batteries across a single bulb circuit affects each of the bulbs and batteries.

The structure of the curriculum has been changed on a number of occasions during the three years. The largest of these changes took place in 2008, with the introduction of the concept of potential and potential difference in a manner which was consistent and inline with the ethos of guided inquiry curriculum.

This chapter discusses the pretest analysis of a single pretest question that was administered in each of three years. The analysis highlights some interesting misconceptions. The reasons behind the changes in the curriculum and the steps which were taken to improve the effectiveness of the curriculum are also discussed. The report concludes with the analysis of relevant post-test questions from each of the three years.

5.1 Multiple Batteries in Multiple Loops: Pretest and Analysis

As with all sections, a pretest addressing the issues of adding batteries in multiple loops was given to students prior to commencing the curriculum. At this stage it is important to remember that students have carried out a considerable amount of work on the concept of voltage and adding batteries in single loops in addition to prior study a traditional undergraduate physics module. They have also investigated the effects of connecting batteries in parallel. The results show that this investigation plays a pivotal role in students' answers.

Multiple Batteries in Multiple Loops Pretest

Rank the relative brightness of the four bulbs shown in the diagram at right. Explain your reasoning.

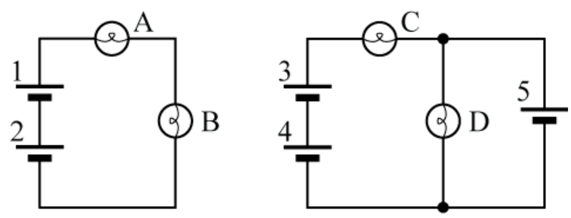


Figure 5.1: Circuit diagrams presented in Multiple Batteries in Multiple Loops Pretest.

Students returned the answers shown in Table 5.1. The analysis of students' reasoning to the two most popular answers is shown afterwards.

Table 5.1: Bulb rankings to Multiple Batteries in Multiple Loops Pretest.

Ranking	Total % (*N*=44)
A=B=C=D	**30 (13)**
C>A=B>D	20 (8)
A=B>C=D	15 (6)
D>A=B=C	10 (4)
A=B=C>D	5 (3)
Other	15 (6)

Bulb Ranking: A=B=C=D

No student who provided the correct answer (A=B=C=D) provided correct reasoning. Eleven students reasoned that the addition of a battery in parallel does not affect the brightness of bulbs in a circuit. This reasoning most likely derives from a false generalisation from their observations of connecting two batteries in parallel. An example of a student's answer is shown in Figure 5.2:

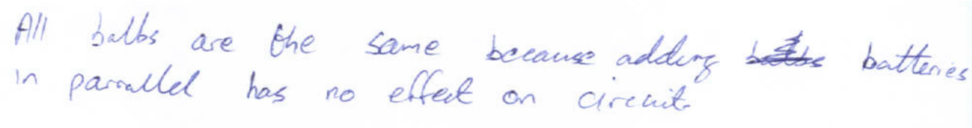


Figure 5.2: Example of a student's answer in response to Multiple Batteries in Multiple Loops Pretest.

Of the two remaining students, one stated that battery 5, placed in parallel across bulb D in Figure 5.1, was short circuited. The other student stated that each circuit was the same as they consisted of two batteries and two bulbs, but did not give a reason for this statement.

Bulb Ranking: C>A=B>D

The data in Table 5.1 shows that eight students answered the question by stating that bulb C is brighter than bulbs A and B, which are equal to each other, and brighter than bulb D (C>A=B>D). The analysis of students' answers reveals that they treated the battery in parallel (battery 5) as a circuit element with characteristics varying from a wire to a bulb.

Two of these students treated battery 5 as a circuit element with resistance similar to that of a bulb. Within this assumption, they reasoned that there was less voltage across bulb D than all other bulbs. One of the student's answers is shown in Figure 5.3.

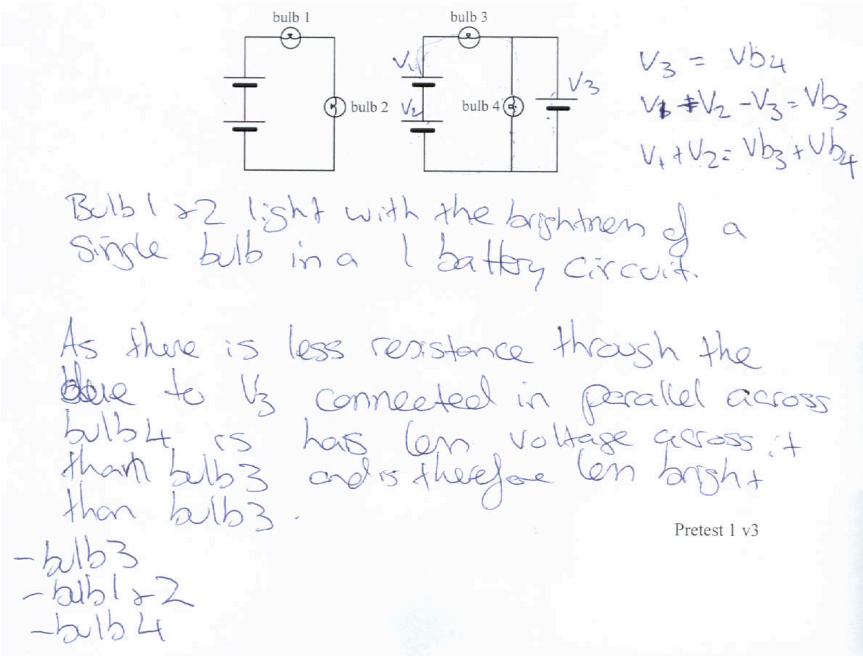


Figure 5.3: Example of a student's answer in response to Multiple Batteries in Multiple Loops Pretest.†

Three of these students treated battery 5 as an element with similar characteristics to a connecting wire, in that its resistance was very low in comparison to the resistance of bulb D. This reasoning leads students to think that the circuit containing bulbs C and D has less resistance than the circuit containing bulbs A and B thus leading them to rank bulb C as the brightest bulb. An example is shown in Figure 5.4.

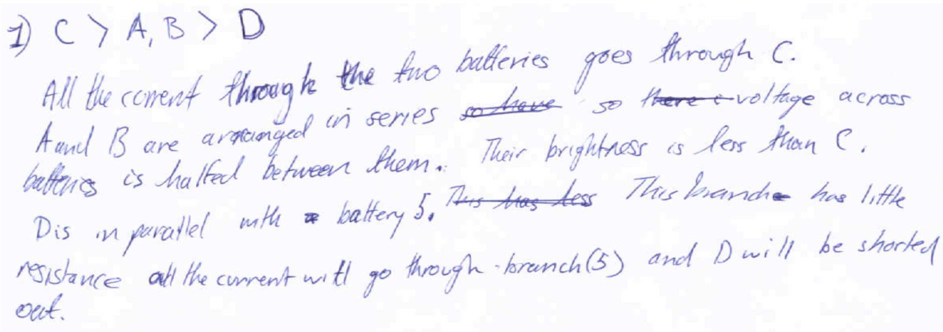
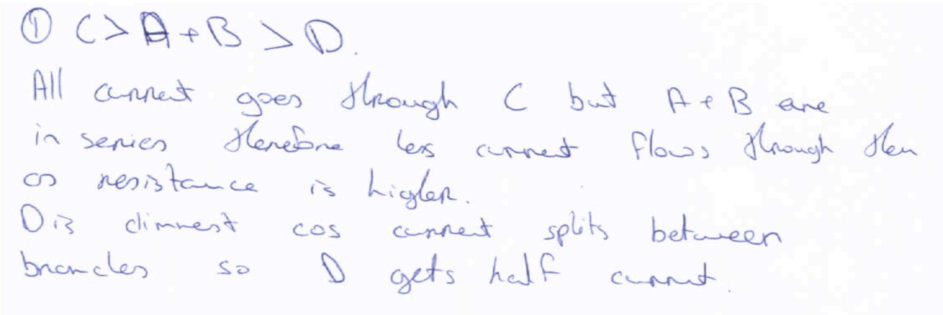

1) C > A, B > D
All the current through the two batteries goes through C.
A and B are arranged in series ~~so have~~ so ~~there~~ voltage across batteries is halfed between them. Their brightness is less than C.
D is in parallel with battery 5. ~~This has less~~ This branch has little resistance all the current will go through branch (5) and D will be shorted out.

Figure 5.4: Example of a student's answer in response to Multiple Batteries in Multiple Loops Pretest.

Similar to the first two students that were discussed, another two students also reasoned on the basis that battery 5 acted like a bulb, although they used current and resistance reasoning only. Treating the battery like a bulb, they reason that the circuit with bulbs C and D is less resistive and therefore more current flows through this

† In the 2006 pretest, bulbs were labelled numerically. Bulbs 1-4 refer to bulbs A-D respectively.

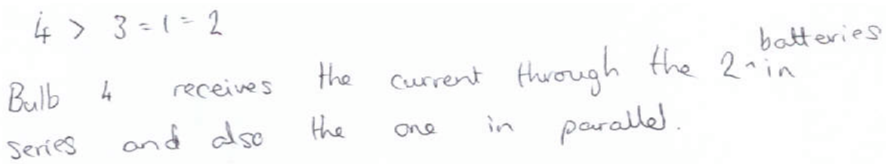
circuit leading them to rank bulb C as the brightest bulb. They then incorrectly ranked bulbs A and B as the second brightest because their circuit has less current due to increased resistance and that bulb D is dimmest as it only gets half of the current through bulb C. Apart from answering this question incorrectly, this line of reasoning also points out that these students still find it difficult to recognise the limitations of the current model (On the basis of their reasoning, bulbs A and B receive all of a smaller amount of current and bulb D receives half of a greater amount of current. These amounts cannot be compared). An example is shown in Figure 5.5.



① C > A + B > D.
All current goes through C but A + B are in series therefore less current flows through them as resistance is higher.
D is dimmest cos current splits between branches so D gets half current.

Figure 5.5: Example of a student's answer in response to Multiple Batteries in Multiple Loops Pretest.

During the analysis, some significant misconceptions were also quite evident with many students still using the 'sink' model[1] by treating the battery as a source of current. It is not uncommon to notice that students revert to old misconceptions when confronted with new and more difficult concepts. This line of reasoning led four students to reason that Bulb D was the brightest of all bulbs using the incorrect reasoning that it received current from three batteries. An example is shown in Figure 5.6.



4 > 3 = 1 = 2
Bulb 4 receives the current through the 2 batteries in series and also the one in parallel.

Figure 5.6: Example of a student's answer in response to Multiple Batteries in Multiple Loops Pretest.

The analysis of students' answers highlights their lack of understanding with this topic, which is understandable considering their background. It was not unexpected to see students rely largely on current and resistance reasoning as this was seen in the previous chapter. It is, however, worrying to see that a small number of students still hold on to the belief that the battery supplies current. The fact that students still use this reasoning after instruction highlights the difficulty in eradicating this misconception.

5.2 Multiple Batteries in Multiple Loops: Curriculum Discussion

In each of the three years, the opening exercise in the section on multiple batteries in multiple loops served as a review of the previous sections. Students are presented with the four circuits shown in Figure 5.7 and asked to compare the brightness of bulbs E and F to bulbs A-D.

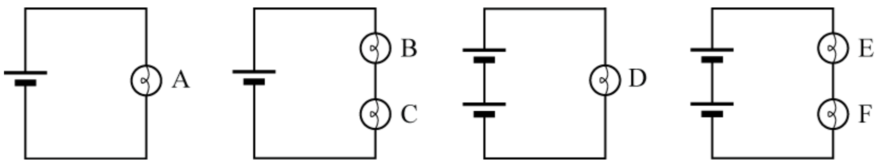


Figure 5.7: Circuits diagrams presented in opening exercise of Multiple Batteries in Multiple Loops curriculum.

In order for students to complete the exercise successfully they must first determine, using Kirchhoff's loop rule, that bulb E and bulb F are as bright as a bulb in a single battery-single bulb circuit, since the voltage across each bulb is equivalent to the voltage across one battery. Using this logic they can rank bulbs E and F as equal in brightness to bulb A. Students can then complete their ranking by also applying Kirchhoff's loop rule to the two centre circuits in Figure 5.7.

This exercise is extended by asking students to apply their rules for batteries in opposite orientation to the circuits shown in Figure 5.8. Students compare the brightness of the bulbs shown in Figure 5.8 to bulbs A-D shown in Figure 5.7 previously.

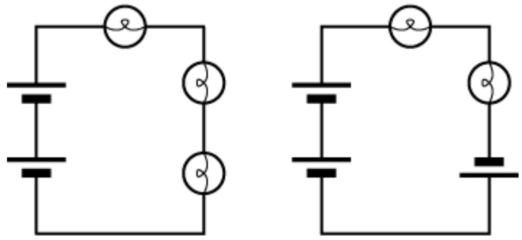


Figure 5.8: Three circuits consisting of bulbs and batteries connected in series.

Students have covered this concept comprehensively in previous sections and they don't find it difficult to compare the relative brightness of the bulbs. This exercise concludes their review of multiple batteries in single loops.

The remainder of the section on multiple batteries in multiple loops has seen a large deal of change over the three years with the majority of development having taken place during November through December of 2008. The latest version of the curriculum begins with an investigation of the addition of a battery in parallel to a single-bulb single-battery circuit, in the context of inferring what happens to the current through the batteries when the second battery is connected in parallel. The following student conversation was included in the 2007 and 2008 curriculum to address the issue.

Student 1: *"The brightness of the bulb did not change when I closed the switch, so the same current flows through the bulb as before. This shows that there is no current through the right battery."*

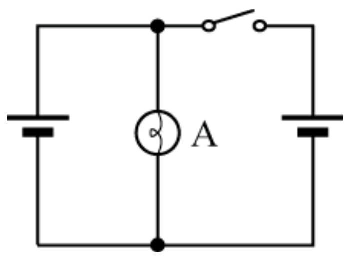


Figure 5.9: Series network of a battery and a switch connected across a single bulb circuit.

Student 2: *"Both batteries are identical and are connected to the circuit in the same way. Therefore the current through both batteries is the same."*

It is hoped that students agree with student 2 using a symmetry argument. When the students add the second battery in parallel, they observe that the brightness of the bulb does not change, thus the current through the bulb does not change. Following this line of reasoning, we guide the students to reason that it is more plausible for the current through bulb A to split between the two batteries rather than all the current through bulb A to pass through one particular battery. Students should therefore reason that when the second battery was added, the current through the first battery halved.

This is then followed by an experiment where students are asked to predict how the brightness of bulbs A and B in Figure 5.10 would compare to bulbs A-D in Figure 5.1. Since outside of the pretest this is the first circuit in which students have seen a network of batteries and a bulb connected across a single bulb circuit, it is not difficult to imagine that the majority of students struggled with this question.

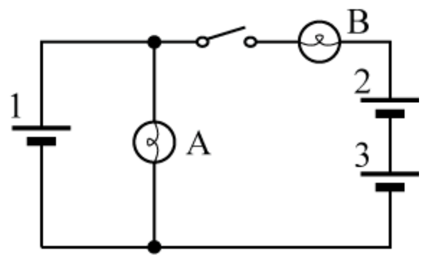


Figure 5.10: Series network of a switch, a bulb, and two batteries connected across a single bulb circuit.

Students were also asked to infer the direction and amount of current through battery 1 when the switch is closed. When the switch is closed students observe that the brightness of the bulbs are equal. Since the issue of current direction had not been discussed in detail in this curriculum, one could come up with four possible ways for current to split and recombine that is consistent with Kirchhoff's junction rule. Two of these are shown diagrammatically below, the other two have the currents reversed.

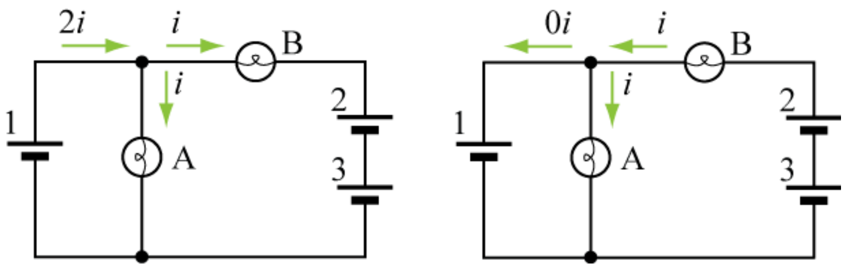


Figure 5.11: Possible inferences for currents through circuit elements.

We chose to solve this issue, by making students aware of the concept of potential, as this would allow them to determine the direction of current through the bulbs. When combined with Kirchhoff's junction rule, this would allow them to determine the direction of current through each of the batteries.

The first attempt to rectify this problem was quite unsatisfactory as it contradicted the ethos of the curriculum. The following narrative was written.

> *By convention, current inside a battery flows from the negative to the positive terminal in a single battery circuit. (This is also described in section 5 of the published PbI curriculum[2])*
>
> *We now introduce the term potential, which we define as follows. Pick any point P in the circuit and say its potential is equal to zero. Go around the loop, using P as the starting point. As long as you stay within a wire, the potential remains the same. When you cross a battery going from the negative to the positive terminal, the value of potential increases by V_0; if you go through it from the positive to the negative terminal, it decreases by V_0. When you cross a bulb, the potential decreases by the voltage across the bulb.*

The narrative shown above is obviously very much in conflict with the ethos of guided inquiry curriculum. Students are 'told' a large amount of information. Being unsatisfied with this material, we omitted as much information as possible from the above narrative in the new version. In the 2008 module the above narrative only included information which we felt could not be determined from experiment or exercise. The updated narrative is shown below.

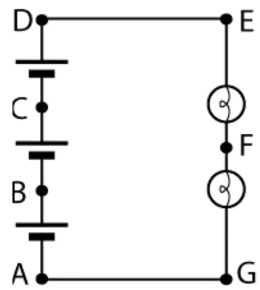
- *Adopt the convention that current inside a battery flows from the negative to the positive terminal in a single battery circuit.*
- *We also introduce a new quantity called potential. At each point in a circuit, potential has a certain value. The absolute value of potential is unimportant; what matters is that the difference in potential between two points is equal to the voltage measured between these two points. For this reason, the voltage between two points is often called the potential difference. For convenience, one point is often arbitrarily chosen where the potential is set to zero.*

In order to guide students to derive the rules which were given in the 2006 and 2007 narrative we designed three new exercises, which when combined with the immediate narrative above, students could discover the rules independently. The first of these exercises is shown in Figure 5.12.

Exercise 10.3

A. The circuit of part A of Experiment 10.2 is shown again at right.

In which direction does the current flow in each of the batteries? Explain your reasoning.



B. A student chooses the potential to be zero at point A. Does this student find that the potential at B is *greater than, less than,* or *equal to* the potential at point A? Explain.

Use your measurements from Experiment 10.2 to calculate the potential at points B, C and D.

C. Use your knowledge of the voltage between points D and E to determine whether the potential at point E is *greater than, less than,* or *equal to* the potential at point D. Explain.

Calculate the potential at point G. Explain your reasoning.

D. Because the potential at any point has a single value, the potential at the starting point must be equal to the potential at the end point when we go around a loop. Considering this, determine the potential at point F. Explain your reasoning.

E. Consider the following student conversation:

Student 1: *"Current flows from the negative to the positive terminal, so the current flows through both bulbs in the upward direction."*

Student 2: *"Current flows from the negative to the positive terminal inside the battery, so the current flows through both bulbs in the downward direction."*

Do you agree with either student? Explain your reasoning.

Figure 5.12: Extract of Exercise 10.3 from Multiple Batteries in Multiple Loops curriculum.

Using the information given in the narrative students may infer that the direction of current in this circuit is clockwise; it is hard to see how adding batteries in series, which is observed to increase the current, would reverse the direction of the current at the same time. Since potential difference is defined as being equivalent to voltage, students can infer that the potential at point B is greater than that at point A. Using this reasoning and the measurements students have taken previously, they can determine that the potential at points C and D are $2V_{\text{battery}}$ and $3V_{\text{battery}}$ respectively.

For part B of the exercise, students need to recall their measurements in Section 8 where they measured the voltage across a connecting wire to be zero. From this, students can infer that the potential difference between points D and E is zero, so the potential at point E is the same as at point D. Using the same reasoning, they can conclude that the potential at point G is equal to that at point A, i.e., zero.

To find the potential at F, students should recognise that the potential difference between the points E and G is $3V_{\text{battery}}$. The voltages across the bulbs are equal, as they are of equal brightness. Thus students should conclude that the potential difference between E and F and between F and G must be equal to ${}^{3}/{}_{2}V_{\text{battery}}$. Since the potential at point G is zero, the potential at F must be ${}^{3}/{}_{2}V_{\text{battery}}$.

To conclude the exercise, students discuss two student statements which are aimed at highlighting the importance of noting the convention taken in regards to the direction of current through a battery. In the narrative, students are asked to adopt the convention that current *inside a battery* in a single battery circuit flows from the negative terminal to positive terminal, thus the current flows in a clockwise direction around the circuit. This reasoning should guide students to agree with student 2.

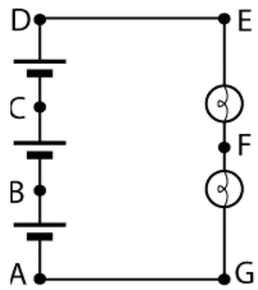
Reviewing this exercise on the basis of its overall objectives we can see that the students have discovered many of the rules that were provided in the 2006 and 2007 curriculum. These are listed overleaf.

- When crossing a battery from the negative terminal to the positive terminal of a battery, the potential increases by V_{battery}.
- The potential difference between two points joined by a wire or direct contact is 0, thus the potential along a wire remains the same.
- When crossing a bulb in the direction of the current, the potential decreases by the potential across the bulb

The next exercise has a much more concise purpose. It only focusses on one key concept, recognising that within a circuit the values of potential may change depending on the chosen reference point, but the values of potential difference do not change. By guiding students to determine the potential differences from two different reference points and also by traversing the loop in two different directions students discover the aforementioned concept. The exercise is shown below.

Exercise 10.4

A. The circuit of Exercise 10.3 is shown again at right.



Choose the potential to be zero at point B. Traverse the loop in the direction of the current, and find the potential at each of the points C, D, E, F, G, and A.

How, if at all, do the values of the potential change at each of the points when the potential is set to zero at point B instead of point A?

How, if at all, do the values of the potential difference between consecutive points change?

B. Again, choose the potential to be zero at point B. This time, traverse the loop in the direction opposite to that of the current, and find the potential at each of the points A, G, F, E, D, and C.

How, if at all, do the values of the potential change at each of the points when the loop is traversed in the opposite direction?

How, if at all, do the values of the potential difference between consecutive points change?

✓ Discuss your answers with a staff member.

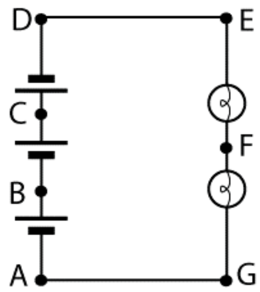
Figure 5.13: Extract of Exercise 10.4 from Multiple Batteries in Multiple Loops curriculum.

Following on from Exercise 10.4, students encounter an exercise which focusses on determining potential values in a circuit which contains a battery connected in opposite orientation. The exercise is shown below.

Exercise 10.5

A. In which direction does current flow through the circuit of part B of Experiment 10.2, shown at right? Explain.

In which direction does the current flow through each of the batteries?



B. Choose the potential at point A to be zero. Determine the potential at each of the points B–G.

C. In order for the potential to return to zero at point A, does the potential *increase, decrease* or *stay the same* when you cross the battery that is connected in opposite orientation? Explain.

Is your answer consistent with your answer to part D of Experiment 10.2? Explain.

D. Consider the following student conversation:

Student 1: *"Based on what I have seen so far, the current inside a battery always flows from the side of lower potential to the side of higher potential."*

Student 2: *"Based on what I have seen so far, the current through a bulb always flows from the side of higher potential to the side of lower potential."*

Do you agree with either student? If you disagree with either statement, give an example that shows the statement is false.

Figure 5.14: Extract of Exercise 10.5 from Multiple Batteries in Multiple Loops curriculum.

Determining the direction of the current in the circuit shown above is an important step which students must take towards the development of their model. In analysing the circuit, students must first apply their rule for adding batteries in opposite orientation.

In doing so they will see that two of the batteries effectively cancel each other, leaving one battery. The current inside this battery flows from the negative terminal to the positive terminal. This is illustrated in the Figure 5.15.

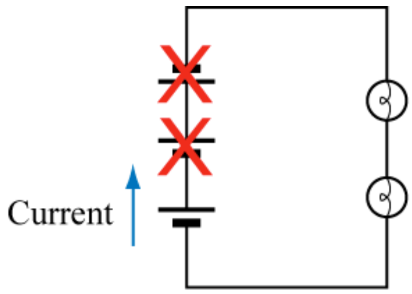


Figure 5.15: Illustration of effectively cancelling batteries that are connected in opposite orientation.

Therefore students should conclude that the current inside the battery flows from the negative terminal to the positive terminal in two of the batteries and from the positive terminal to the negative terminal in the remaining battery. This is consistent with their observations in previous sections, where they have seen that current can flow in both directions through a battery.

In determining the potential at different points in the circuit, students see that the potential has to decrease when they cross the battery which is connected in opposite orientation. The explanation is the same as that used in Exercise 10.3. It is also consistent with part D of Exercise 10.2 where students discovered that the voltage across the battery in opposite orientation must be subtracted from the potential to satisfy Kirchhoff's loop rule.

In relation to the student conversation in part D of the exercise, students conclude that student 1 is incorrect. Careful analysis of this circuit and those shown previous, leads students to see that the current can flow through a battery either from higher potential to lower potential or vice versa. This analysis should also highlight that in no circuit that they have discussed so far, has the current flowed through the bulbs from lower potential to higher potential, thus leading them to agree with student 2.

In the final exercise students encounter a circuit which they must traverse in an anti-clockwise direction.

Once students have completed the three exercises detailed above, we ask students to conclude their findings by writing a set of rules which explain their calculations, much like what was done for the concepts of current and resistance in Exercise 3.10 in the published PbI curriculum. The exercise and expected rules are shown below.

Exercise 10.7

Write a set of rules that allow you to determine the potential at each point of a single loop circuit, and the direction of the current. Your rules should allow for any ordering of any number of bulbs and batteries, and for both possible orientations of some of the batteries.

Figure 5.16: Extract of Exercise 10.7 from Multiple Batteries in Multiple Loops curriculum.

(1) For a circuit which has all batteries in the same orientation, inside each battery, the current flows from the negative terminal to the positive terminal.

(2) For a circuit which has batteries in opposite orientation, determine the effective number of batteries. The direction of current through the circuit is consistent with rule 1.

(3) Crossing a battery of voltage V_0 from the negative terminal to the positive terminal the potential increases by V_0. Crossing a battery from the positive terminal to the negative terminal the potential decreases by V_0.

(4) Going *in the direction of the current*, crossing a bulb the potential decreases by the voltage across the bulb. The current through a bulb always flows from a point of higher potential to a point with lower potential.

This set of rules can be generalised to multiple loop circuits. We guide our students through a set of experiments in which they analyse the circuits of Figure 5.17 below.

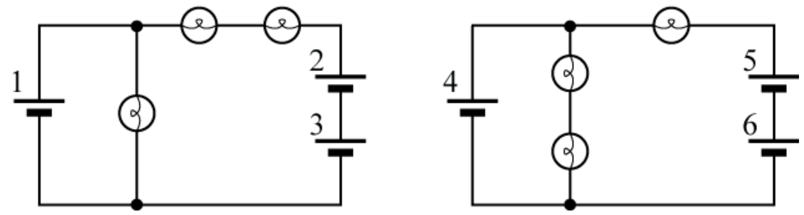


Figure 5.17: Circuits with multiple batteries in multiple loops.

For example in the left circuit in Figure 5.17, students can determine the potential at any point in the circuit as shown diagrammatically in Figure 5.18. We suggest where students set the potential to zero. Rule 3 determines the potential everywhere apart from the point between bulbs B and C; the latter value is determined by symmetry reasoning.

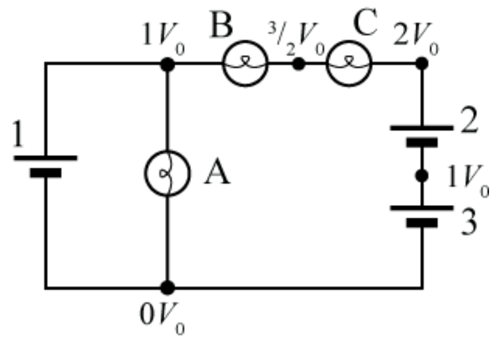


Figure 5.18: Applying values of potential to a circuit.

Once students have found the potentials in the circuit, they can determine that bulb A is brighter than bulbs B and C since there is a potential difference of V_0 across bulb A while bulbs B and C only have a potential difference of $^1/_2V_0$ across them. Since the direction of current through a bulb is always from high potential to low potential, they can determine that the current through bulbs B and C is from right to left and is downwards through bulb A. They can also reason that the current through bulb A is greater than the current through bulbs B and C, as reasoned above. By Kirchhoff's junction rule, the current through battery 1 must be upwards. This reasoning is illustrated in Figure 5.19.

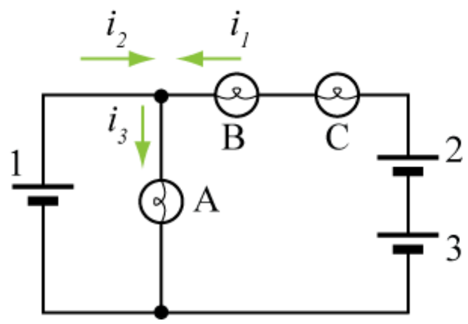


Figure 5.19: Illustration of direction of current through a circuit with multiple batteries in multiple loops.

The process detailed over the last number of pages allows students to develop a comprehensive understanding of multiple batteries in multiple loops. The rules which have been formed experimentally provide students with the ability to assess complex circuits and make accurate predictions on the current through each of the circuit elements.

5.3 Multiple Batteries in Multiple Loops: Post-Test and Analysis

The post-test data on this section consisted of three questions, all of which were carried out in the students' terminal exam. One of these questions was based on a circuit quite similar to the circuits presented in the curriculum. It was asked in two years. The other two questions expect some transfer to less similar circuits.

5.3.1 Multiple Batteries in Multiple Loops Post-Test 1

The post-test question which was presented on the 2007 and 2008 final exams had a large resemblance to the circuits which students encountered in the curriculum. The first part of the question asked students to rank the relative brightness of the bulbs in the circuit shown in Figure 5.20.

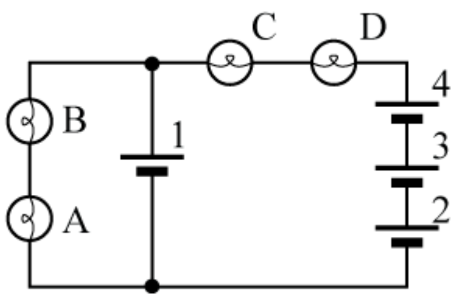


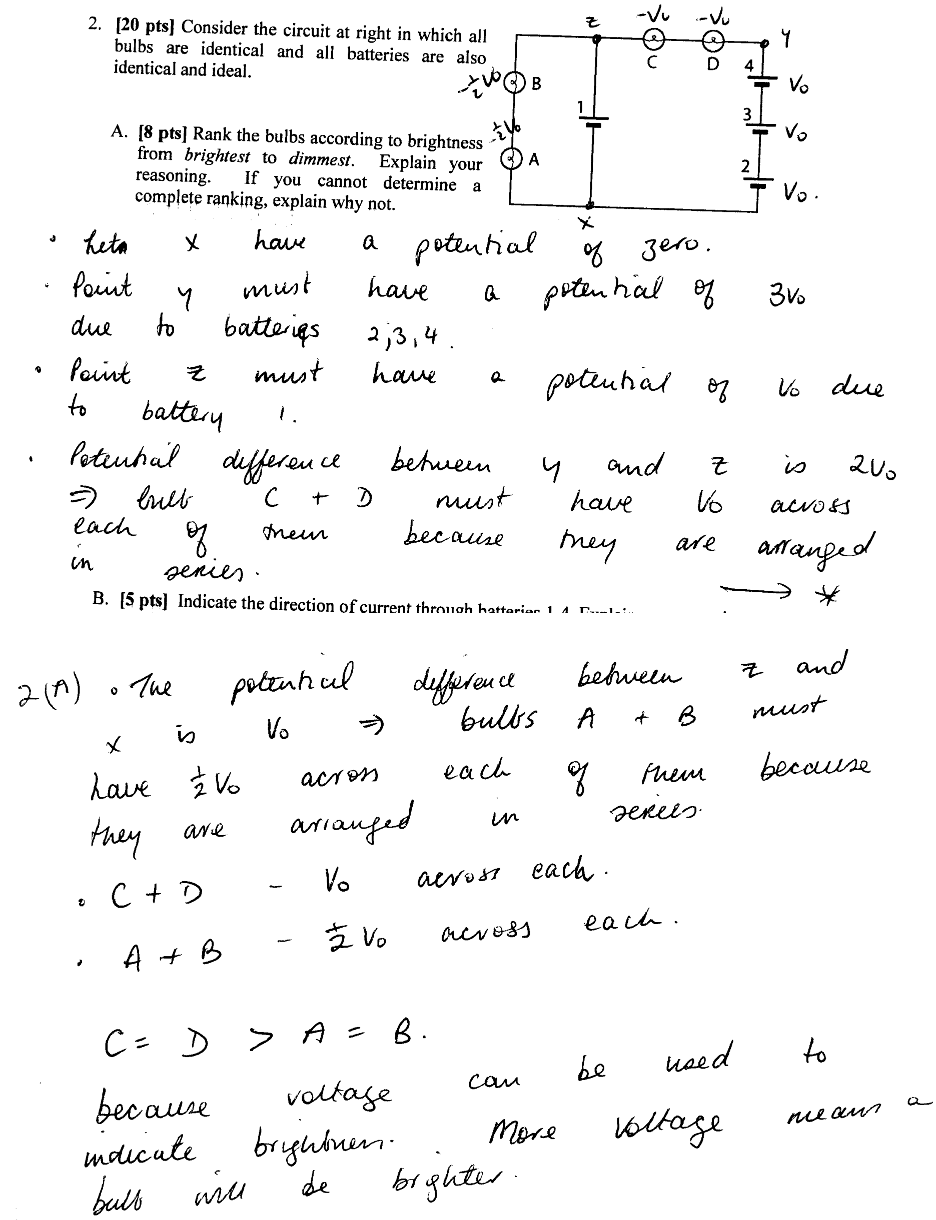
Figure 5.20: Circuit diagram presented in Multiple Batteries in Multiple Loops Post-Test 1.

The analysis of students' answers provided the data shown below in Table 5.2.

Table 5.2: Students' answers to Multiple Batteries in Multiple Loops Post-Test 1, Question 1.

Ranking	2007 % (*N*=17)	2008 % (*N*=14)	Total % (*N*=31)
C=D>A=B	**95 (16)**	**95 (13)**	**95 (29)**
A=B=C=D	5 (1)	5 (1)	5 (2)

Of the 95% of students who answered the question correctly, 50% provided a complete and well reasoned answer. An example of such an answer is shown in Figure 5.21.


2. **[20 pts]** Consider the circuit at right in which all bulbs are identical and all batteries are also identical and ideal.

A. **[8 pts]** Rank the bulbs according to brightness from *brightest* to *dimmest*. Explain your reasoning. If you cannot determine a complete ranking, explain why not.

- Let x have a potential of zero.
- Point y must have a potential of $3V_0$ due to batteries 2, 3, 4.
- Point z must have a potential of V_0 due to battery 1.
- Potential difference between y and z is $2V_0$ ⇒ bulb C + D must have V_0 across each of them because they are arranged in series.

→ *

B. **[5 pts]** Indicate the direction of current through batteries 1-4. Expl...

2(A) • The potential difference between z and x is V_0 ⇒ bulbs A + B must have $\frac{1}{2}V_0$ across each of them because they are arranged in series.

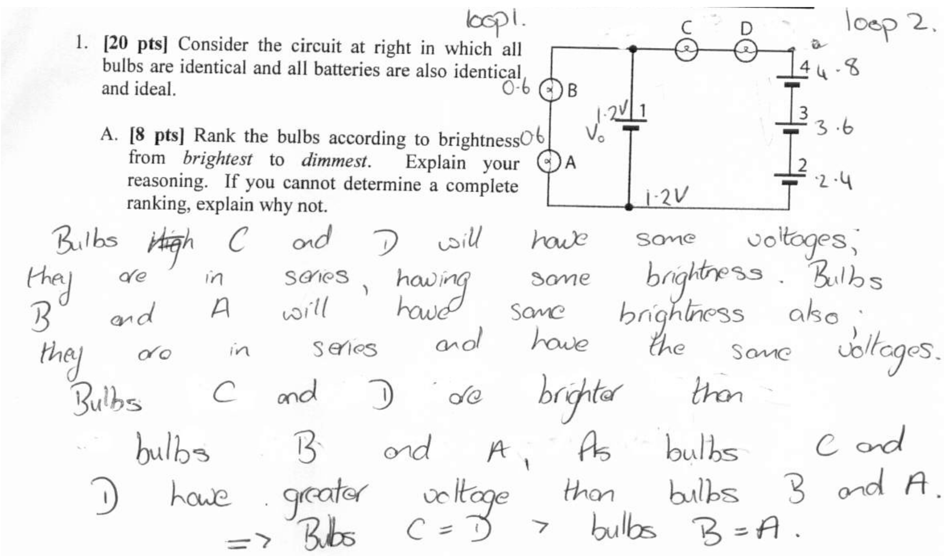
• C + D – V_0 across each.
• A + B – $\frac{1}{2}V_0$ across each.

C = D > A = B.

because voltage can be used to indicate brightness. More voltage means a bulb will be brighter.

Figure 5.21: Example of a student's answer in response to Multiple Batteries in Multiple Loops Post-Test 1, Question 1.

A further seven students that answered the question correctly provided incomplete reasoning with their ranking. An example of such an answer is shown in Figure 5.22.



1. **[20 pts]** Consider the circuit at right in which all bulbs are identical and all batteries are also identical and ideal.

A. **[8 pts]** Rank the bulbs according to brightness from *brightest* to *dimmest*. Explain your reasoning. If you cannot determine a complete ranking, explain why not.

Bulbs ~~High~~ C and D will have same voltages; they are in series, having same brightness. Bulbs B and A will have same brightness also: they are in series and have the same voltages. Bulbs C and D are brighter than bulbs B and A, As bulbs C and D have greater voltage than bulbs B and A.
=> Bulbs C = D > bulbs B = A.

Figure 5.22: Example of an incomplete answer to Multiple Batteries in Multiple Loops Post-Test 1, Question 1.

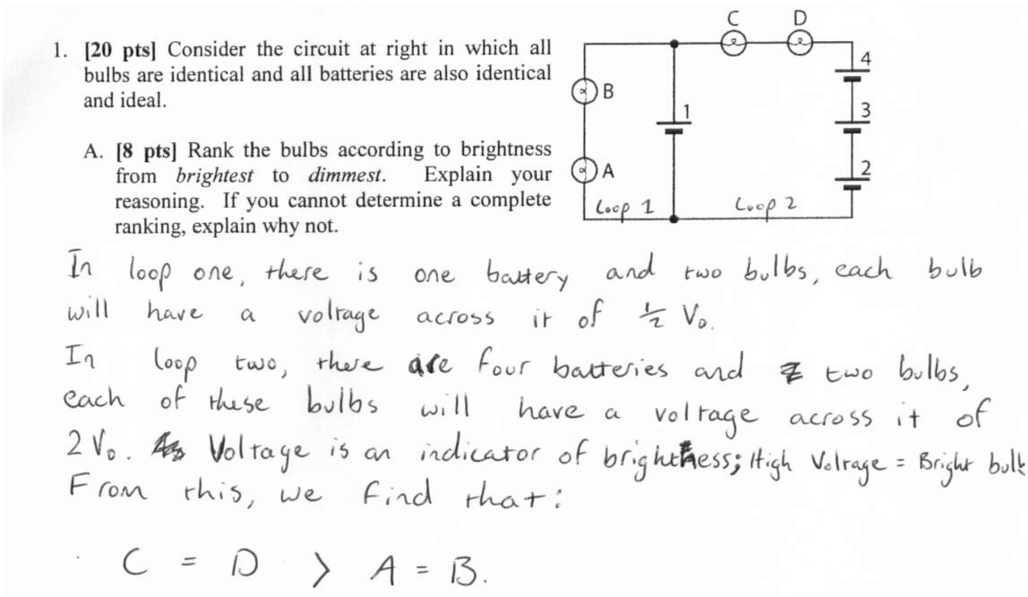
Notice that the above student's answer does not refer to any specific values of voltage or potential and thus does not provide complete reasoning for their ranking. Although the values listed on the students diagram hints at correct reasoning.

Of the 29 students who provided the correct ranking, five provided answers with misconceptions or incorrect reasoning. Two of these are shown below:

Branch [1] is independent of branch [2,3,4]

Battery 1 is on a branch independent of battery 2,3 and 4. C and D are in series with one another. B and A are in series with one another on a branch independent of C&D. C&D are on one loop, while B&A are on another loop. Kirchhoff's loop rule states the sum of the voltages across all of the elements along any path is the same for all paths between two nodes, the voltage across the battery in a current loop is equal to the sum of the voltages across the other elements

Considers only two loops


1. **[20 pts]** Consider the circuit at right in which all bulbs are identical and all batteries are also identical and ideal.

   A. **[8 pts]** Rank the bulbs according to brightness from *brightest* to *dimmest*. Explain your reasoning. If you cannot determine a complete ranking, explain why not.

In loop one, there is one battery and two bulbs, each bulb will have a voltage across it of $\frac{1}{2} V_0$.
In loop two, there are four batteries and ~~2~~ two bulbs, each of these bulbs will have a voltage across it of $2V_0$. ~~As~~ Voltage is an indicator of brightness; High Voltage = Bright bulb
From this, we find that:

$C = D > A = B$.

Figure 5.23: Example of a correct answer based on incorrect reasoning to Multiple Batteries in Multiple Loops Post-Test 1, Question 1.

In the second part of the question, students were asked to indicate the direction of current through batteries 1-4. For the analysis I have split the batteries in two groups where batteries 2-4 are grouped together and battery 1 remains on its own since the reasoning for both groups is somewhat separate. To correctly reason the direction of current through batteries 2-4, I wanted students to make reference to the direction of current through bulbs C and D. Since the potential is higher to the right of bulb D than it is to the left of bulb C, the direction of current through bulbs C and D is from right to left. On this basis, the current through batteries 2-4 is upwards or from the negative to the positive terminal inside each battery. The analysis of students' answers provided the data shown in Table 5.3.

Table 5.3: Students' answers to Multiple Batteries in Multiple Loops Post-Test 1, Question 2.

Answer	2007 % (N=17)	2008 % (N=14)	Total % (N=31)
Upwards through batteries 2-4	**95 (16)**	**85 (12)**	**90 (28)**
Other	5 (1)	15 (2)	10 (3)

Of the 28 students who answered the question correctly, only seven used the reasoning based on the direction of current through bulbs C and D while the vast majority of the remaining answers applied incomplete reasoning that the current through the battery is from the negative terminal to the positive terminal inside a battery.

To determine the direction of current through battery 1, students must reason on the basis of potential in conjunction with Kirchhoff's junction rule. The large majority of students have reasoned that bulbs C and D are brighter than bulbs A and B. On the basis of potential, they can reason that the direction of current through bulbs C and D is from right to left and the direction of current through bulbs A and B is downwards. Since bulbs A and B are dimmer than bulbs C and D, students must infer that the current through battery 1 is downward. Students's answers are shown in Table 5.4.

Table 5.4: Students' answers to Multiple Batteries in Multiple Loops Post-Test 1, Question 2.

Answer	**2007 % (*N*=17)**	**2008 % (*N*=14)**	**Total % (*N*=31)**
Downwards through battery 1	**75 (13)**	**50 (7)**	**65 (20)**
Upwards through battery 1	20 (3)	15 (2)	15 (5)
No current through battery 1	5 (1)	20 (3)	15 (4)
Other	0 (0)	15 (2)	5 (2)

Of the 20 students who answered the question correctly, eight provided complete reasoning, eight provided answers that were incomplete and the remaining four answers contained some misconceptions.

Three more questions were asked in the same setting. They referred to the circuit shown in Figure 5.24 in which battery 5 has been added in series to battery 1.

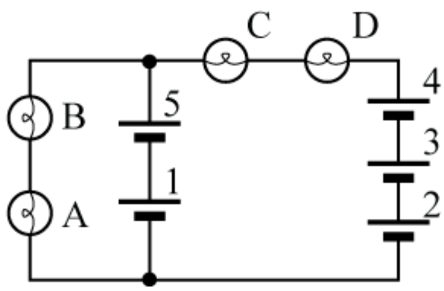


Figure 5.24: Second circuit presented in Muliple Batteries in Multiple Loops Post-Test 1.

The first of these questions asked students to explain whether the brightness of bulb A would increase, decrease or remain the same. The answers are shown in Table 5.5.

Table 5.5: Students' answers to Multiple Batteries in Multiple Loops Post-Test Question 1, Question 3.

Answer	2007 % (*N*=17)	2008 % (*N*=14)	Total % (*N*=31)
Bulb A increases	**95 (16)**	**80 (11)**	**85 (27)**
Bulb A decreases	0 (0)	5 (1)	5 (1)
Bulb A stays the same	5 (1)	15 (2)	10 (3)

As the results in Table 5.5 above shows that 85% of students answered the question correctly and stated that the brightness of bulb A increases when battery 5 is added in series with battery 1. Of these students, 65% provided a complete and well reasoned answer. An example is shown in Figure 5.25.

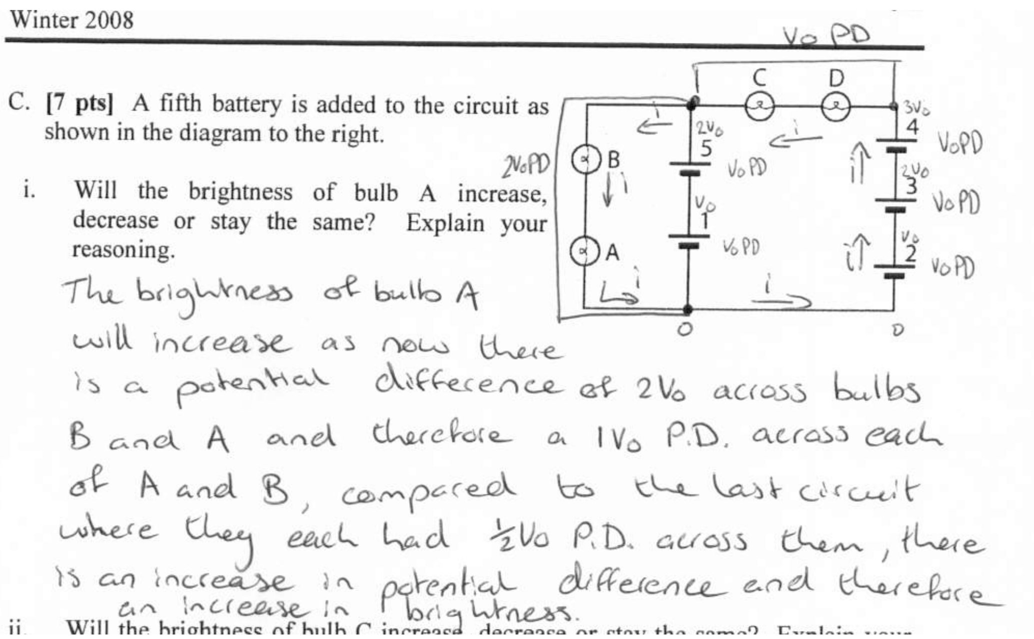


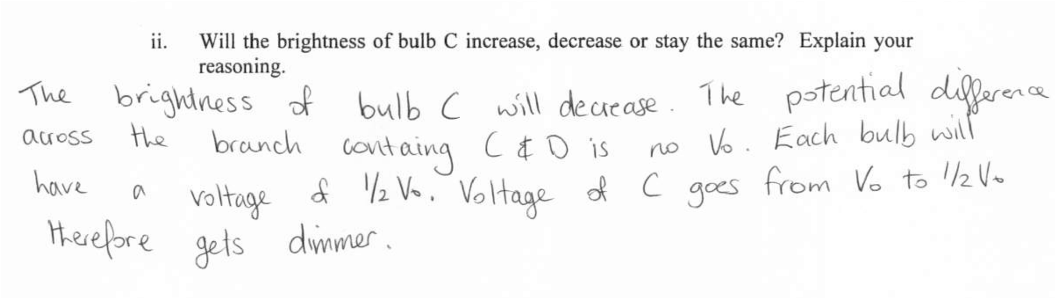
Figure 5.25: Example of a complete correct answer to Multiple Batteries in Multiple Loops Post-Test 1, Question 3.

In conjunction with the previous question, students were also asked to comment on whether the brightness of bulb C would increase, decrease or stay the same when battery 5 was added to the circuit. Students' answers are shown in Table 5.6.

Table 5.6: Students' answers to Multiple Batteries in Multiple Loops Post-Test 1, Question 4.

Answer	2007 % (*N*=17)	2008 % (*N*=14)	Total % (*N*=31)
Bulb C decreases	**70 (12)**	**65 (9)**	**70 (21)**
Bulb C increases	5 (1)	10 (2)	10 (3)
Bulb C stays the same	25 (4)	20 (3)	25 (7)

As the results in Table 5.6 show, 70% of students answered the question correctly in relation to the change in brightness of bulb C and of these students, 70% gave a well reasoned answer. An example is shown in Figure 5.26.


ii. Will the brightness of bulb C increase, decrease or stay the same? Explain your reasoning.

The brightness of bulb C will decrease. The potential difference across the branch containg C & D is no V_0. Each bulb will have a voltage of $1/2\,V_0$. Voltage of C goes from V_0 to $1/2\,V_0$ therefore gets dimmer.

Figure 5.26: Example of a complete correct answer to Multiple Batteries in Multiple Loops Post-Test 1, Question 4.

In the final question, students were asked to comment on the direction of current through battery 5. Essentially this is the most complex question students encounter as it requires a complete understanding of the rules they have developed and the ability to apply them in conjunction with Kirchhoff's loop rule. Tables 5.5 and 5.6 show the majority of students have answered the questions correctly regarding the brightness of bulb A and bulb C which is essential for answering the question on the direction of current through battery 5. On this basis, they can reason that bulbs C and D are dimmer than bulbs A and B. Applying their rules for the direction of current, they can determine that the current through bulbs C and D is right to left and the current through bulbs A and B is downward. Therefore the current through battery 5 must be upward since the current through bulbs C and D is less than that through bulbs A and B. The reasoning is also shown diagrammatically in Figure 5.27.

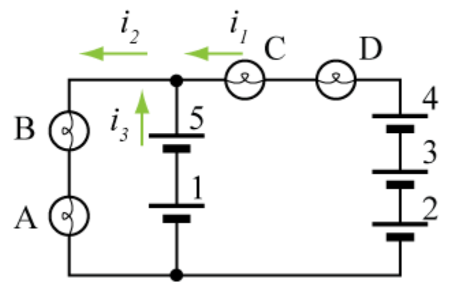
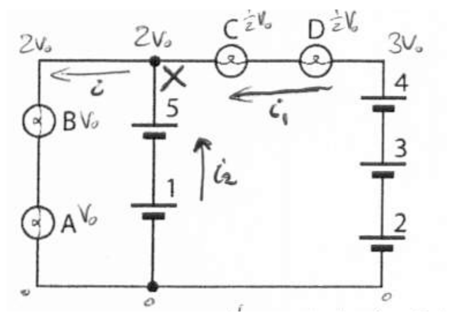


Figure 5.27: Illustration of current direction in second circuit of Multiple Batteries in Multiple Loops Post-Test 1.

Of the 31 students, 50% of them answered the question correctly stating that the current through battery 5 is upwards, however only 30% of these students gave a complete answer. An example of a complete answer is shown in Figure 5.28.



iii. Indicate the direction of current through battery 5. Explain your reasoning

The current through battery 5 flows from bottom to top.

Since A and B are brighter than C and D, more current must be flowing through ~~them~~ A and B. ie $i > i_1$

Therefore, more current must be flowing into node X than just i_1, so $i_2 > 0$, and it flows from bottom to top.

Figure 5.28: Example of a complete correct answer to Multiple Batteries in Multiple Loops Post-Test 1, Question 5.

5.3.2 Multiple Batteries in Multiple Loops Post-Test 2

In the second question of the 2008 final exam students were presented with the circuit shown in Figure 5.29. The circuit is quite different to what they had encountered in the curriculum in that there are two branches with a bulb and a battery. The illustration of the circuit diagram is also different, which may seem superficial, but we find it can have an impact on the students' responses.

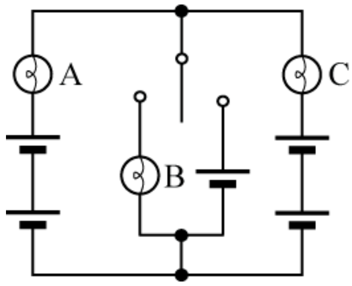


Figure 5.29: Circuit presented in Multiple Batteries in Multiple Loops Post-Test 2.

More importantly, the question presents students with a problem in which they have to apply Kirchhoff's junction rule before the rules on potential.

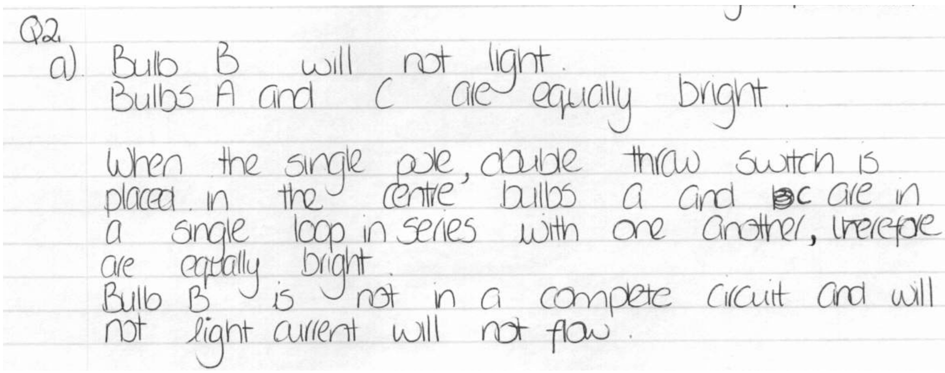
In the first part of the question, students were asked to rank the relative brightness of the bulbs when the switch was in the centre position . Although this part of the question may have more value on the section of multiple batteries in single loops, it is presented here in order to form a connection with the following questions. The results were reasonably satisfactory with 65% of students correctly stating that none of the bulbs would light when the switch was in the centre position as shown above. The results are shown in Table 5.7.

Table 5.7: Students' answers to Multiple Batteries in Multiple Loops Post-Test 2, Question 1.

Answer	% (*N*=14)
All bulbs do not light	**65 (9)**
A = C > B is off	35 (5)

Of the nine students who answered the question correctly, eight provided complete and correct reasoning. One student reasoned on values of potential and potential difference while the remaining seven reasoned on the basis that opposing orientation of batteries effectively cancel each other. The last student gave an answer which was almost complete and used the reasoning of the orientation of the batteries, however did not explicitly state that they effectively cancel each other.

For the five students who gave an incorrect answer, all noted that bulb B did not light, however they did not take into account the orientation of the batteries when reasoning their answer about bulbs A and C. On this basis, they ranked bulb A and C equal in brightness since they were arranged in series. An example of such an answer is shown in Figure 5.30.


Q2.
a) Bulb B will not light.
Bulbs A and C are equally bright.

When the single pole, double throw switch is placed in the centre bulbs A and ~~B~~C are in a single loop in series with one another, therefore are equally bright.
Bulb B is not in a complete circuit and will not light current will not flow.

Figure 5.30: Example of an incorrect answer to Multiple Batteries in Multiple Loops Post-Test 2, Question 1.

In the second question of the post-test, students were once again asked to rank the brightness of bulbs in the case when the switch in Figure 5.29 was turned to the right, adding a battery to the circuit. In this case a potential difference is created across bulbs A and C while bulb B is excluded from the circuit. Bulbs A and C are thus equal in brightness, and brighter than bulb B. Table 5.8 shows that many students stated the correct ranking. Further analysis of students' answers highlighted some unsatisfactory responses.

Table 5.8: Students' answers to Multiple Batteries in Multiple Loops Post-Test 2, Question 2.

Answer	% (N=14)
A = C > B does not light	**70 (10)**
C > A > B does not light	5 (1)
A > C = B	5 (1)
No bulbs light	5 (1)
No answer	5 (1)

Only 5 of the 10 students who answered the question correctly, provided appropriate reasoning while a further three provided reasoning which was also correct but incomplete. Examples of complete and incomplete answers are shown in Figure 5.31 and 5.32 respectively.

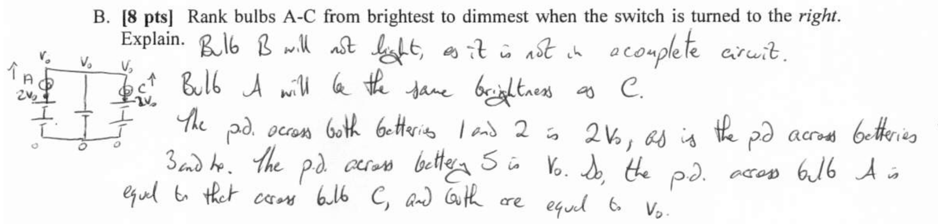
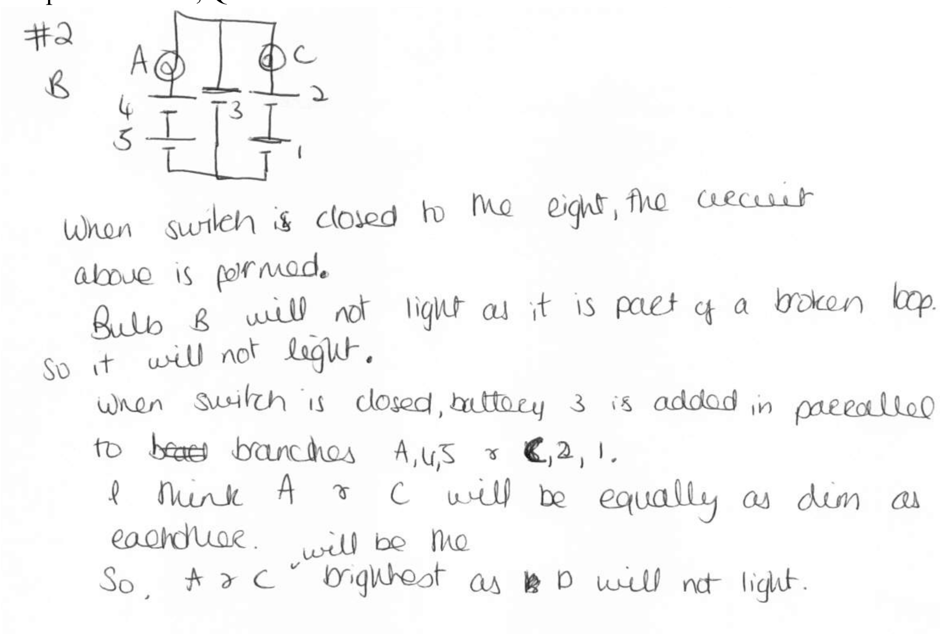

B. **[8 pts]** Rank bulbs A-C from brightest to dimmest when the switch is turned to the *right*. Explain. Bulb B will not light, as it is not in a complete circuit. Bulb A will be the same brightness as C. The p.d. across both batteries 1 and 2 is $2V_0$, as is the p.d across batteries 3 and 4. The p.d. across battery 5 is V_0. So, the p.d. across bulb A is equal to that across bulb C, and both are equal to V_0.

Figure 5.31: Example of a complete correct answer to Multiple Batteries in Multiple Loops Post-Test 2, Question 2.


#2
B

When switch is closed to the right, the circuit above is formed.
Bulb B will not light as it is part of a broken loop. So it will not light.
When switch is closed, battery 3 is added in parallel to ~~beae~~ branches A,4,5 & C,2,1.
I think A & C will be equally as dim as eachother.
So, A & C will be the brightest as B will not light.

Figure 5.32: Example of an incomplete answer to Multiple Batteries in Multiple Loops Post-Test 2, Question 2.

In the last questions of the post-test, students were asked to comment on the brightness of the bulbs when the switch in Figure 5.29 was moved to the left, which includes bulb B in the circuit. The potential below bulb B is less than the potential above bulb B, so current is in the downward direction. By symmetry, the current through bulbs A and C are equal and in the same direction; by Kirchhoff's junction rule, this must be upward. The leads to bulb B being brighter than bulbs A and C, which are equal. No student used this line of reasoning, although three students did provide the correct ranking with incomplete reasoning. A further three students ranked all bulbs equal in brightness.

Overall, the question was answered reasonably well considering that the circuit was quite different to what students had previously encountered.

5.3.3 Multiple Batteries in Multiple Loops Post-Test 3

In the final exam of the 2006 module students were given the circuit diagram in Figure 5.33. It looks quite different to the circuits shown in the curriculum, but can be drawn as shown in Figure 5.34.

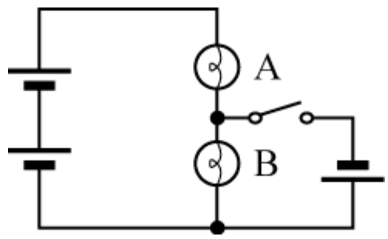


Figure 5.33: Circuit presented in Multiple Batteries in Multiple Loops Post-Test 3.

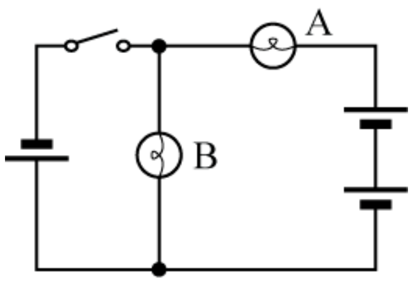


Figure 5.34: Different representation of the Circuit presented in Multiple Batteries in Multiple Loops Post-Test 3.

The opposing orientation of the batteries in the two independent parallel branches is new to students. Moreover, the curriculum that was presented to the students in 2006 was relatively underdeveloped.

This question began with an easy opening question by asking students to compare the brightness of bulb A to that of bulb B when the switch is open. Of the 20 students who answered the question, all stated that bulb A is equal in brightness to bulb B using the following reasons.

- Eight used voltage reasoning and stated that the voltage across the bulbs was equal or that the voltage across the batteries was divided equally across the bulbs.
- Seven used current reasoning and stated that the bulbs were equal as they were connected in series.

- Two used both voltage and current reasoning.
- One student stated incorrectly that the two bulbs share the current equally. Another stated correctly that bulbs A and B were equal as they are in series, but stated that battery 3 was short circuited.
- The final student did not provide a specific reason other than stating that “when the switch is open, only the batteries and A and B are connected.”

In the second question of the post-test students were asked to comment on the change, if any, to the brightness of bulb B when the switch was closed. This question is relatively easy if it is reasoned on the basis of voltage. Students’ answers are tabulated below in Table 5.9.

Table 5.9: Students’ answers to Multiple Batteries in Multiple Loops Post-Test 3, Question 2.

Answer	% (*N*=20)
Bulb B remains the same	**55 (11)**
Bulb B decreases	35 (7)
Bulb will not increase	5 (1)
Unclear	5 (1)

Only 11 of 20 students answered the question correctly by stating that the brightness of bulb B remains the same when the switch was closed. Of the 11 students, nine provided a complete answer while one stated that “adding a battery in parallel has no effect” and one gave no reason.

Of the seven students who stated that bulb B decreases in brightness, five students referred to the orientation of battery 3, incorrectly assuming that one of the other batteries is effectively cancelled and the overall voltage across the circuit is decreased. It is interesting to note that no student treated the battery in parallel like a bulb as they had done in a similar pretest question.

In the last question of the post-test, students were asked to comment on the change, if any, to the brightness of bulb A when the switch is closed. This question is undoubtedly more difficult than the previous question as students must determine the potential difference across bulb A in order to correctly determine the change in brightness. When done correctly the potentials could be assigned as shown below.

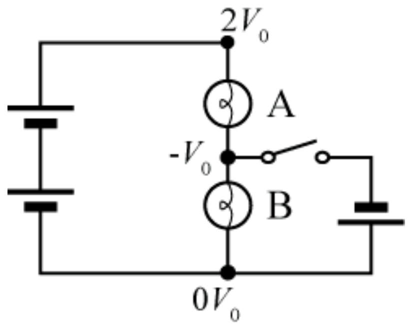


Figure 5.35: Applying potential values to circuit presented in Multiple Batteries in Multiple Loops Post-Test 3, Question 3.

Five students (25%) correctly stated that bulb A increases in brightness when the switch is closed. Two of them reasoned their answer on the basis that in the outside loop, bulb A is connected in series with three batteries with the same orientation and thus becomes brighter. This is correct, even though this type of reasoning fails for circuits shown previously. Other students looked upon the battery as another circuit element, which when connected in parallel, reduces the resistance of the circuit, resulting in an increased current through bulb A.

Of the 13 students (65%) who incorrectly stated that the brightness of bulb A would remain the same, 10 reasoned on the basis that the voltage across bulb A did not change when the switch was closed. This stemmed from only considering either the left loop or right loop.

5.4 Conclusion

This research has made a significant contribution to the body of physics education research on students' understanding of circuits consisting of multiple batteries in multiple loops. The pretest carried out on this topic identified that the large majority of students were unable to explain the effects of adding batteries in multiple loops. Since this topic is not covered at second level and only in minor detail at third level, this was expected. As with previous concepts, students relied largely on their understanding of current and resistance, in an attempt to rank the relative brightness of the bulbs in the circuits shown in Figure 5.36.

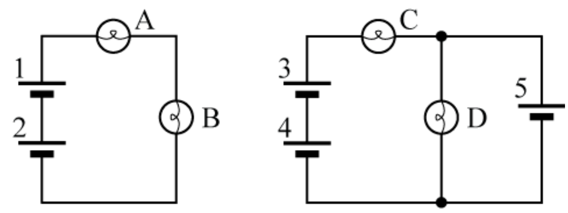


Figure 5.36: Circuits presented in Multiple Batteries in Multiple Loops Pretest.

Some misconceptions highlighted in Chapters 3 and 4 were also prevalent, with the belief that the battery supplies current being the most significant. However, students did display an ability to model a circuit based on their conceptual understanding of voltage, current and resistance. In this case students tried to model the behaviour of battery 5 in Figure 5.36 as an element similar to a bulb or a connecting wire. This is an ability that was not prevalent prior to instruction.

The development of curriculum that addressed students' difficulties has been a continual learning process. The largest change to the curriculum involved the introduction of the concepts of potential and potential difference, as it was evident that the analysis of the circuits shown in curriculum, was not possible without these concepts. The first attempt at introducing the concept was unsatisfactory as a large amount of information and rules were provided and little emphasis was placed on discovery. Further revisions which involved intensive redevelopment, produced a number of exercises that allowed students to systematically discover rules for how circuits can be modelled on values of potential and potential difference.

Post-test results show that the majority of students were able to apply their newly developed model to make accurate predictions on complex circuits. Students displayed a competent ability to differentiate between the concepts of voltage, current and resistance. The analysis of their answers also revealed an understanding of the role that each concept plays in their model for electric circuits. However, in some cases, students found it difficult to transfer their understanding to a more difficult context when presented with unfamilar post-test questions. This finding is not exclusive to the topic of multiple batteries in multiple loops and is consistent with all other key concepts presented in the electric circuits module.

References

1. N. Fredette, J. Lochhead, *Student conceptions of simple circuits*, Phys. Teach, 1980
2. L. C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry vol II*, 419, Wiley, New York 1996

Chapter 6

RC Circuits

6.1 Introduction

The final section of the electric circuits curriculum focusses on developing a conceptual model for the behaviour of capacitors in circuits. The curriculum begins with an investigation of the effects of a capacitor in single loop circuits. The students model the behaviour of a capacitor as a circuit element with characteristics of various other circuit elements. They discover that an uncharged capacitor behaves initially like a copper wire and charges over time. A charged capacitor is modelled as a battery whose voltage can change. In their investigations, they differentiate between the behaviour of a capacitor in single loop circuits and its behaviour when connected in parallel across a bulb. They determine that the capacitor becomes charged to the net voltage of the batteries in a single loop. When a capacitor is connected in parallel across a bulb, they notice that it charges to the same voltage that the element or branch its connected to would have in the absence of the capacitor.

The curriculum on capacitors in single loops has grown out of curriculum that was developed by Mike Gearen (Pumahou School, Honolulu, Hawaii) and Andrew Crouse, then a graduate student in the Physics Education Group at the University of Washington. It was extended by Paul van Kampen during his sabbatical visit to that group in 2004–2005 to include curriculum on capacitors connected in parallel with bulbs. Other than some small changes to the wording of student statements contained within some of the experiments and exercises, little else has been changed.

Since the large majority of students have not had any prior experience with capacitors, interpretation of the pretest analysis is difficult. Many students used a large amount of guesswork when completing the questions.

This chapter discusses some of the minor changes to the curriculum and the process in which the original curriculum achieves its objectives. The chapter is concluded with the analysis of the post-test questions administered over the three years. Despite students' lack of prior experience with capacitors, a large portion of them excelled in answering the questions.

6.2 Capacitors in Single Loops: Pretest and Analysis

In each of the three years students were given the same pretest prior to commencing the curriculum on capacitors in single loops. The opening question of the first pretest addressed students' preconceptions of the function of a capacitor by asking them the following question.

Capacitors in Single Loops Pretest

The circuit at right contains a battery, a bulb, a switch and a capacitor. The capacitor is initially uncharged.

Predict the behaviour of the bulb from just after the switch is closed to a long time after. Explain your reasoning.

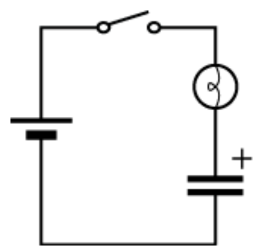


Figure 6.1: Single loop circuit consisting of a battery, switch, bulb and capacitor.

The analysis of students' answers revealed that 15% of students made a correct prediction for the behaviour of the bulb. An additional 30% stated that the brightness of the bulb would decease after a period of time, but did not explicitly state that the bulb would not light a long time after the switch is closed. A breakdown of the students' answers in shown in Table 6.1.

Table 6.1: Students' answers to Capacitors in Single Loops Pretest.

Answer	**2006 %** **(*N*=18)**	**2007 %** **(*N*=14)**	**2008 %** **(*N*=7)**	**Total %** **(*N*=39)**
Bulb lights initially and then goes out	**5 (1)**	**20 (3)**	**15 (1)**	**15 (5)**
Bulb lights initially and gets dimmer	35 (6)	5 (1)	70 (5)	30 (12)
Bulb is initially dim and gets brighter	10 (2)	15 (2)	15 (1)	15 (5)
Bulb lights initially and gets brighter	5 (1)	15 (2)	0 (0)	10 (3)
Bulb doesn't light initially and gets brighter	15 (3)	5 (1)	0 (0)	10 (4)
Bulb lights, then dims, and then brightens	5 (1)	5 (1)	0 (0)	5 (2)
No time reference	15 (3)	15 (2)	0 (0)	15 (5)
I don't know	0 (0)	15 (2)	0 (0)	5 (2)
Other	5 (1)	0 (0)	0 (0)	5 (1)

Of the five students (15%) who answered the question correctly, two referred to the 'storing function' of the capacitor. These answers are shown below.

> *"A capacitor stores charge so the bulb will light once the switch is closed and will then stop shining once the capacitor begins to take all of the voltage of the battery."*
>
> *"Light at start and go out after time, capacitor will store the batteries power, leaving the bulb unlit."*

Of the three remaining students, one referred to the accumulation of charge in the capacitor, one did not give a specific reason and one student's answer was difficult to interpret. This student's answer is shown below.

> *"Bulb lights brightly initially but goes out as there is a lot of pressure on the battery"*

The most popular answer overall was to predict correctly that the bulb would light initially and then get dimmer as time passed. The analysis of these 12 students' answers is listed overleaf.

- Five students gave no detail other than stating that the bulb becomes dimmer over time.
- Three students referred to the 'storing function' of the capacitor with two students stating that it stored energy and one stating that it stored current.
- Two students stated that the bulb will get dimmer as the capacitor charges.
- One student reasoned on the basis that the resistance of the capacitor increases over time.
- One student stated that "*over time the bulb brightness will decrease as the voltage decreases*."

Overall, the large variance in students' answers may be a testament to the lack of understanding they have for the function of a capacitor. In spite of this, it is interesting to note that almost every student made an attempt at the question. A breakdown of the main concepts present in students' answers is shown in Table 6.2.

Table 6.2: Concepts referenced in answers to Capacitors in Single Loops Pretest.

Concept	**% (*N*=39)**
Capacitor stores current, charge, energy, power	30 (11)
Charging of capacitor	20 (8)
Unsure of capacitor function	10 (4)

In conjunction with this question, students were asked to comment on the potential difference across the capacitor and the bulb at the same two instants; just after the switch is closed and a long time after the switch is closed. Although it was difficult to recognise some of the students' misunderstandings in the previous question, the answers to this question highlighted some key areas of difficulty. Since students have made a prediction for the behaviour of the bulb in Figure 6.1 shown previously, it would be expected that students follow with a correlated prediction for the voltage across each element at the two instances.

However, the analysis showed that many students could not make the link between the two questions. For the most popular answer (bulb lights initially and then dims or goes out), only five of the 12 students made a correct correlation for the voltages across these elements stating that V_{cap} was low and V_{bulb} was high just after the switch is closed and vice versa for a long time after the switch is closed. Of these five answers:

- One student based their answer on the conflict of current stored versus current used. This student stated that V_{cap} was low and V_{bulb} was high because the capacitor had little current stored and that current was used respectively. Answers were then reversed for the case of when the switch was closed for a long time.
- One student based their answer on the changing resistance of the capacitor where they stated that "*as time goes on the capacitor becomes more resistant so takes up more of the voltage*".
- One student reasoned on the basis of the storing function of the capacitor.
- Two students did not provide a detailed answer.

Of the remaining seven students, many gave answers which were in direct conflict with their answer to the first question. These students state that the voltage across the capacitor was high or equal to V_{battery} and that the voltage across the bulb was low or zero just after the switch was closed. This obviously contradicts the statement that the bulb lights brightly at this instant.

It is also interesting to note that 5 of the 12 students also stated that the voltage across the bulb, a long time after the switch was closed, was equal to zero, however did not state in their answer to the previous question that the bulb would go out. This suggests that their first answer was possibly careless or incomplete but not incorrect.

6.3 Capacitors in Parallel with Bulbs: Pretest and Analysis

The pretest on capacitors in parallel with bulbs was completed by students at different stages in the curriculum. In the 2006 and 2007 module, the pretest on capacitors in parallel was given prior to commencing the curriculum on capacitors on single loops, while in the 2008 module it was given after students had completed the curriculum on single loops.

In each of the three years students were presented with the circuit shown in Figure 6.2. In the question students were asked to describe the behaviour of bulbs A and B from just after the switch is closed to a long time later. They are told that the capacitor is initially uncharged.

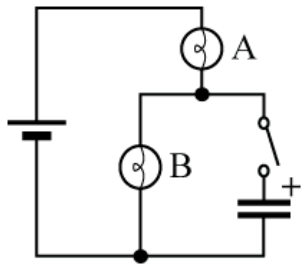


Figure 6.2: Circuit diagram presented in Capacitors in Parallel with Bulbs Pretest.

The analysis of the 2006 and 2007 pretests highlighted 17 different descriptions from a total of 34 answers. The breakdown of these answers is bulleted below.

- Three students correctly described the bulb brightness, stating that bulb A would light initially while bulb B would not light until the capacitor had charged. Two of their answers are shown below, one using voltage reasoning, the other current.

  "When the switch is closed bulb A will light. As charge builds up on the capacitor its p.d will increase. The increase in p.d will result in a higher voltage across bulb B also over time. Therefore the brightness of bulb B will increase over time."

  "When the switch is closed bulb A will light and the capacitor will charge from the current from bulb A. Bulb B will not light until the capacitor is fully charged a long time after the switch is closed, when the capacitor starts acting like a battery"

- The most popular answer was to describe both bulbs as being bright when the switch is closed and to decrease in brightness over a period of time. This was also the most popular answer for describing the behaviour of the bulb in the single loop circuits. Eight of the 34 students (25%) provided this description with three of those basing their answer on the storing ability of the capacitor. Some of their answers are shown below:

  "When the switch is closed the bulbs light. Eventually the bulbs will dim because the battery will run out but there is a capacitor in the circuit. This stores charge so it will keep the bulbs lighting."

  "At first the bulbs will light the same but eventually will dim as the capacitor stores a build up of current."

- Nine students stated that the bulbs remain equal in brightness. This is correct a long time after the switch is closed, but not immediately after. Of the nine students, four did not provide any reason, three stated that the capacitor had no effect on the circuit, while the remaining two referred specifically to the two instants. Their answers are shown below:

  "The bulbs will light just after the switch is closed and stay at the same brightness a long time after. N.B Bulb B will be lit before switch is closed as the capacitor will light it."

  "The capacitor and bulb B will be in series to bulb A and the battery. For a short time bulb A and B will light. Later the battery will be dead and the capacitor will power the circuit. Bulb B will be in parallel to bulb A. Both will be equal."

- The remaining 14 answers often gave common views of the brightness of the bulbs just after the switch was closed, but differed when the switch had been closed for a long time. Some of their answers are shown below:

  "Bulb A lights initially but as capacitor reaches same voltage as battery, bulb A goes out. Bulb B has same brightness throughout experiment."

  "When the switch is closed, the capacitor stores some charge. After a long time, bulbs A and B would begin to increase in brightness."

> *"Bulb B will be brighter than bulb A because it is connected in parallel with a capacitor."*

Students who completed the pretest in 2008 had already completed the curriculum on capacitors in single loops. This knowledge, combined with the multiple loops curriculum suffices in principle to answer all questions on capacitors connected in parallel with bulbs (see section 6.3). Hence, it was expected that a greater number of students would make the correct prediction. However, the analysis shows that all students made an incorrect prediction, note that albeit different from earlier years, only six pretests were completed. The analysis of students' answers is shown below.

- Four students predicted that bulb A and B would light when the switch was closed, but over a period of time bulb A would decrease in brightness while bulb B remained the same. Three of these students reasoned their answer on the basis of independent parallel branches where they stated that bulb B was independent of the capacitor.
- The remaining two students stated that the two bulbs would light initially but one stated that both would dim after a period of time while the other stated that only bulb B decreases in brightness.

The large inconsistency in students' answers over the three years is a clear indication of students' lack of understanding of the function of the capacitor. Although many students have referred to concepts such as charge, potential difference, charging of a capacitor, the large variation in their answers suggests that students cannot link the concepts together or understand their application in the circuits presented.

6.4 Capacitors in Single Loop Circuits: Curriculum Discussion

The curriculum which addresses the function of a capacitor is comprised of two sections, one focussed on capacitors in single loops (discussed below) while the second looks at adding capacitors in parallel with bulbs (see next section).

In the first section, the main objective is to guide students to form a phenomenological model for a capacitor. The effect of a capacitor on a circuit is compared with that of other, known circuit elements. The first experiment allows students to immediately confront their misconceptions by allowing them to investigate the effects of a capacitor in a single loop circuit.

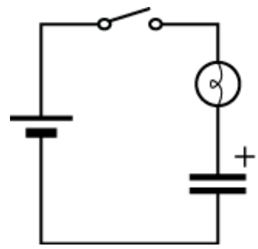


Figure 6.3: Single loop circuit consisting of a battery, switch, bulb and capacitor.

When students close the switch they observe that the bulb is as bright as a bulb in a single-bulb, single-battery circuit. The bulb then slowly dims until its brightness can no longer be observed. The use of 1F capacitors allow for a sufficient time constant where the dimming of bulb brightness can be observed easily. For many students this observation is unexpected, as Table 6.1 shows that a large portion of students predicted that the bulb would get brighter over time.

On the basis of this experiment, we ask students to compare the behaviour of the capacitor to a wire, an insulator, an open switch or battery, just after the switch is closed. Since the bulb had the same brightness as a bulb in a single bulb circuit just after the switch is closed, students can only make the inference that the capacitor behaves like a copper wire. This can also be reasoned on an exclusion basis: if the capacitor behaved like an insulator or an open switch, the bulb would not light, if it behaved like a battery in the same orientation, the bulb would be brighter than a single bulb, and if it behaved like a battery in opposite orientation, the bulb would not light.

Once students have worked through this line of reasoning, they have to form a model for the behaviour of the capacitor a long time after the switch is closed. This is a little more difficult as it behaves like a number of circuit elements. Since the bulb does not light, the behaviour of the capacitor could be likened to an open switch or an insulator, or to a battery in opposite orientation. The latter is a possible comparison which students find difficult to recognise at this stage, despite having studied multiple batteries in single loop circuits (see Chapter 5).

The experiment that follows aims to shed some light on the behaviour of a capacitor a long time after the switch is closed, by asking students to connect a charged capacitor to a bulb as shown in Figure 6.4.

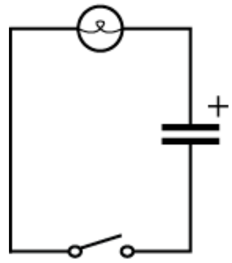


Figure 6.4: A capacitor connected in series with a bulb and a switch.

When students close the switch they observe that the bulb lights with the same brightness as a bulb in a single bulb circuit, and then fades over a short period of time.

On the completion of these experiments, our objective is for students to form the smallest set of elements that model the behaviour of the capacitor. In the circuit in Figure 6.3 the capacitor only behaved like a copper wire just after the switch is closed. For the same circuit, the capacitor behaved like a number of elements a long time after the switch was closed. However, since the capacitor behaved like a battery just after the switch was closed in the circuit in Figure 6.4, it is more natural to think that a long time after the switch is closed in Figure 6.3 it behaved like a battery in opposite orientation. On the basis of this reasoning students recognise that the smallest set of elements to describe the behaviour of a capacitor is that of a wire and battery in opposite orientation, where it behaves like a wire just after the switch is closed and then like a battery in reverse orientation a long time after the switch is closed. Alternatively, they can think of the capacitor as a battery with varying voltage.

In the experiment that follows, students do not expand considerably on the conclusions they have drawn from the first experiment, but they do consider their observations in the context of charging and discharging a capacitor. They define a capacitor that behaves like a battery in reverse orientation as being charged while a capacitor which behaves like a wire is said to be discharged.

Now that students have laid the foundation for their model for the behaviour of the capacitor, they consider its behaviour in the context of the voltage across it. Students measure the voltage across each of the circuit elements shown in Figure 6.5 when the capacitor is initially uncharged. They then compare these values to the measurements across the circuit elements when the switch has been closed for a long period time.

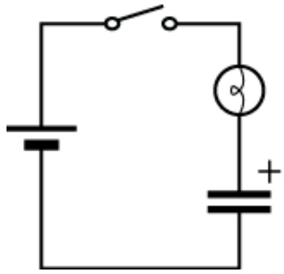


Figure 6.5: Single loop circuit consisting of a capacitor, battery, switch and bulb.

The contrast of values serves as additional validation to the students' model of the capacitor, as students measure zero voltage across a discharged capacitor (as they would for a piece of copper wire). They also measure a voltage of V_{battery} across the charged capacitor. The leads of the voltmeter must be reversed to make the measurement, which highlights the similarity to a battery connected in opposite orientation.

In the final two experiments of the curriculum, students investigate the behaviour of a capacitor when it is attached to more than one battery such as in the circuit shown in Figure 6.6. Students discover that the capacitor can be charged to a voltage greater than that of a single battery and form a rule that when a capacitor is placed in a single loop, it charges to the same voltage as the sum of the voltages of the batteries in the circuit.

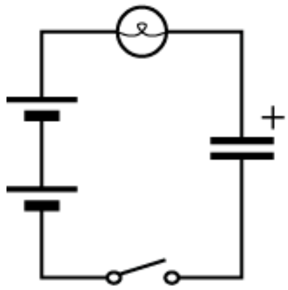


Figure 6.6: Single loop circuit consisting of a capacitor, two batteries, a bulb and a switch.

Thus students have been allowed to form a coherent model for the behaviour of a capacitor. This model can be carried forward to the section on capacitors in parallel with bulbs.

6.5 Capacitors in Parallel with Bulbs: Curriculum Discussion

In the opening experiment of the curriculum, students encounter a very similar circuit to the circuit that was presented in the second pretest. The circuit is shown in Figure 6.7.

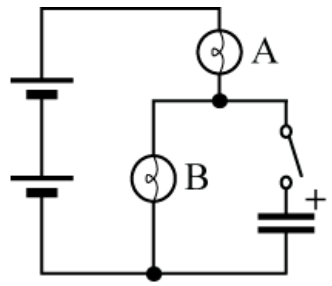


Figure 6.7: Circuit consisting of a single bulb in series with a parallel network of a bulb and a capacitor.

When students close the switch they notice that bulb A is as bright as a bulb in a single-bulb two-battery circuit while bulb B is off. This observation is consistent with their model that an uncharged capacitor behaves like a copper wire which in this case would mean that bulb B is shorted out. Over a period of a few seconds students observe that bulb A decreases in brightness and bulb B increases in brightness until they both shine with the same brightness as if the capacitor were not there. Thus students see that, although the capacitor is connected in a circuit with two batteries in series, it only obtains the voltage that, the element it is connected across would have in the absence of the capacitor.

To firm up this conclusion students carry out similar experiments on the circuits shown in Figure 6.8. This particular experiment and the ones that follow are very aesthetically pleasing and allow the process to be very visual.

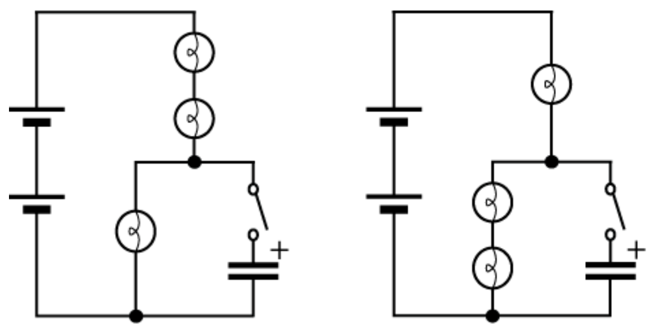


Figure 6.8: Circuits consisting of parallel network of a bulb(s) and a capacitor in series with a bulb(s).

In the final experiment students take some quantitative measurements on the circuit shown in Figure 6.9 and use it to investigate the relationship between the discharging time of a capacitor and the voltage across it.

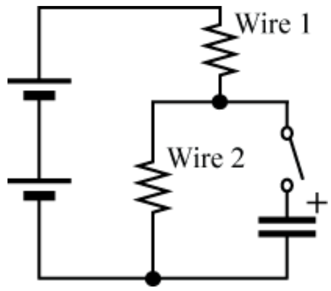


Figure 6.9: Circuit consisting of a linear resistor in series with a parallel network of a linear resistor and a capacitor.

Initially students are asked to predict how the voltage across the capacitor will change when the switch is closed and then when it is opened a long time later, in the case that both wires are of equal length. Students then confirm these measurements with a voltmeter and measure the discharge time of the capacitor. Students are then asked to make predictions when the length of wire 1 is reduced to a third of its original length. If students apply their voltage model correctly they can determine that the voltage across wire 2 will be greater than wire 1 and since the capacitor is connected across wire 2 it will have the same voltage as wire 2. Students then recognise that by changing the length of wire 1, the voltage across the capacitor can be varied and thus they can determine the discharge time for various voltage values.

This experiment concludes the students' investigation of capacitors and also concludes the module.

6.6 Overview of Post-Test and Analysis

The post-test questions on capacitors were carried out over three years. One question was given in each of the three years and presented circuits similar to those in the curriculum. Two additional questions were given which examined students' ability to transfer their understanding of capacitors in parallel with bulbs to a different context. The first question proved to be quite difficult while the second was presented in an easier setting.

6.6.1 Capacitors in Parallel with Bulbs Post-Test 1

In each of the three years, students were presented with the following post-test. Since the post-test consisted of a number of individual questions, it has been divided into two parts, each with several questions.

Capacitor in Parallel with Bulbs Post-Test 1, Part I

In this question, all batteries are ideal and identical, and all bulbs are identical. You will be asked to compare the brightness of bulbs A, B and C to that of bulbs 1, 2, 3 and 4 at different time instances.

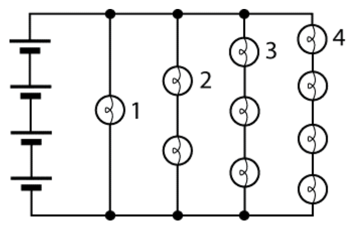


Figure 6.10: First circuit presented in Capacitors in Parallel with Bulbs Post-Test 1.

(1) *Is the brightness of bulb A most like that of bulb 1, bulb 2, bulb 3, bulb 4, or is it off, when the switch is open? Explain.*

(2) *Immediately after the switch is closed, is the brightness of bulb A most like that of bulb 1, bulb 2, bulb 3, bulb 4 or is it off? Explain*

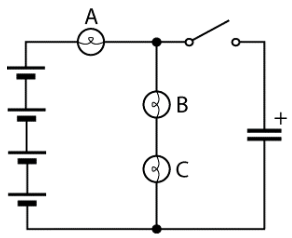


Figure 6.11: Second circuit presented in Capacitors in Parallel with Bulbs Post-Test 1.

(3) *Immediately after the switch is closed, is the brightness of bulb B most like that of bulb 1, bulb 2, bulb 3, bulb 4 or is it off? Explain*

Like many opening post-test questions, the first question was relatively easy. It was answered particularly well, with 95% (41 of 47 students) providing the correct answer, and 90% of these answers were supported by correct reasoning.

The second question of the first part of the post-test once again focussed on the brightness of bulb A. This time students needed to make the comparison immediately after the switch is closed. Since students have modelled the behaviour of an uncharged capacitor as being similar to that of a piece of copper wire, it was expected that students would determine that bulbs B and C would be shorted out immediately after the switch is closed, and thus conclude that the voltage across bulb A is $4V_0$ making it most like bulb 1.

Students' answers that are shown in Table 6.3 highlight that a large portion of students recognised the aforementioned reasoning and answered the question correctly. A small portion of students from the 2006 and 2007 class stated that bulb A was most like bulb 3. The reasons provided for both answers is discussed below.

Table 6.3: Analysis of students' answers to Capacitors in Parallel Post-Test 1, Question 2.

Answer	2006 % (*N*=20)	2007 % (*N*=17)	2008 % (*N*=14)	Total % (*N*=51)
Bulb A = Bulb 1	**75 (15)**	**75 (13)**	**70 (10)**	**75 (38)**
Bulb A = Bulb 2	0 (0)	5 (1)	0 (0)	<5 (1)
Bulb A = Bulb 3	20 (4)	10 (2)	0 (0)	10 (6)
Bulb A = Bulb 4	5 (1)	5 (1)	5 (1)	5 (3)
Bulb A is off	0 (0)	0 (0)	5 (1)	<5 (1)
No answer	0 (0)	0 (0)	15 (2)	5 (2)

Of the students who provided the correct answer, 70% provided a complete answer while 30% provided an incomplete answer. An example of a complete and incomplete answer is shown in Figure 6.12 and 6.13 respectively.

Complete answer

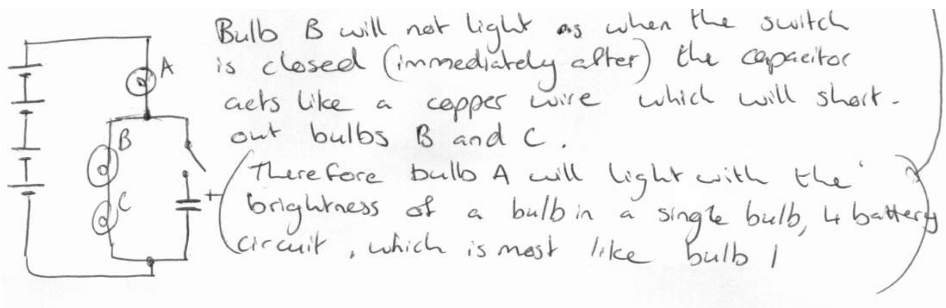


Figure 6.12: An example of a complete correct answer to Capacitors in Parallel with Bulbs Post-Test 1, Question 2.

Incomplete answer

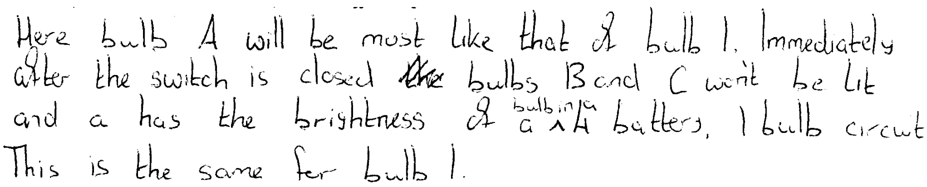

Here bulb A will be most like that of bulb 1. Immediately after the switch is closed ~~the~~ bulbs B and C won't be lit and a has the brightness of a bulb in a 4 battery, 1 bulb circuit This is the same for bulb 1.

Figure 6.13: An example of a incomplete correct answer to Capacitors in Parallel with Bulbs Post-Test 1, Question 2.

In the first example the student clearly states the behaviour of an uncharged capacitor thus giving a reason for why bulbs B and C don't light. However in the second example, the student only states that bulbs B and C won't light and doesn't provide a specific reason.

The analysis of the small portion of students' answers from the 2006 and 2007 class who stated that bulb A was still equal to bulb 3, did not highlight a common line of incorrect reasoning. Although two of the six students recognised that the initial behaviour of the capacitor was similar to a copper wire, they could reason correctly its affects on the circuit.

In the third question of the first part of the post-test students had to comment on the brightness of bulb B immediately after the switch was closed. Since the correct reasoning to the previous question provides the correct answer to this question, it was expected that similar answers would be obtained. The analysis of the students' answers provided the data shown in Table 6.4.

Table 6.4: Students' answers to Capacitors in Parallel with Bulbs Post-Test 1, Question 3.

Answer	2006 % (*N*=20)	2007 % (*N*=17)	2008 % (*N*=14)	Total % (*N*=51)
Bulb B is off	**75 (15)**	**65 (11)**	**65 (9)**	**70 (35)**
Bulb B = Bulb 2	0 (0)	20 (3)	0 (0)	5 (3)
Bulb B = Bulb 3	25 (5)	5 (1)	5 (1)	15 (7)
Bulb B = Bulb 4	0 (0)	5 (1)	15 (2)	5 (3)
No answer	0 (0)	5 (1)	15 (2)	5 (3)

The analysis of students' answers show that of the students who answered the question correctly, 85% provided a complete answer, 15% provided an incomplete answer and 5% used incorrect reasoning.

The second series of questions is shown below.

Capacitors in Parallel with Bulbs Post-Test 1, part II

The switch is then closed until the brightness of bulb A is equal to that of bulb 2. (The switch is then opened again)

(4) Just before the switch is opened again, is the brightness of bulb C most like that of bulb 1, bulb 2, bulb 3, bulb 4 or is it off? Explain

The switch is then closed again.

After a very long time, the switch is opened and the batteries are removed from the circuit and replaced by a wire. The switch is then closed.

(5) Immediately after the switch is closed, is the brightness of bulb B most like that of bulb 1, bulb 2, bulb 3, bulb 4 or is it off? Explain

(6) A long time after the switch is closed, is the brightness of bulb C most like that of bulb 1, bulb 2, bulb 3, bulb 4 or is it off? Explain

In the fourth question, students must recognise that in order for bulb A to be like bulb 2, it must have $2V_0$ across it. This consequently means that the branch consisting of bulbs B and C also have $2V_0$ across it. Since bulbs B and C are connected in series, students can determine that bulb C has $1V_0$ across it, thus making it like bulb 4. The analysis of students' answers provided the data shown in Table 6.5. Note that the 2006 data is omitted from the table, as the question in that year was ambiguous.

Table 6.5: Analysis of students' answers to Capacitors in Parallel with Bulbs Post-Test 1, Question 4.

Answer	**2007 % (*N*=17)**	**2008 % (*N*=14)**	**Total % (*N*=31)**
Bulb C = Bulb 4	**55 (9)**	**50 (7)**	**50 (16)**
Bulb C = Bulb 2	35 (6)	15 (2)	25 (8)
Bulb C = Bulb 3	10 (2)	5 (1)	10 (3)
Bulb C is off	0 (0)	15 (2)	5 (2)
No answer	0 (0)	15 (2)	5 (2)

Of the 16 students who answered the question correctly, only eight provided a complete answer.

The last two questions of the exam were based on a new circuit where students were told that the batteries were removed from the circuit shown in Figure 6.11, once the capacitor had been charged. The circuit which is thus formed is shown in Figure 6.14.

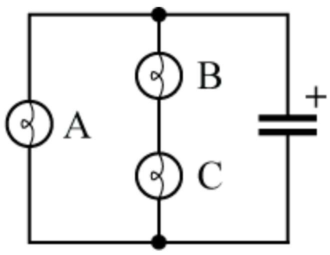


Figure 6.14: A capacitor connected across a single bulb and a two bulb series network.

We wanted students to recognise that the capacitor was charged to $^{8}/_{3}V_0$ and therefore bulb B and C would have $^{4}/_{3}V_0$ across them, resulting in them being equal in brightness to bulb 3. However, the data in Table 6.6 shows that only a small percentage of students in each class could answer the question correctly.

Table 6.6: Students' answers to Capacitors in Parallel with Bulbs Post-Test 1, Question 5.

Answer	**2006 %** **(*N*=20)**	**2007 %** **(*N*=17)**	**2008%** **(*N*=14)**	**Total %** **(*N*=51)**
Bulb B = Bulb 3	**25 (5)**	**30 (5)**	**15 (2)**	**25 (12)**
Bulb B = Bulb 2	40 (8)	40 (7)	35 (5)	40 (20)
Bulb B = Bulb 1	5 (1)	5 (1)	5 (1)	5 (3)
Bulb B = Bulb 4	20 (4)	25 (4)	5 (1)	20 (9)
Bulb B is off	5 (1)	0 (0)	20 (3)	10 (4)
No answer	5 (1)	0 (0)	15 (2)	5 (3)

The analysis of the 12 answers which correctly stated that bulb B was the same as bulb 3, revealed four complete answers, four incomplete answers and four answers based on incorrect reasoning. Examples are shown in Figure 6.15, 6.16 and 6.17 respectively:

Complete Reasoning

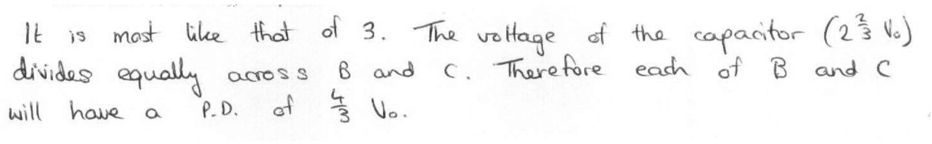

It is most like that of 3. The voltage of the capacitor ($2\frac{2}{3} V_0$) divides equally across B and C. Therefore each of B and C will have a P.D. of $\frac{4}{3} V_0$.

Figure 6.15: An example of a complete correct answer to Capacitors in Parallel with Bulbs Post-Test 1, Question 5.

Incomplete Reasoning

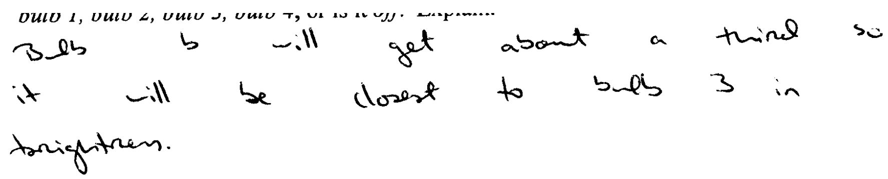
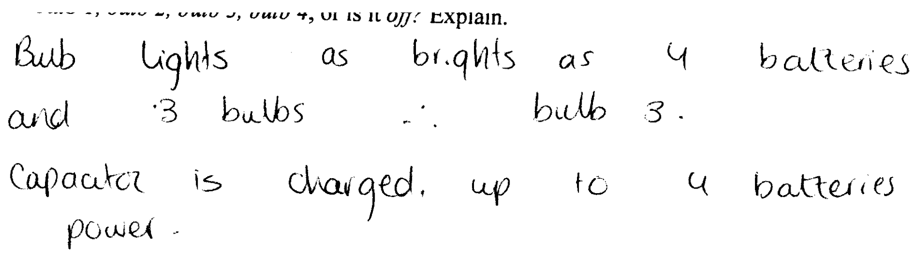

Bulb b will get about a third so it will be closest to bulb 3 in brightness.

Figure 6.16: An example of a incomplete correct answer to Capacitors in Parallel with Bulbs Post-Test 1, Question 5.

Incorrect Reasoning


..., bulb 4, or is it off? Explain.

Bulb lights as brights as 4 batteries and 3 bulbs ∴ bulb 3.
Capacitor is charged up to 4 batteries power.

Figure 6.17: An example of a correct answer based on incorrect reasoning to Capacitors in Parallel with Bulbs Post-Test 1, Question 5.

The analysis of the reasoning used to support the most common incorrect answer revealed that the majority of these students incorrectly applied the rule based on the behaviour of capacitors in single loop circuits. Many stated that the capacitor charged to a voltage of $4V_0$ a long time after the switch was closed, thus bulb B and C had a voltage of $2V_0$ across them. Hence, they stated that bulb B was most like bulb 2.

The last question asked students to comment on the brightness of bulb C a long time after the switch is closed. Since students have determined that an uncharged capacitor behaves like a copper wire, this question should be relatively easy and as Table 6.7 below shows, many students answered the question correctly.

Table 6.7: Students' answers to Capacitors in Parallel with Bulbs Post-Test 1, Question 6.

Answer	**2006 % (*N*=20)**	**2007 % (*N*=17)**	**2008 % (*N*=14)**	**Total % (*N*=51)**
Bulb C is off	**80 (16)**	**80 (14)**	**70 (10)**	**80 (40)**
Bulb C = Bulb 1	5 (1)	0 (0)	0 (0)	<5 (1)
Bulb C = Bulb 2	0 (0)	5 (1)	5 (1)	5 (2)
Bulb C = Bulb 3	5 (1)	5 (1)	5 (1)	5 (3)
Bulb C gets dim	0 (0)	5 (1)	0 (0)	<5 (1)
No answer	10 (2)	0 (0)	15 (2)	10 (4)

Overall this question was answered quite well over the three years which highlighted the ability of the curriculum to guide students to form a phenomenological model for the behaviour of capacitors in circuits.

6.6.2 Capacitors in Parallel with Bulbs Post-Test 2

In the 2007 final exam, students were given an additional question focussed on the voltage model and on the behaviour of capacitors in circuits. The question is posed in an unseen context and examines students' ability to transfer their understanding to a new situation.

Capacitors in Parallel with Bulbs Post-Test 2

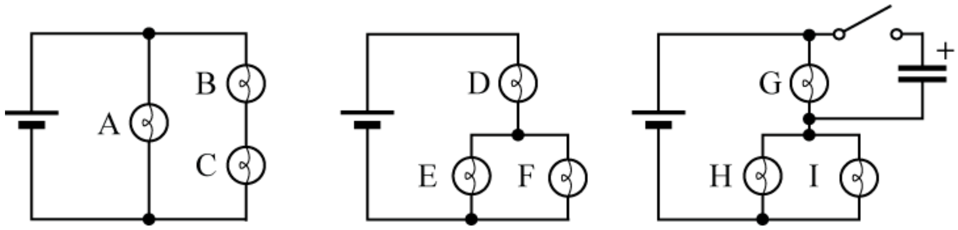


Figure 6.18: Circuits presented in Capacitors in Parallel with Bulbs Post-Test 2.

(1) Rank the brightness of bulbs A-I from brightest to dimmest, explaining your reasoning in each case:
(a) When the switch is open.
(b) Immediately after the switch is closed.
(c) A long time after the switch is closed.

(2) When the switch has been closed for a long time, bulb I is unscrewed (the switch remains closed). Explaining your reasoning in each case, state what happens to the brightness of:
(a) bulb G
(b) bulb H.

The first part of the first question addressed students' ability to apply their voltage model since they had to rank the brightness of the bulbs when the switch is open. With the switch open, the middle and right circuit are identical, so the question was essentially asking students to rank the brightness of bulbs A-F. This particular ranking has been seen on a number of occasions previously where students need to apply their voltage model to rank the relative brightness of bulbs B and C to bulbs E and F. The results are shown in Table 6.8.

Table 6.8: Students' rankings in answer to Capacitors in Parallel with Bulbs Post-Test 2, Question 1(a).

Ranking	**% (*N*=17)**
A>D=G>B=C>E=F=H=I	**65 (11)**
A=D=G>E=F=H=I>B=C	10 (2)
D=G>A>E=F=H=I>B=C	10 (2)
Other	10 (2)

Although the majority of the class gave the correct ranking, only four students provided valid reasoning by using their voltage model correctly. A further five provided an incomplete answer while two reasoned on the basis of current and resistance only.

In the second part of the first question, students were once again asked to rank the brightness of the bulbs. In this case the switch in the right circuit of Figure 6.18 was closed. If the students apply their model for capacitors correctly, they can reason that since the capacitor is uncharged it behaves like a wire and will therefore short out bulb G. Using this line of reasoning students can conclude that the voltage across bulb G is zero which consequently results in the voltage across bulbs H and I being equal to V_0, making them as bright as bulb A. However as the results in Table 6.9 below show, only four students provided the correct ranking.

Table 6.9: Analysis of students' rankings in answer to Capacitors in Parallel with Bulbs Post-Test 2, Question 1(b).

Ranking	**% (*N*=17)**
A=H=I>D>B=C>E=F>G	**25 (4)**
A>D>B=C>E=F=H=I>G	20 (3)
A>D=G>B=C>E=F=H=I	10 (2)
Other	45 (8)

It is important to note that although only four students provided the correct answer, 13 of the 17 students recognised that bulb G would not light when the switch is closed however many could not recognise the effect that it would have on bulbs H and I. (There were six of these students in the 'other' category).

In the last part of the first question, students were asked to rank the bulbs after the switch had been closed for a long time. Since the capacitor is connected in parallel across bulb G it will only charge to the same voltage across bulb G and a long time after the switch is closed, the circuits will return to the same state as when the switch is open.

In their answers, 10 of the 18 students stated that the ranking would return to the same as question 1(a), although two of these answers referred to an incorrect ranking in question 1(a).

In the second question of the post-test students were confronted with a new problem. Students were asked to comment on the brightness of bulb G and bulb H when bulb I is unscrewed in the case of the switch being closed for a long time.

Before unscrewing bulb I, the voltage across the capacitor is greater than $^1/_2V_0$ and the voltage across bulb H is less than $^1/_2V_0$. When bulb I is removed, the system wants to revert to a case where there is $^1/_2V_0$ across bulb G and bulb H. This will not happen immediately as it takes time for the capacitor to discharge from greater than $^1/_2V_0$ to $^1/_2V_0$. Students' answers are shown in Table 6.10.

Table 6.10: Students' answers in answer to Capacitors in Parallel with Bulbs Post-Test 2, Question 2(a).

Answer	**% (*N*=17)**
Bulb G decreases	**45 (8)**
Bulb G stays the same	30 (5)
Bulb G is off	10 (2)
Bulb G increases	5 (1)
Other	5 (1)

The results show that only approximately half the class answered the question correctly while only two provided complete reasoning.

Unfortunately students' responses for bulb H were much worse as no student provided an answer with correct reasoning. The answers for bulb H are shown in Table 6.11.

Table 6.11: Students' answers in answer to Capacitors in Parallel with Bulbs Post-Test 2, Question 2(b).

Answer	% (*N*=17)	Complete reasoning %	Incomplete reasoning %	Incorrect reasoning %
Bulb H increases	**80 (14)**	**0 (0)**	**70 (10)**	**30 (4)**
Bulb H decreases	20 (3)			100 (3)

6.6.3 Capacitors in Single Loop Circuits Post-Test

In the 2008 final exam students were also asked an additional question on capacitors to that reported in section 6.6.1. Unlike the question in the previous section, this question was posed in a simpler context as it was focussed entirely on capacitors in single loops. The question is shown below.

Capacitors in Single Loop Circuits Post-Test, Part I

In the circuit shown below, the switch is initially open and the capacitor is uncharged. The switch is then closed.

(1) *Immediately after the switch is closed, is the brightness of the bulb most like that of a single bulb in a three-battery circuit, in a two battery circuit, in a one battery circuit, or is it off? Explain.*

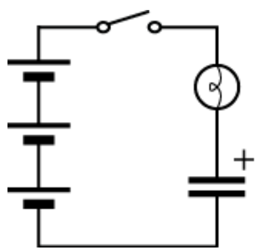


Figure 6.19: First circuit presented in Capacitors in Single Loops Post-Test.

(2) *A long time after the switch is closed, is the brightness of the bulb most like that of a single bulb in a three-battery circuit, in a two battery circuit, in a one battery circuit, or is it off? Explain.*

Students' answers for the first question are shown in Table 6.12.

Table 6.12: Students' answers to Capacitors in Single Loop Circuits Post-Test, Question 1.

Answer	% (N=14)	Complete Reasoning %	Incomplete Reasoning %	Incorrect Reasoning %
Three battery circuit	**70 (10)**	**80 (8)**	**10 (1)**	**10 (1)**
Two battery circuit	15 (2)			100 (2)
Off	5 (1)			100 (1)
No answer	5 (1)			

Since students have investigated the circuit in Figure 6.19 with a single battery in the opening experiment of the curriculum and observed that the capacitor behaves like a piece of copper wire just after the switch is closed, it was expected that they would answer the question successfully. Table 6.12 shows that the majority of students who provided the correct answer supported their answer with correct reasoning.

The second question of the post-test asked the students to comment on the bulb brightness a long time after the switch has been closed. This is not a difficult question since all students have previously seen that a charged capacitor acts like a battery in reverse orientation and obtains the same voltage as the sum of the voltages of the batteries it is connected to. The answers shown in Table 6.13 reveal that the majority of students answered the question correctly.

Table 6.13: Students' answers to Capacitors in Single Loop Circuits Post-Test, Question 2.

Answer	% (N=14)	Complete Reasoning %	Small Mistakes %	Incorrect Reasoning %
Off	**80 (11)**	**75 (8)**	**10 (1)**	**20 (2)**
Two battery circuit	15 (2)			100 (2)
No answer	5 (1)			

In the second part of the post-test, students were presented with the following questions.

Capacitors in Single Loops Post-Test Question, Part II

The middle battery is then removed, while the switch is left closed. A gap is left in the circuit where the middle battery was, as shown at right.

(3) Immediately after the battery is removed, is the brightness of the bulb most like that of a single bulb in a three-battery circuit, in a two battery circuit, in a one battery circuit, or is it off? Explain.

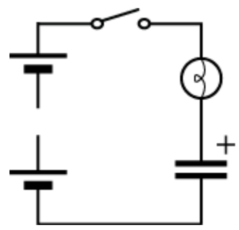


Figure 6.20: Second circuit presented in Capacitors in Single Loops Post-Test.

The switch is opened, and the middle battery is put back into the circuit in opposite orientation as shown at right. The switch is then closed again.

(4) Immediately after the switch is closed, is the brightness of the bulb most like that of a single bulb in a three-battery circuit, in a two battery circuit, in a one battery circuit, or is it off? Explain.

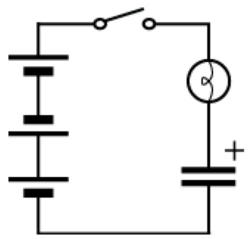


Figure 6.21: Third circuit presented in Capacitors in Single Loops Post-Test.

A long time after the switch was closed, it is opened again, and the batteries are removed. The capacitor is then connected directly across the bulb.

(5) Immediately after the capacitor is connected to the bulb, is the brightness of the bulb most like that of a single bulb in a three-battery circuit, in a two battery circuit, in a one battery circuit, or is it off? Explain.

In the third question of the post-test, students were expected to reason that the bulb would be off since the circuit is incomplete, so the capacitor cannot discharge. However, only 50% do so. A breakdown of students' answers are shown in Table 6.14.

Table 6.14: Students' answers to Capacitors in Single Loop Circuits Post-Test, Question 3.

Answer	**Total % (*N*=14)**
Off	**50 (7)**
One battery circuit	30 (4)
Three battery circuit	5 (1)
Two battery circuit	5 (1)
No answer	5 (1)

All students who stated that the bulb was off provided correct reasoning. The student who stated that the bulb would be most like a single bulb in a three battery circuit, has ignored that the circuit is incomplete, but otherwise reasoned correctly. Students who chose the one battery circuit did not recognise that the capacitor had been charged to $3V_0$.

In the fourth question, students are told that the middle battery is put back into the circuit but in the opposite orientation as shown in Figure 6.21 previously. Students are asked to comment on the brightness of the bulb immediately after the switch is closed.

Unfortunately this question was answered very poorly with many students failing to recognise that the capacitor was charged to $3V_0$ before the middle battery was taken out. Students' answers are shown in Table 6.15.

Table 6.15: Students' answers to Capacitors in Single Loop Circuits Post-Test, Question 4.

Answer	**% (*N*=14)**
Two battery circuit	**20 (3)**
One battery circuit	50 (7)
Off	20 (3)
No answer	5 (1)

In the last question students are told that after a long time the switch has been closed, the batteries are removed, and the capacitor is connected directly across the bulb. In this case, we wanted students to recognise that the capacitor is charged to the sum of the voltage across the batteries it is connected to and to apply their rule for batteries in opposite orientation. As Table 6.16 shows, only 55% of students made a correct comparison by stating that the bulb would be most like a single bulb in a one battery circuit. Of the 55% of students, 90% of those gave complete reasoning.

Table 6.16: Students' answers to Capacitors in Single Loop Circuits Post-Test, Question 5.

Answer	**% (*N*=14)**
One battery circuit	**55 (8)**
Three battery circuit	15 (2)
Off	20 (3)
No answer	5 (1)

6.7 Conclusion

The curriculum dedicated to capacitors can be viewed as a success. A large amount of the post-test data showed considerable improvements in students' understanding of the behaviour of capacitors both in single loop circuits and when connected in parallel to bulbs.

It was evident from the analysis that this understanding did not exist prior to instruction. This was supported by pretest results in which the majority of students failed to describe how a capacitor would affect the brightness of a bulb in a single loop circuit. The analysis of students' reasoning revealed that many used guesswork in their explanations. The answers were also dotted with concepts such as capacitance, storage of energy, storage of charge and the discharge of a capacitor through a bulb. Much of this knowledge may have been obtained from a Leaving Certificate and a third level introductory physics module. However, very little understanding of these concepts was portrayed in students' answers.

The process in which students develop a phenomenological model for the behaviour of a capacitor was adopted successfully. Many students were comfortable in modelling the behaviour of the capacitor on circuit elements of which they already had a sound understanding. The experiments were very visual due to the large time constant of the capacitors. We found that once students had formed the foundation of their model, they accelerated through the curriculum, building incrementally on their understanding.

The majority of the post-test questions given were completed with a high rate of success while some specific questions were answered poorly. The analysis shows that a large number of students applied their model successfully to a number of different circuits.

Part II

Curriculum for First Year Undergraduate Physics Laboratories

Chapter 7

First Year Current and Resistance Laboratories

7.1 Introduction

In the summer of 2007, I began the development of curriculum for three electric circuits labs for implementation in first year undergraduate physics laboratories at Dublin City University. The labs were designed at an introductory level for non-physics majors and focussed on the concepts of current, resistance and voltage. They were largely influenced by the curriculum and data analysis discussed in Chapters 3 and 4. The curriculum for the current and resistance laboratories in addition to a discussion of relevant pretest and post-test data takes place in this chapter. A similar discussion for the voltage laboratory is given in Chapter 8. The background information that follows applies to all three laboratories.

The redevelopment of the laboratory curriculum was motivated by the unsatisfactory emphasis on conceptual understanding in the traditional labs, and the lack of enjoyment students experienced while carrying out the practicals. Evidence for this was supported by a survey that was administered to 150 students at the conclusion of the traditional labs in 2005. Some of the most relevant results are shown in Table 7.1.

Table 7.1: Results of first year undergraduate student survey.

Statement (*N*=150)	**Strongly disagree %**	**Disagree %**	**Mixed feelings %**	**Agree %**	**Strongly agree %**
The laboratory manual is well constructed and easily understood	15	30	25	25	5
The experiments help to reinforce lecture material	10	25	30	25	10
I found Physics practicals very stimulating	20	40	25	10	5

The values shown in Table 7.1 highlights that many students did not find physics laboratories interesting and found the lab manual difficult to comprehend. This is not surprising considering that the majority of students had not done higher level physics at secondary school, while the labs appeared at just that level.

The main goal of the project was to design a set of labs that would prioritise conceptual understanding. Additionally, I wanted to design the labs in a manner which would allow students to engage in the curriculum and promote an environment in which they could enjoy carrying out the experiments. The method that was chosen to achieve these goals was based on guided inquiry as it has been shown to improve students' understanding of physics concepts. However, compromises were made to cater for the time constraints imposed.

The labs were used for the first time in February 2008. The first implementation proved to be a success with many students improving their conceptual understanding of the topics and a large number reported that they had enjoyed the labs. However some areas were highlighted for redevelopment as the level of improvement was unsatisfactory for a number of specific concepts.

After some changes were made, the curriculum was presented for the second time at DCU in 2009. The curriculum was also taught at Ithaca College (IC) in the same year. The acceptance to run our labs at Ithaca College was a significant breakthrough for the curriculum as it would provide independent data as well as providing a valuable insight on the effectiveness of the curriculum.

In this chapter, I present the data on the current and resistance laboratories which were carried out separately. The data is presented in the same fashion as previous chapters where the pretest analysis is discussed initially followed by the curriculum discussion. The chapter is concluded with a review of post-test analysis. The data analysis begins with the concept of a complete circuit and is followed by questions addressing conductors and insulators. Later sections in the chapter cover the concepts of current and resistance both in a qualitative and quantitative manner.

7.2 Instructional Background

The data presented in this chapter looks at the comparison, where possible, of pretest and post-test data gathered at Dublin City University and at Ithaca College. Each of these introductory physics modules have similarities and differences.

The first year introductory physics course at DCU is comprised of lectures, tutorials and labs. Students take lectures twice weekly along with a single tutorial. Lecture and tutorial attendance is not compulsory, but lab attendance is. Practical laboratories take place once a week for a period of 3 hours[†]. The lectures and tutorials at DCU were not integrated with the new laboratories, although the labs do make an attempt to follow the concepts introduced in lectures. Questions presented in tutorials are generally back-of-chapter problems and are tutored by a postgraduate student. Topics covered in the lecture course are typical of a general introductory physics course.

Students taking the introductory physics course at Ithaca College were divided into two groups, one denoted scal and the other, trad. The denotation scal refers to SCALE-UP as students were taught in an environment modelled on the SCALE-UP (Student-Centered Activities for Large Enrollment Undergraduate Programs) program initiated at North Carolina State University, where an attempt is being made to take educational innovations that have been proven in small groups and scale them up for use in larger groups[1]. Students in the SCALE-UP class took the three electric circuits labs also taken by DCU students. The also took the same pretest presented to DCU students that addressed the concepts of complete circuits, conductors and insulators and current. In addition to participating in the laboratories, students completed on-line problems each day that were based on back-of-chapter problems. They also had to complete one homework assignment each week, which resembled many of the problems in the curriculum and required the use of qualitative reasoning. It is suggested that these differences play a significant role in the difference between results gathered at Ithaca College and at DCU, which are discussed later. However,

[†] Tradtional labs are scheduled for 3 hours. New labs take place over 2.5 hours with 30 min allocated to the completion of a pre-lab[2] and an online pretest.

it is difficult at this stage to be definitive on the effect of the homework problems as other variables may also have been contributing factors.

7.2.1 Educational Background of DCU Students

In both years in which the laboratories were implemented at DCU, approximately 150 students were in attendance. The students were categorised into two groups, those who had completed Leaving Certificate Physics (LC) and those who had not. In both groups, all students had completed Junior Certificate Science (JC). Descriptions of each of these secondary school courses was discussed previously in Chapter 2. The breakdown of courses taken by students is shown below in Table 7.2.

Table 7.2: Breakdown of background courses in first year introductory labs.

Year	JC %	LC %
2008 (*N*=144)	80 (112)	20 (32)
2009 (*N*=146)	70 (99)	30 (47)

Although the large majority of students participating in the labs had not taken Leaving Certificate Physics, it is compulsory for them to take another Leaving Certificate science subject. A breakdown of these subjects is shown below in Table 7.3.

Table 7.3: Breakdown of LC science subjects taken by students who have not taken LC Physics.

Leaving Certificate Subject	2008 % (*N*=112)	2009 % (*N*=99)
Biology	45 (48)	45 (45)
Chemistry & Biology	40 (43)	40 (42)
Chemistry	10 (10)	5 (6)
Agricultural Science	<5 (2)	<5 (1)
Geology and another science	5 (3)	<5 (1)
Agricultural Science & another science	5 (6)	5 (4)

Of the 79 students who had taken Leaving Certificate Physics, many of them also took a second science subject. These are categorised in Table 7.4.

Table 7.4: Breakdown of LC subjects taken by students who have completed LC Physics.

Leaving Certificate Subject	2008 % (*N*=32)	2009 % (*N*=47)
Physics & Biology	35 (11)	25 (11)
Physics & Chemistry	25 (8)	35 (17)
Physics & Chemistry & Biology	20 (7)	20 (9)
Physics	15 (5)	15 (7)
Other	5 (1)	5 (3)

Summary

The data displayed in this chapter is presented in the context of four separate groups. Students at DCU are divided into two groups, one denoted JC and the other LC. Students in the JC group have a minimal understanding of physics concepts amounting to one year's experience with the subject. Students in the LC group have also taken the JC course but have two additional years experience with physics concepts. Although there are differences in these groups, it must be noted that all students are non-physics majors.

Students at Ithaca College are split into two groups, one denoted scal and the other trad. These students are also non-physics majors. Students in the scal group participated in practical laboratories in which the curriculum developed at DCU was implemented. These students have had a similar experience to the students at DCU. The students in the trad group have had a much different experience. These students participated in traditional lectures and carried out traditional laboratories. An overview of pretests and post-tests taken by each group is shown in Table 7.5.

Table 7.5: Overview of pretests and post-tests taken by DCU and IC students.

Pretest / Post-test	2008	2009
Complete Circuits Pretest 1 (Arrangements and Bulb Diagrams)	DCU (JC & LC) only	Not carried out.
Complete Circuits Pretest 2 (Fan Question)	Not carried out.	DCU (JC & LC) and IC (scal only)
Complete Circuits Post-test (Fan Question)	DCU (JC & LC) only	Not carried out.
Conductors and Insulators Pretest (Circuits with boxes X and Y)	Not carried out.	DCU (JC & LC) and IC (scal only)
Conductors and Insulators Post-test (Circuits with boxes X and Y)	DCU (JC & LC) only	Not carried out.
Resistance Pretest	DCU (JC & LC) only	DCU (JC & LC) only
Resistance Post-Test 1 (Adding bulbs in series)	DCU (JC & LC) only	DCU (JC & LC) only
Resistance Post-Test 2 (Adding bulbs in parallel)	DCU (JC & LC) only	DCU (JC & LC) only
Resistance Post-Test 3 (Student statement)	Not carried out.	DCU (JC & LC) only
Qualitative Current Pretest (Rank bulbs A-E)	DCU (JC & LC) only	Not carried out.
Qualitative Current Post-Test (Rank bulbs A-F)	DCU (JC & LC) only	DCU (JC & LC) and IC (scal & trad)
Quantitative Current Pretest	Not carried out.	DCU (JC & LC) and IC (scal only)
Quantitative Current Post-Test 1	DCU (JC & LC) only	Not carried out.
Quantitative Current Post-Test 2	Not carried out.	DCU (JC & LC) and IC (scal & trad)
Quantitative Current Post-Test 3	Not carried out.	DCU (JC & LC) only
Quantitative Current Post-Test 4	DCU (JC & LC) only	Not carried out.

7.3 Complete Circuits

Since the concept of a complete circuit is arguably the most primary concept in teaching electric circuits, it was treated as the first concept in the curriculum. This is also the same for the introductory Physics by Inquiry electric circuits module given to pre-service teachers and is also recommended by others[3]. Although the concept may be viewed as elementary, the pretest analysis that follows suggests otherwise.

7.3.1 Complete Circuits: Pretest and Analysis

Two different on-line pretests on the concept of a complete circuit were carried out in both years. In 2008, the pretest was carried out at DCU only, while in 2009 it was carried out at DCU and at IC (scal students only). The first question of the 2008 pretest is shown below.

Complete Circuits Pretest 1, Question 1†

Shown at right are six arrangements of a bulb, battery and one or two copper wires.

Choose the arrangements in which the bulb will light. You may choose more than one arrangement.

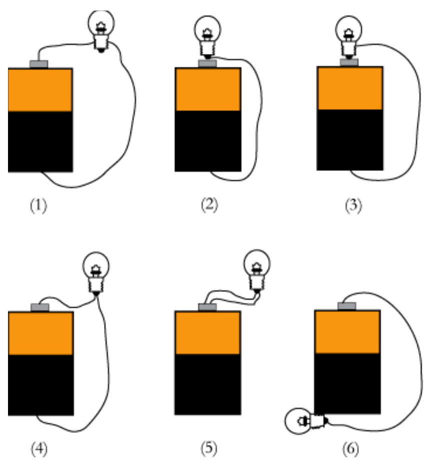


Figure 7.1: Six different arrangements of a battery, wire(s) and a bulb.

The choice of arrangements was quite widespread with a large number of variations for both JC and LC students. The results of the analysis is shown in Figure 7.2.

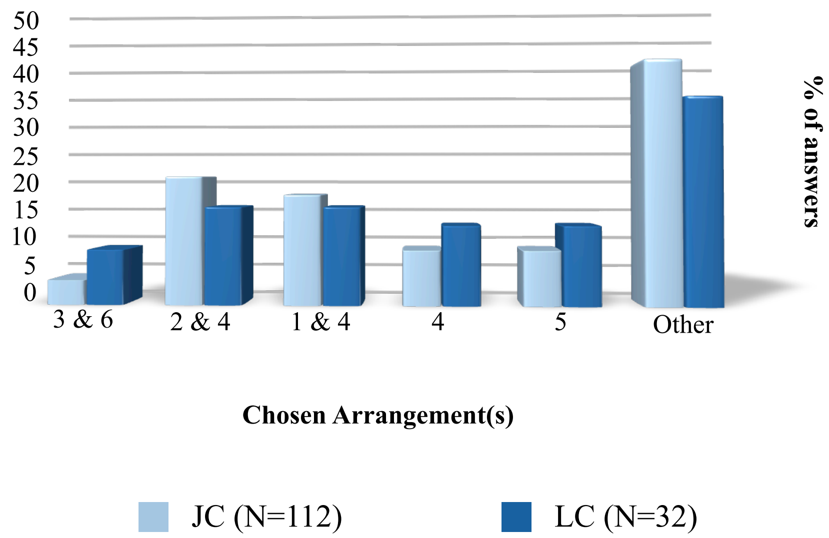


Figure 7.2: Frequency of arrangement choices from Complete Circuits Pretest, Question 1.

† This pretest is a revised version of the pretest on complete circuits provided by UW that was discussed in Chapter 3. The number of arrangements has been reduced from 11 to 6.

The analysis of the students' answers highlights that ~5% of JC students and ~10% of LC students chose the correct arrangements (3 & 6). This is a slightly lower percentage than the results of the pre-service teacher pretest where 15% chose the correct arrangement. The most popular choices, which are incorrect, remained the same in both groups with 20% of students choosing arrangements 2 and 4, and 15% choosing arrangements 1 and 4. The emphasis on arrangement 4, which connects the battery terminals to the base of the bulb, was similar to that displayed in the pre-service teacher pretest. The analysis highlighted that ~50% of students in both groups chose arrangement 4 as a correct arrangement.

Unfortunately in the 2008 pretest we did not ask students to explain their reasoning in choosing particular arrangements. However, one can assume with some confidence that students who choose arrangements 2 and 4 believe that the circuit must include the positive and negative terminal of the battery and a connection to the bottom of the bulb only. In arrangements 1 and 4, students again choose arrangements that include both terminals of the battery but also include the two sides of the bulb as well as the bottom. The reasoning is likely to be similar to that used by the pre-service teachers in the complete circuits pretest discussed in Chapter 3.

The next question on the pretest analysed students' knowledge of electrical connections within a light bulb. The question is shown below.

Complete Circuits Pretest 1, Question 2

"Three students have made diagrams (1-3) indicating how they think the vertical wires in the bulb used in the previous question are connected.

Which of these diagram(s) could represent the connections of the wires?"

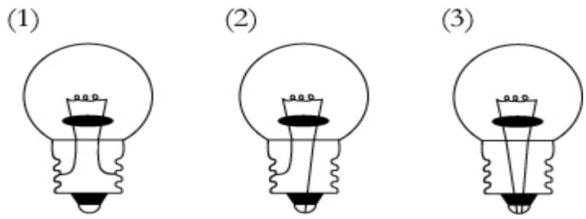


Figure 7.3: Diagram of possible connections of vertical wires in bulb.

The results for the question shown previously are shown in Figure 7.4.

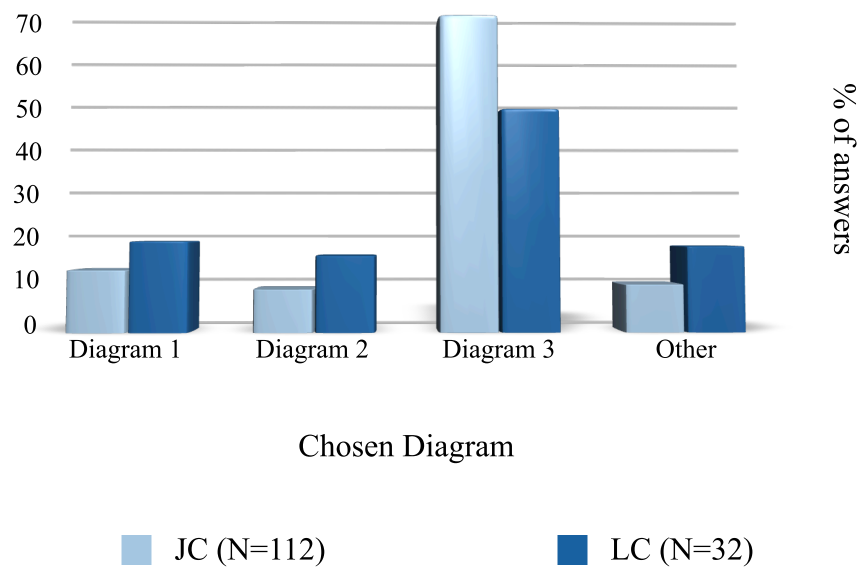


Figure 7.4: Frequency of chosen diagrams for Complete Circuits Pretest 1, Question 2.

This question was answered very poorly as only 10% of JC students and 15% of LC students chose the correct arrangement (diagram 2). The most popular answer in both groups was diagram 3 which illustrated the filament wires connected to the bottom of the bulb. These results are very similar to those discussed in Chapter 3 where 60% of pre-service teachers chose diagram 3 which is closer to the JC results (65%) than the LC results (45%).

As part of the question, students were asked to comment on the reasoning used in their choice of diagram. Some examples are shown below:

Student comments for Diagram 1

"The wires are split to opposite ends like positive and negative"

"When the wires from the battery come into contact with the screw component of the light the bulb will light up"

Student comments for Diagram 2

"Both points cannot be wired to the same point of contact"

"As if the wires entered at the same point it would short the circuit"

Student comments for Diagram 3

"The wires need to touch the source of energy which means that diagram 3 would be correct"

"In diagram 3, both wires are touching the bottom of the bulb which is connected to the power source. Both wires can then carry the electricity."

The choice of arrangements in question 1 and the diagrams in question 2 led to some interesting correlations. Considering the correct arrangements of 3 & 6, students would be expected to choose diagram 2 since this is consistent with their choice of arrangement. This was shown to be true: all seven students who chose arrangements 3 & 6 in question 1, chose diagram 2 in question 2. However the expected correlations varied in the choice of arrangements 1 & 4. The breakdown of correlated results is shown in Table 7.6.

Table 7.6: Correlation between answers to Complete Circuits Pretest 1, Question 1 and Question 2.

Chosen Arrangement	Diagram 1 & 3 %	Diagram 3 %	Diagram 1 %	Diagram 1 & 2 %
1&4 (N = 25)	**10 (3)**	65 (16)	20 (5)	5 (1)

It seems that when choosing the correct arrangement in question 1, many students ignore the connections in the bulb and only focus on the connections to the battery terminals. This is consistent with the results presented in Chapter 3.

In the opening question of the pretest given in 2009 at DCU and at IC (scal only), students were posed with the fan question as shown below and also discussed in Chapter 3.

Complete Circuits Pretest 2†

When a small fan is connected to a battery using two wires, as shown at right, it is observed that the blades of the fan rotate.
Suppose that the fan is now connected to two batteries using two wires as shown below.

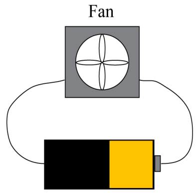


Figure 7.5: Fan connected to a single battery.

Is the following statement true or false?
"The blades of the fan rotate when the fan is connected to the two batteries as shown."

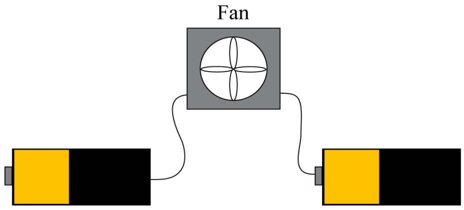


Figure 7.6: Fan connected to opposite terminals of two batteries.

The purpose of the pretest is to highlight students' misconceptions regarding the requirements necessary to form a complete circuit. In Figure 7.6 the fan is connected to opposite terminals of two batteries. Many students incorrectly believe that this is all that is necessary for the fan to rotate. The analysis of students' answers shown in Table 7.7 reveals that a surprising number of students agree with the student statement, thus highlighting their lack of understanding of a complete circuit.

Table 7.7: Students' answers to Complete Circuits Pretest 2.

Answer	JC % (*N*=101)	LC % (*N*=43)	IC Scal % (*N*=66)
FALSE	**55 (53)**	**65 (29)**	**70 (46)**
TRUE	40 (42)	30 (13)	30 (20)
No answer	5 (6)	<5 (1)	0 (0)

When analysing students' reasons for those who said the student's statement was false, it became evident that many used correct reasoning by stating that the circuit was incomplete. There was also a small number of students from the JC and IC scal cohort that used partial correct reasoning by giving an appropriate answer although

† For the pretest given at Ithaca College, students were asked if the blades of the fan would rotate when it was connected to the batteries as shown in the second figure. Therefore stating that the blades of the fan would rotate is analogous to stating that the statement in the question above is true and vice versa.

not explicitly stating that the circuit was incomplete or open. The breakdown of answers is shown in Table 7.8. Examples of students' reasoning are shown immediately afterwards.

Table 7.8: Students' reasoning in response to Complete Circuits Pretest 2.

Reasoning	JC % (*N*=53)	LC % (*N*=29)	IC scal % (*N*=46)
Circuit is incomplete/ broken/not closed	**40 (21)**	**70 (20)**	**65 (30)**
Partial complete circuit reasoning	20 (10)	0 (0)	25 (11)

Example of complete reasoning:

"False, because the above circuit isn't a closed circuit (incomplete circuit)"

Example of partial reasoning

"There is no circuit being provided for the blades to turn"

The majority of students who agreed that the blades of the fan would rotate when it was connected to the two batteries, stated that the fan was still connected to a positive and negative terminal.

From this pretest analysis, it is quite evident that a significant number of students do not completely understand the concept of a complete circuit. Since all subsequent concepts are in someway reliant on the concept of a complete circuit it was crucial that it was addressed in some detail in the opening section of the first laboratory.

7.3.2 Complete Circuits Curriculum Discussion

As stated in the introduction, the labs were limited to 2.5 hours each, therefore the time dedicated to each concept would need to be carefully allocated. In the PbI course discussed in Chapter 3, the students begin their investigation of electric circuits by trying to form an arrangement in which the bulb lights, using a battery, a bulb and a single wire. Although we think that this is a critical experiment, we find in practice that this experiment can take more than 20 minutes in spite of a very favourable staff to student ratio of 1:12. Therefore in the first year labs, where the staff to student ratio is approximately 1:20, we foresaw that the time needed for this experiment would be excessive. We shortened the investigation by providing three possible arrangements, two incorrect and one that is correct. These arrangements are shown in Figure 7.7.

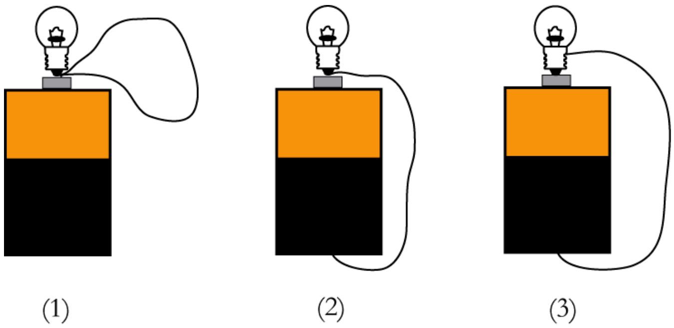


Figure 7.7: Three possible arrangements of a battery, a bulb and a single wire.

Before the students set up each of the arrangements we first ask them to predict in which of the arrangements shown above will the bulb light, forcing them to commit to a particular arrangement. We find from the analysis of 60 worksheets that 70% of students predict that arrangement 2 is the correct set up. Remarkably in the complete circuits pretest only 35% of students state this. A breakdown of the data provided from the analysis of the lab worksheets is shown in Table 7.9.

Table 7.9: Data provided from analysis of students' worksheets from the first year current laboratory.

Arrangement	Prediction % (On) (*N*=60)	Prediction % (Off) (*N*=60)
1	0 (0)	100 (60)
2	70 (41)	30 (19)
3	60 (35)	40 (25)

This percentage maybe somewhat inaccurate, as we find that 8 of the 60 students changed their answer for arrangements 2 and 3. Although we have no evidence for when this change was made, we find from discussions with students during the practical, that they made the change to their answer after they have made their observation. We find that some students feel uncomfortable writing down an incorrect answer. An example of such a case is shown in Figure 7.8.

Table 1.1: Battery circuit table

Arrangement	Prediction: (on/off)	Observation (on/off)
1	off	off
2	~~on~~ off	off
3	on	on

Figure 7.8: A sample of a student's worksheet from the first year current laboratory.

Once the students have set up the three arrangements and discover that arrangement 3 is correct, we ask them to find three other possible arrangements which promotes the investigate nature of the experiment. We find this method allows us to reduce the time dedicated to the concept without sacrificing a considerable amount of the laboratory investigation.

At this early stage in the experiment, students have confronted many of the issues that were presented in both pretests and it is hoped that their observations will help them resolve any inconsistencies in their understanding. The next section on insulators and conductors, reinforces many of the concepts. However, before the section on insulators and conductors is discussed, the post-test data on complete circuits is addressed.

7.3.3 Complete Circuits: Post-Test and Analysis

The pretest in 2009, where the students were presented with the fan question, also served as the 2008 post-test, allowing us to estimate the efficacy of the curriculum. The students taking the module in 2008 had not seen this question. The analysis of students' answers in Table 7.10 below shows a large increase in correct answers when compared to the 2009 pretest answers shown previously on page 166 in Table 7.7.

Table 7.10: Students' answers to Complete Circuits Post-Test.

Answer	JC% (*N*=60)	LC% (*N*=6)	Total % (*N*=66)
Blades won't rotate	**90 (53)**	**85 (6)**	**90 (59)**
Blades will rotate	10 (7)	15 (1)	10 (8)

The analysis of the reasons behind students' answers revealed that a large percentage of students supported their answer with correct reasoning as shown in Table 7.11.

Table 7.11: Students' reasoning in response to Complete Circuits Post-Test.

Reasoning	(*N*=59)
Circuit is incomplete/broken/not closed	80 (47)

The increase in the number of correct answers in addition to the reasoning used seems to suggest that many of students have shifted or broadened their understanding of complete circuits where they no longer solely focus on the connections to the battery terminals. Additional post-test questions on complete circuits is covered in the next section on conductors and insulators.

7.4 Conductors and Insulators

The second concept that students are introduced to is that of the behaviour of conductors and insulators. In the first section students have seen that a complete circuit in which both parts of the bulb, battery and wire are connected in a loop, is necessary for the bulb to light. The section on conductors and insulators allows the students to broaden their understanding of a complete circuit by allowing them to examine the structure and purpose of a light bulb. Although the concept of conductors and insulators is a significant topic in students' secondary school education, the pretest analysis which follows suggests that little conceptual understanding is attained.

7.4.1 Conductors and Insulators: Pretest and Analysis

The concept of conductors and insulators was only present as a post-test in 2008 but was included in the 2009 pretest. The pretest was completed by students online before they had carried out the current laboratory. The pretest is shown below.

Conductors and Insulators Pretest†

In the circuits shown below, box X contains an insulator while box Y contains a conductor.

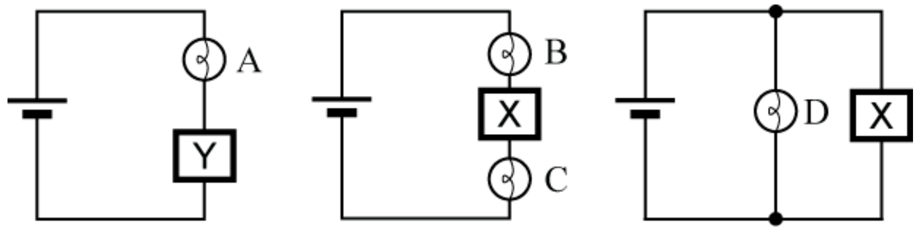


Figure 7.9: Three circuits containing either an insulator or conductor

State whether each of the bulbs shown above will light. If you think a bulb doesn't light, state so explicitly. Explain your reasoning.

When students examine the circuits above, they are expected to recognise that only bulb A and bulb D light since these are the only two bulbs which have a conducting pathway between the bulb and the battery. However the results in Table 7.12 shows that less than half of each student cohort made this recognition.

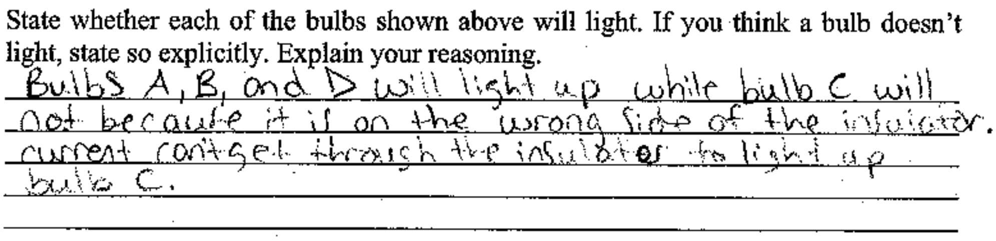
Table 7.12: Students' answers to Conductors and Insulators Pretest.

Bulbs that light	JC % (*N*=101)	LC % (*N*=43)	IC scal % (*N*=66)
Bulb A and D	**30 (28)**	**45 (19)**	**40 (29)**
Bulb A only	25 (27)	20 (9)	5 (3)
Bulbs A, B and D	5 (5)	10 (5)	30 (9)
Bulbs A, C and D	5 (6)	10 (4)	<5 (1)
Bulb D only	10 (10)	<5 (1)	<5 (1)
Other	15 (17)	15 (5)	20 (13)
No answer	10 (8)	0 (0)	0 (0)

The results in Table 7.12 show that a similar percentage in each group correctly answered the question by stating that bulb A and D light. It is also interesting to note the large percentage of Ithaca students who chose bulbs A, B and D while a similar percentage of DCU students only choose bulb A. The analysis of students' reasoning highlights a local or sequential approach rather than holistic approach[4,5].

† This question was developed at DCU.

An example of the reasoning used by a student who chose bulbs A, B and D is shown in Figure 7.10:


State whether each of the bulbs shown above will light. If you think a bulb doesn't light, state so explicitly. Explain your reasoning.

Bulbs A, B, and D will light up while bulb C will not because it is on the wrong side of the insulator. current cont get through the insulator to light up bulb C.

Figure 7.10: An example of a student's answer in response to Conductors and Insulators Pretest.

For students who chose bulb A only, the analysis shows that 50% only provide an answer for why bulb A lights while the other half also explain why bulbs B-D don't light. A breakdown of students' answers who only gave reasons for bulb A is shown below in Table 7.13.

Table 7.13: Students' reasoning in response to Conductors and Insulators Pretest.

Bulb A only (conductor only reasoning)	**% (*N*=17)**
Conductor conducts electricity/electrons/energy	40 (7)
A conductor is present	30 (5)
Conductor allows current to flow	20 (3)
Other	10 (2)

The reasoning used by students who provided reasons for why bulbs B-D don't light are categorised in Table 7.14.

Table 7.14: Students' reasoning in response to Conductors and Insulators Pretest.

Bulb A only (reasons for all bulbs)	**% (*N*=18)**
Insulator stops current	60 (11)
Conductor allows current to flow	50 (9)
A conductor is present	15 (3)
Conductor conducts electricity	15 (3)
Insulator doesn't conduct electricity	5 (1)
No conductor present	5 (1)
Other	20 (4)

7.4.2 Conductors and Insulators: Curriculum Discussion

The method in which conductors and insulators is addressed is very similar to that in the traditional PbI course where students investigate how the addition of a number of materials into a circuit, affects the brightness of the bulb. In the laboratory students place four different materials, two conductors and two insulators, into the circuit as shown in Figure 7.11 and note any affects on the bulb brightness. On the basis of observations, students categorise the materials according to how they affect the brightness of the bulb and then tabulate their data. An example of a student's table is shown in Figure 7.12.

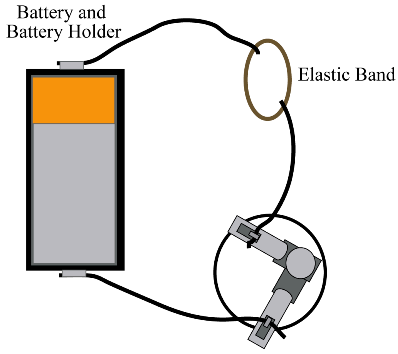


Figure 7.11: Circuit consisting of a bulb connected in series with an elastic band.

Material	Did it light the bulb	Brightness
Crocodile clip	yes	# 1
fahnstock clip	yes	# 2
Paper	no	# 3
elastic band.	no.	# 3

Figure 7.12: An example of a student' s observations for the conductors and insulators section in the first year current laboratory.

Once students have completed their investigation, they are then introduced to the terms conductor and insulator and informed that objects which allow the bulb to light are called conductors while objects that cause the bulb to go out are called insulators. This process is a very good example of how the use of inquiry reinforces the scientific method. Students begin by carrying out an investigation with little instruction and take note of their observations. By analysing their data, the students can group the materials into two groups according to their effect on bulb brightness. It is only then, that the students name the group of materials.

To build on students' understanding of conductors and insulators, students investigate the properties of the different materials that make up a light bulb and a bulb holder. By carrying out this investigation students discover the location of the filament wires which were pretested in 2008. By carrying out the investigation in conjunction with the bulb holder, students can easily identify its function and also probe the purpose of the round strip at the base of the bulb as shown in Figure 7.13.

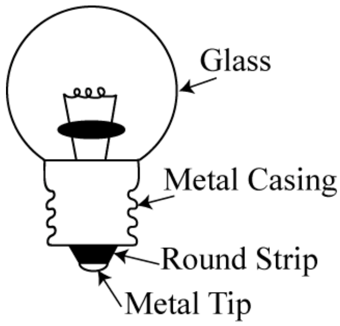


Figure 7.13: Diagram of bulb identifying its parts.

The curriculum on conductors and insulators is concluded with a thought experiment where students analyse observations from a particular experiment. This question is also given as a homework question in the traditional PbI course. Students are told that when the small bulb is connected to the bulb with the broken filament as shown in the diagram in Figure 7.14, a student observes that the small bulb lights.

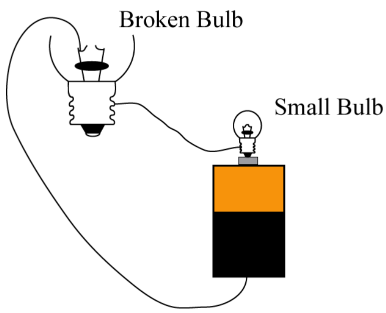


Figure 7.14: Illustration of a circuit connected to a broken bulb.

From this information, we ask students to determine the connections of the filament wires inside the broken bulb. Students are expected to reason that since the small bulb lights, the left filament post must be connected to the metal casing of the broken bulb since if it was connected to the metal tip, a conductive pathway would not be formed between the post and the small bulb.

We find that most students can follow this line of reasoning, but some still struggle or if successful, they tend to draw the connections incorrectly as show in Figure 7.15. With some guidance students soon resolve any difficulties they have with the question.

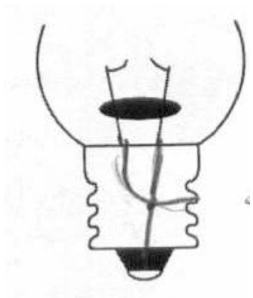


Figure 7.15: Incorrect illustration of the connections of filament posts inside a bulb.

In the second part of the question, we tell students that the wire is moved to the right filament post as shown in Figure 7.16 and ask them what would happen the brightness of the small bulb in this case. Since students have determined in the previous question that the left filament post is connected to the metal casing, they are then expected to reason that the right filament post is connected to the metal tip. Therefore they should reason that the small bulb will not light in this case.

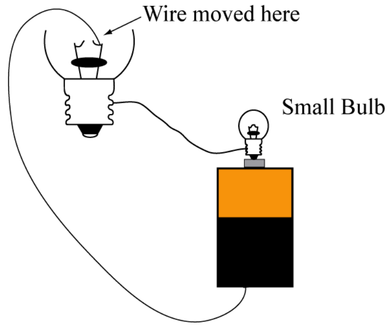


Figure 7.16: Illustration of a circuit connected to a broken bulb.

This experiment concludes the development of students' understanding in regards to complete circuits. When considering the section as a whole, it is obviously more condensed that the traditional PbI module for pre-service teachers, but it includes a sufficient blend of the key concepts and satisfies the time constraints of the lab.

7.4.3 Conductors and Insulators: Post-Test and Analysis

The post-test data that is presented below was gathered from a mid-term exam during 2008. The question which students were given was identical to that in the 2009 pretest, shown on page 171, but it must be noted that there was a slight difference in the phrasing of the pretest and post-test question. In the 2009 pretest, students were asked to state which bulbs would light but also asked to state which bulbs would not light. In the 2008 post-test question students were only asked to state the bulbs they think will light and but not asked explicitly to state reasons for bulbs which they think will not light. Therefore in the results shown in Table 7.15, if a student did not provide an answer for a particular bulb, I have assumed that this student believes that it will not light.

Table 7.15: Students' answers to Conductors and Insulators Post-Test.

Answer	**JC %** **(*N*=51)**	**LC%** **(*N*=10)**	**Total %** **(*N*=62)**
Bulb A & Bulb D	**55 (29)**	**90 (9)**	**60 (38)**
Bulb A only	10 (4)	0 (0)	5 (4)
Bulbs A, B and D	10 (6)	10 (1)	10 (7)
Bulbs A, C and D	5 (3)	0 (0)	5 (3)
Bulbs B, C and D	5 (3)	0 (0)	5 (3)
Other	10 (5)	0 (0)	10 (5)

The results show a moderate gain in students' understanding with results increasing from 30% to 55% for the JC group. Due to the small number of LC students, it is difficult to assess the improvement in their understanding.

7.5 Resistance

Although the concept of resistance is covered after the concept of current, I present the data on resistance first as many of the current post-test questions require the concept of resistance. The concept of resistance is covered in a single laboratory where students focus on the effects of adding bulbs in series and in parallel.

7.5.1 Resistance: Pretest and Analysis

In the 2009 pretest we asked students specific questions on the concept of resistance. In the first question, students had to compare the brightness of bulb A to bulb B in the circuit of Figure 7.17.

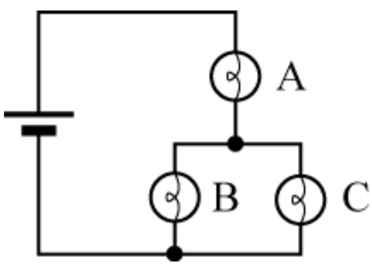


Figure 7.17: Single bulb in series with a two bulb parallel network.

The analysis of students' answers provided the data shown in Table 7.16.

Table 7.16: Students' answers to Resistance Pretest, Question 1.

Answer	2008/2009 JC % (N=197)	2008/2009 LC % (N=72)
Bulb A > Bulb B	**40 (81)**	**70 (51)**
Bulb A = Bulb B	45 (87)	30 (20)
Bulb A < Bulb B	10 (15)	<5 (1)
I don't know	5 (12)	0 (0)
No answer	<5 (2)	0 (0)

The results for the JC cohort were quite interesting as only 40% correctly ranked bulb A brighter than bulb B. The most popular answer chosen by this group was to rank the bulbs equal in brightness. The analysis of students' reasons in Table 7.17 highlight a lack of understanding of the behaviour of current in parallel networks.

Table 7.17: Partial analysis of students' reasoning in response to Resistance Pretest, Question 1.

Reasoning for A=B	2008 JC % (N=47)
Same amount of current	55 (26)
Same circuit	25 (12)
Same amount of energy	15 (6)
Other	10 (4)
No answer	5 (2)

In the second question of the 2009 pretest, students were told that an additional bulb (bulb D) was placed in the circuit as shown in Figure 7.18.

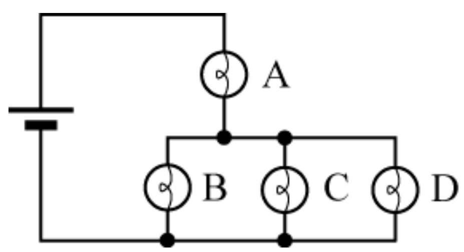


Figure 7.18: Single bulb in series with a three bulb parallel network.

Students had to determine whether bulb D was added in series, in parallel, neither or both. The results are shown in Table 7.18.

Table 7.18: Students' answers to Resistance Pretest, Question 2.

Answer	JC % (*N*=91)	LC % (*N*=42)
Parallel	**65 (59)**	**65 (27)**
Series	15 (15)	5 (3)
Neither	<5 (2)	<5 (1)
Both	15 (12)	25 (11)
No answer	5 (3)	0 (0)

It is interesting to note that a large percentage of students stated the correct answer, however it is also interesting to see the amount of students who stated both. An example of such an answer is shown below.

> "*D is added in parallel with bulbs B and C but D is also in series with A. This is a series parallel circuit*"

This type of reasoning was also quite evident during discussions in the laboratory. It is not easy to distinguish careless use of language from a misconception in this case.

Students were then asked how the addition of bulb D affected the resistance of the circuit. With many students stating that bulb D was added in parallel, it would be expected that a similar percentage would state that the resistance of the circuit would decrease. However Table 7.19 shows a much smaller percentage state that the resistance decreased. Remarkably the prevalence of answers in this table is independent of whether students thought the bulb was added in series, parallel or otherwise.

Table 7.19: Students' answers to Resistance Pretest, Question 3.

Answer	JC % (*N*=91)	LC % (*N*=42)
Decreased	**25 (22)**	**5 (3)**
Increased	30 (29)	60 (25)
Stayed the same	15 (14)	25 (11)
I don't know	25 (24)	5 (2)
No answer	<5 (2)	<5 (1)

In the last question, students were asked how the addition of bulb D would affect the brightness of bulb A. Since the previous two tables have shown contradictory results, it is not surprising to see that very few students in each group recognised that bulb A would increase in brightness when bulb D was added. There appears to be little correlation between resistance and the brightness of bulb A.

Table 7.20: Students' answers to Resistance Pretest, Question 4

Answer	JC % (*N*=91)	LC % (*N*=42)
Increased	**< 5 (2)**	**< 5 (1)**
Decreased	60 (55)	50 (20)
Stayed the same	30 (27)	50 (21)
I don't know	5 (5)	0 (0)
No answer	<5 (2)	0 (0)

7.5.2 Resistance: Curriculum Discussion

The development of the concept of resistance mirrors the method presented in the PbI curriculum[6]. The students begin by making a prediction on the change in brightness of bulb A when another bulb is added in series to the circuit in Figure 7.19.

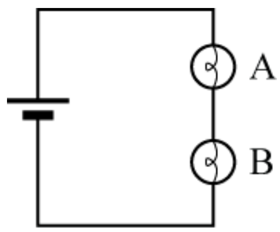


Figure 7.19: A two bulb series circuit.

Many students make the correct prediction by stating that bulb A decreases in brightness. They confirm their prediction by carrying out the experiment. To help explain their observations, students are guided to think of adding a bulb in series as an obstacle or resistance to the current. Students conclude their investigation by stating a rule that allows them to predict the change in the current through the battery when an extra bulb is added in series. The concept of resistance is included in their rule.

To investigate the affect of adding a bulb in parallel, students first consider the exercise in Figure 7.20 which has been adapted from the published PbI current curriculum.

Consider the circuit shown at right. The black box represents an arrangement of circuit elements. A change is made within the black box and the brightness of the indicator bulb A increases. What can you infer about the change in resistance of the circuit after the connections in the box have been changed?

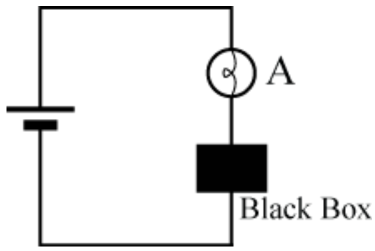


Figure 7.20: Extract of an exercise from the Resistance Laboratory

Since students are told that the brightness of bulb A increases, they can infer that the current through the bulb and thus the battery has increased. To be consistent with their rules for bulbs in series, students infer that the resistance of the circuit has decreased when the connections inside the box have been changed.

Students then observe that bulb A in Figure 7.19 gets brighter when another bulb is added in parallel across bulb B. Students are encouraged to think of the network of bulb B and the new bulb as the black box in the exercise shown in Figure 7.20. Since the brightness of bulb A increases, students infer that the resistance of the circuit has decreased. They then formulate a rule that allows them to predict the change in the resistance of the circuit and thus the current through the battery, when a bulb is added in parallel.

The final section of the laboratory guides students to apply their model thus far to two unseen circuits, one of which is discussed here. The exercise presents students with the following circuits.

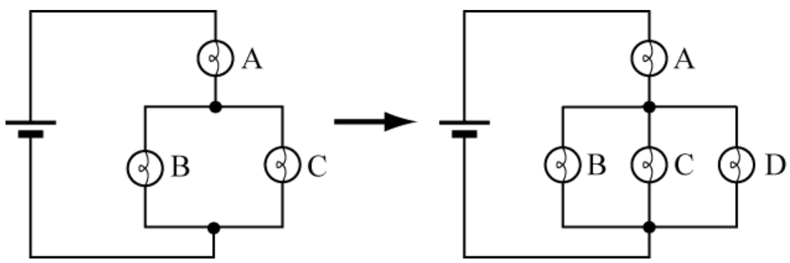


Figure 7.21: Two circuits presented in Resistance Laboratory as part of the Application of Model Section.

A number of questions follow which guide students through a specific line of reasoning that we recommend them to take in order to reason how the addition of bulb D affects the brightness of bulb A. The steps which we intend students to take are listed below.

(1) Recognition that bulb D is added in parallel.

(2) Apply their rule for the addition of bulbs in parallel to infer the resistance of the circuit has decreased.

(3) As a consequence, they can reason that the current through the battery has increased.

(4) Finally, this allows them to reason that the brightness of bulb A increases as the current through bulb A is the same as that through the battery.

When students have completed the exercise by qualitatively reasoning that bulb A increases in brightness, they confirm the results with an ammeter. We find that in some cases, the ammeter can act as an instructor and help confirm their qualitative answers. This view was also expressed by instructors at Ithaca College.[7]

The final exercise, continues with a similar process of reasoning for the addition of an extra bulb in series as shown in Figure 7.22.

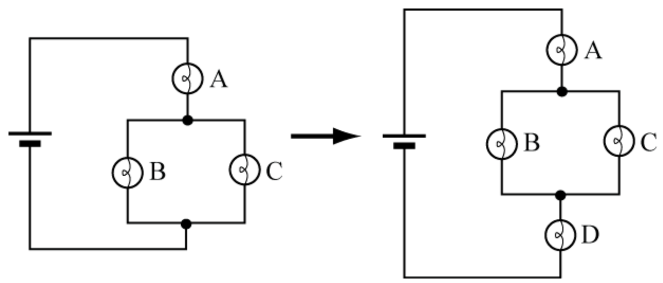


Figure 7.22: Two Circuits presented in Resistance Laboratory as part of the Application of Model Section.

7.5.3 Resistance: Post-Test and Analysis

The resistance post-test questions were presented in two types, one which referred to a comparison in circuits while one asked students to comment on a particular student statement.

In the 2008 and 2009 mid-term exam, DCU students were given the following question.

Resistance Post-Test 1

Consider the circuits shown at right.
Compare the resistance of circuit 1 to circuit 2. Explain.

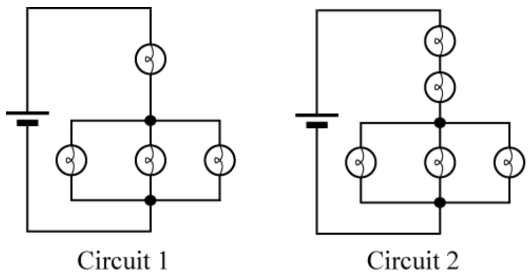


Figure 7.23: Circuits presented in Resistance Post-Test 1.

The purpose of the question is quite simplistic as it focusses on one concept only. It is hoped that students recognise that circuit 2 contains an extra bulb which has been connected in series and thus state that the resistance of circuit 2 is greater than circuit 1. Students' results are shown in Table 7.21.

Table 7.21: Students' answers to Resistance Post-Test 1.

Answer	2008/2009 JC % (*N*=97)	2008/2009 LC % (*N*=30)
Circuit 2 > Circuit 1	**90 (86)**	**95 (28)**
Circuit 1 > Circuit 2	10 (7)	5 (2)
Circuit 1 = Circuit 2	<5 (2)	0 (0)
Inconclusive	<5 (2)	0 (0)

Although a large percentage of students in each group answered the question correctly, it is vital to analyse the reasoning used, as many students believe that resistance is dependent only on the number of bulbs and not how they are connected.

By examining the circuits shown in Figure 7.23 this misconception would lead students to the correct answer. The analysis of students' answers in Table 7.22 show that 30% of the 2008 student group and only 5% of the 2009 student group used this incorrect line of reasoning to explain their answer.

Table 7.22: Student' reasoning in response to Resistance Post-Test 1.

Reason for answer	**2008 % (*N*=54)**	**2009 % (*N*=60)**	**Total % (*N*=114)**
Extra bulb has been added in series	**55 (29)**	**85 (51)**	**70 (80)**
Circuit 2 has more bulbs	30 (16)	5 (4)	20 (20)
Other	15 (9)	10 (5)	10 (14)

It is difficult to explain the large difference between both years as no significant changes were made to this part of the curriculum. Factors such as tutor instruction may have contributed to the change.

In the same mid-term exam, a separate group of students was given a very similar question, which would examine their understanding of adding bulbs in parallel.

Resistance Post-Test 2

Consider the circuits at right.
Compare the resistance of circuit 1 to circuit 2. Explain.

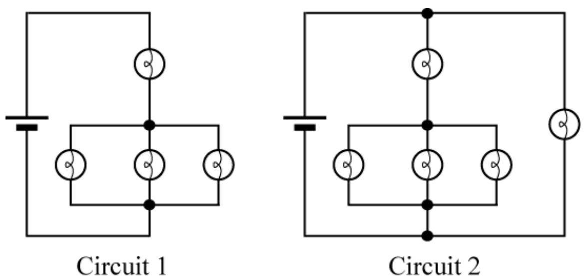


Figure 7.24: Circuits presented in Resistance Post-Test 2.

Here the incorrect reasoning that resistance increases when bulbs are added does not lead students to the correct answer. The results are shown in Table 7.23.

Table 7.23: Students' answers to Resistance Post-Test 2.

Answer	2008/2009 JC % (*N*=98)	2008/2009 LC % (*N*=18)
Circuit 1 > Circuit 2	**50 (50)**	**55 (10)**
Circuit 1 = Circuit 2	10 (10)	10 (2)
Circuit 2 > Circuit 1	35 (33)	35 (6)
Inconclusive	5 (5)	0 (0)

In both groups of the 2008 module, about 75% of those who chose the correct answer used correct reasoning. This percentage was raised to 80% in the 2009 class. Again it is difficult to identify factors contributing to the improved results in 2009.

The last resistance post-test question which was asked is shown below.

Resistance Post-Test 3

Consider the student statement below
Student: "Adding bulbs to a circuit increases the total resistance. There is a bigger obstacle to the current so less flows."

Do you agree or disagree with the student's statement? Explain your reasoning

In analysing students' answers for the previous question, it was quite apparent that many students base their comparison of resistance in both circuits on the number of bulbs in the circuit rather than how they are connected. Therefore the question above is aimed at highlighting this incorrect line of reasoning. Students' results are shown in Table 7.24.

Table 7.24: Students' answers to Resistance Post-Test 3.

Answer	JC % (*N*=45)	LC % (*N*=12)
Disagree	**15 (6)**	**10 (1)**
Partially agree	**25 (12)**	**40 (5)**
Agree	45 (21)	40 (5)
Agree for series connections	15 (6)	10 (1)

The analysis of students' reasoning for those who stated the correct answer are shown in Table 7.25. Examples of such answers are shown afterwards.

Table 7.25: Students' reasoning in response to Resistance Post-Test 3.

Answer	Correct reasoning %	Incorrect reasoning %	Correct with misconceptions %
Disagree (*N*=7)	30 (2)	70 (5)	0 (0)
Partially agree (*N*=17)	70 (12)	5 (1)	25 (4)

Correct Reasoning

Do you *agree* or *disagree* with the student's statement? Explain your reasoning

I disagree with this students statement. adding bulbs in series increases the total resistance. However adding a bulb in parall would ~~&~~ decrease resistance.

Figure 7.25: Example of correct reasoning in response to Resistance Post-Test 3.

Incorrect reasoning

Do you *agree* or *disagree* with the student's statement? Explain your reasoning

I DISAGREE WITH THE STATEMENT BECAUSE THE CURRENT IS THE SAME. INCREASING RESISTANCE WILL DECREASE VOLTAGE BECAUSE IT WOULD TAKE MORE WORK TO CARRY CURRENT, BUT THE CURRENT ITSELF WILL STILL BE THE SAME ON THE OTHER SIDE OF A RESISTOR AS IT WAS WHEN IT REACHED THE RESISTOR.

Figure 7.26: Example of incorrect reasoning in response to Resistance Post-Test 3.

Partially agree

Do you *agree* or *disagree* with the student's statement? Explain your reasoning

I agree with this statement if the circuit is in series, as the more bulbs that are added, the greater the resistance to current. But if it is a parallel circuit I disagree with this statement as there is a decrease in resistance and an increase in current

Figure 7.27: Example of correct reasoning used by a student who partially agreed with the statement in Resistance Post-Test 3.

From the results shown in Table 7.22 it is quite clear that many students agreed with the student statement. The analysis shows that 55% of students agreed with the statement, however 10% of these students did refer to a series circuit such as the example shown below.

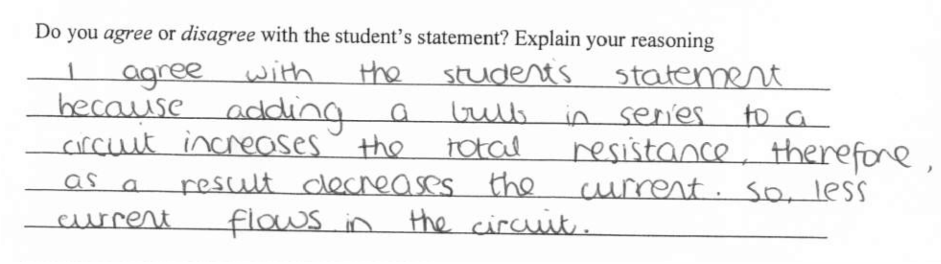

Do you *agree* or *disagree* with the student's statement? Explain your reasoning
I agree with the students statement because adding a bulb in series to a circuit increases the total resistance, therefore, as a result decreases the current. So, less current flows in the circuit.

Figure 7.28: Example of reasoning used by a student who agreed with the statement in Resistance Post-Test 3.

Assessing the laboratory on resistance from an overall perspective, it was considered to be a success. Over a very minimal period of teaching, many students have understood the affects of adding bulbs in series and in parallel. This understanding was not evident before instruction. Further evidence for the success of the curriculum was supported by the survey carried out at its conclusion. The combined analysis for both years (*N*=275) is shown in Table 7.26.

Table 7.26: Results of a survey on the Resistance Laboratory.

Statement (*N*=275)	**Strongly disagree %**	**Disagree %**	**Neutral %**	**Agree %**	**Strongly agree %**
I enjoyed the Resistance Laboratory	< 5 (6)	5 (9)	30 (82)	55 (151)	10 (27)
I found the Resistance Laboratory too hard	5 (19)	50 (131)	35 (99)	10 (24)	< 5 (2)
I learnt something from the Resistance Laboratory	< 5 (4)	5 (7)	15 (44)	65 (182)	15 (38)

7.6 Developing Current Qualitatively

One of the main aims of the laboratories is to develop students' conceptual understanding of electric circuits. This should allow them to analyse circuits in a qualitative manner. Similar to the curriculum published in PbI, the development of the students' model begins with the concept of current. It is well documented that many students have considerable difficulties with the concept and hold many misconceptions, many of which have been discussed in Chapter 3. Over the course of this section, I discuss the findings of the pretest analysis and how they contributed to the curriculum development.

7.6.1 Qualitative Current: Pretest and Analysis

In 2008, students were given the same pretest as in the PbI module in which they had to rank the relative brightness of the bulbs shown in Figure 7.29. However rather than asking students to make a complete ranking, we asked them a number of questions in which they had to rank the relative brightness of specific pairs of bulbs.

Qualitative Current Pretest

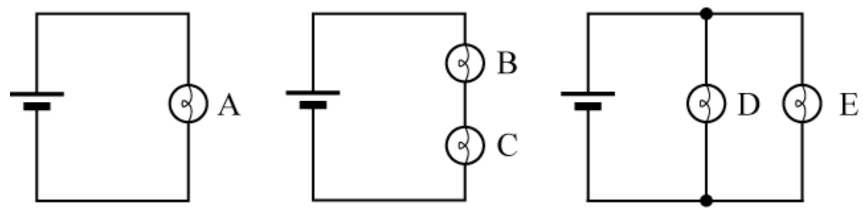


Figure 7.29: A single bulb circuit, a two bulb series circuit and a two bulb parallel circuit.

(1) Compare the brightness of bulb B to bulb C. Explain your reasoning.
(2) Compare the brightness of bulb D to bulb E. Explain your reasoning.
(3) Compare the brightness of bulb A to bulb B. Explain your reasoning.

In the first question students were asked to compare the brightness of bulb B to bulb C which is aimed to highlight some key misconceptions. The results are shown below in Figure 7.30.

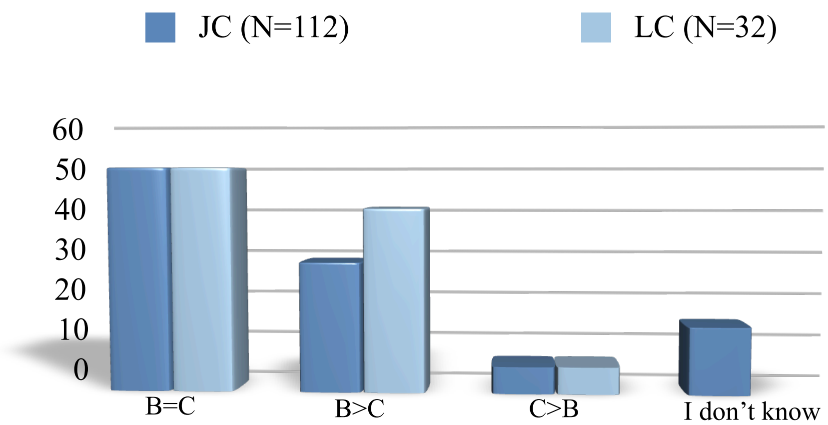


Figure 7.30: Analysis of Qualitative Current Pretest, Question 1.

This question was answered quite poorly with only 50% of each group correctly stating that bulb B was in equal in brightness to bulb C. Since it is possible to provide this answer based on incorrect reasoning, it is crucial to analyse students' reasoning. The analysis of students' answers provided the data shown in Table 7.27.

Table 7.27: Students' reasoning in answer to Qualitative Current Pretest, Question 1.

Reasoning for B=C	Total % (*N*=55)
Same circuit/physical layout	55 (31)
Same current/power/energy passing through both	30 (16)
Equal distance	5 (3)
Share current/energy equally	<5 (1)
Other	15 (6)
In Series	<5 (1)
Same voltage	5 (4)
No answer	5 (4)

In the analysis of students' answers, many students stated that the bulbs were equal in brightness as they were part of the same circuit. This is not a line of reasoning which is prevalent in the pre-service teachers module. However, similar findings were highlighted in students' inability to differentiate between related concepts and the belief that current is shared between bulbs in series. Some examples of students' reasoning are shown below.

> *"They are in same circuit connected to same battery"*

> *"They are both on the same circuit and in a linear pattern so the amount of energy flowing should be the same for both bulbs"*

Further misconceptions were highlighted in the analysis of students' answers who ranked bulb B brighter than bulb C. The results of the analysis are shown in Table 7.28.

Table 7.28: Students' reasoning in answer to Qualitative Current Pretest, Question 1.

Reasoning for B>C	Total % (*N*=32)
Bulb B is closer to the battery	30 (9)
Bulb B uses up some current/power	15 (4)
Bulb B receives current before bulb C	20 (6)
Bulb B gets more energy/power/current	10 (4)
Other	15 (5)
No answer	10 (4)

The analysis of students' answers revealed the belief that the proximity to the battery affects bulb brightness, as 30% of the students stated that bulb B was brighter than bulb C as it was closer to the battery. The application of a 'used up' model was also evident. We found similar reasons for students who ranked bulb C brighter than bulb B.

In the second question of the pretest students are asked to compare the brightness of bulb D to bulb E in Figure 7.29. The results are shown in Figure 7.31.

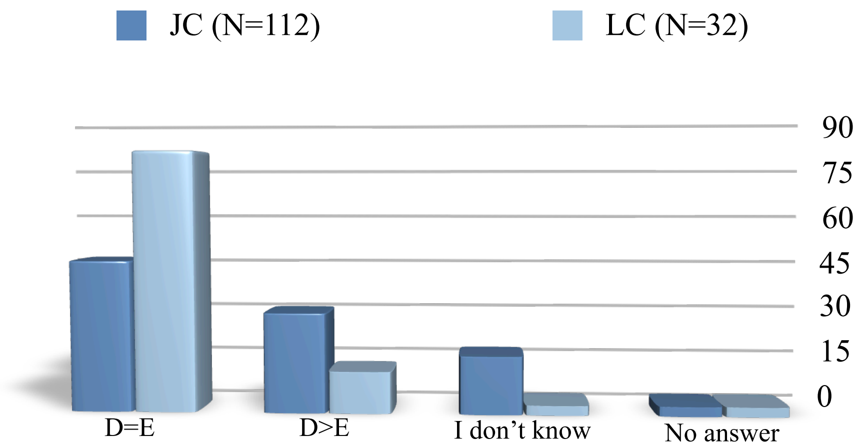


Figure 7.31: Students' answers in response to Qualitative Current Pretest, Question 2.

This was the first question in which there was a large difference between the answers of the LC and JC group. The LC group answered the question quite well with 80% of students answering the question correctly, however the question was answered poorly by the JC students.

The analysis of students' reasoning for those who stated that the bulbs were equal in brightness is shown in Table 7.29. The use of 'same' as an adjective in students' answers is ambivalent here as its difficult to distinguish whether students are referring to the equal magnitudes of current or that the same current (same electron) is going through both paths.

Table 7.29: Students' reasoning in answer to Qualitative Current Pretest, Question 2.

Reasoning for D=E	Total % (*N*=53)
Same current/electricity/power/charge	50 (26)
Same circuit/same connections	25 (14)
Bulbs in parallel	10 (5)
Same voltage	<5 (1)
I don't know	5 (2)
Other	5 (3)
No answer	10 (6)

The misconception that the proximity of a bulb to the battery affects its brightness was once again identified in students' answers who ranked bulb D brighter than bulb E. This is shown in Table 7.30.

Table 7.30: Students' reasoning in answer to Qualitative Current Pretest, Question 2

Reasoning for D>E	Total % (*N*=35)
Current/energy/power has a shorter distance to travel	40 (13)
Bulb D is closer to the battery/power source	40 (13)
Other	10 (4)
No answer	15 (6)

The pretest continues by asking students to compare the brightness of bulb A to bulb B. The results are shown in Figure 7.32.

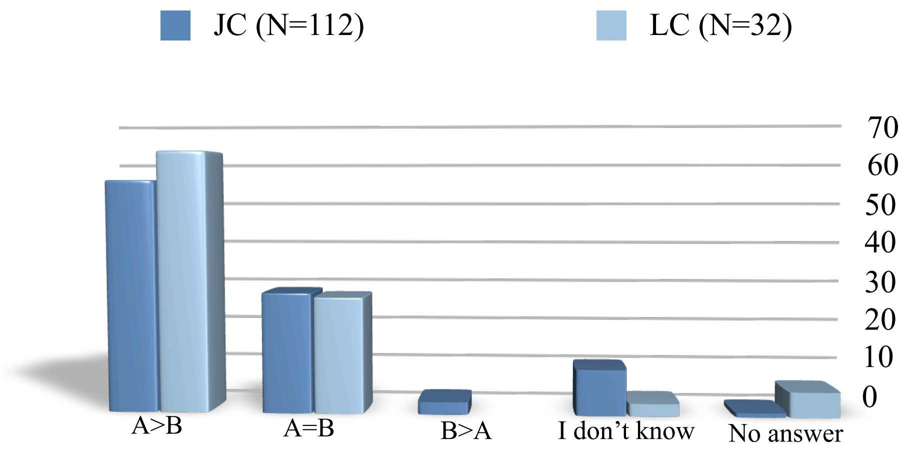


Figure 7.32: Analysis of Qualitative Current Pretest, Question 3.

This question was answered well by both groups but the reasoning used contained many misconceptions. The analysis of students' reasoning for those who correctly ranked bulb A brighter than bulb B is shown in Table 7.31.

Table 7.31: Students' reasoning in answer to Qualitative Current Pretest, Question 3.

Reasoning for A > B	Total % (*N*=63)
Only a single bulb vs two bulbs	45 (28)
Bulb A does not have to share	45 (27)
Bulb A gets more power/current/energy	20 (13)
Bulb C is in the way-obstacle	<5 (1)
No answer	10 (5)

The two most popular reasons highlight some significant misconceptions. Similar to the analysis of the pre-service teacher modules, students relate bulb brightness to the number of bulbs in the circuit. This was also evident in the analysis of the resistance post-test questions discussed previously. The same number of students state that bulb A is brighter than bulb B since it does not have to share (the quantity that is shared generally refers to current but some state power and energy also). This can be identified as an application of a 'used up' model where students believe that bulb A receives all the current while it is shared between bulbs B and C. It also hints at a constant current model where the same current through bulb A is shared between bulbs B and C in Figure 7.29.

The analysis of the reasoning used to support the ranking of bulb A equal in brightness to bulb B is shown in Table 7.32.

Table 7.32: Students' reasoning in answer to Qualitative Current Pretest, Question 3.

Reasoning A=B	**Total % (*N*=33)**
Same current/electricity/energy/power	35 (12)
Same circuit/connections	20 (7)
Both get current first	10 (4)
Same distance from the battery	5 (2)
Other	10 (4)
No answer	15 (5)

The analysis of this pretest highlights some significant misconceptions. The large majority of these have been discussed in Chapter 3 where comparisons have been made with the literature. Although the circuits shown in Figure 7.29 are some of the most simplistic, the analysis shows that students find it very difficult to qualitatively reason the relative brightness of the bulbs. This supports the view that introductory physics courses at secondary and tertiary level do not provide an adequate structure in which a coherent and conceptual model of physics concepts can be developed.

7.6.2 Current: Curriculum Discussion

Students are introduced to current in the first laboratory after they have completed their investigations on complete circuits and conductors and insulators. The opening section introduces students to the assumptions of the model as stated in Chapter 3 and shown below.

(1) There is a flow around a circuit; we will call this flow current.

(2) Bulb brightness indicates the amount of current, an increase in brightness indicates an increase in current.

Students are guided to think of a round trip model in which the flow is continuous throughout the circuit.

The section which follows introduces students to series circuits which are used as a context for guiding students to discover that the current through the battery can change. This particular section has seen some revisions, since we find that the belief that the battery is a constant current source is the most prevalent and one that is difficult to eradicate. The investigation is based on observations of bulb brightness in a single bulb circuit and a two bulb series circuit. The sequence of reasoning that is followed is listed below.

(1) Compare the current through battery 1 and bulb A. We find that most students rank these currents as equal.

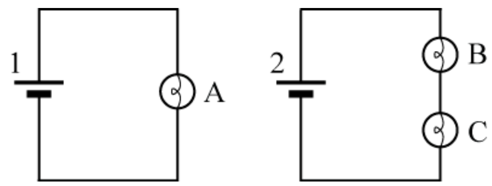


Figure 7.33: A single bulb circuit and a two bulb series circuit.

(2) Compare the brightness of bulb A to bulb B and make an inference about the current through each bulb. Students observe that bulb A is brighter than bulb B. By their model, they must infer that the current through bulb A is greater than that through bulb B.

(3) Compare the currents through bulb B and bulb C. Since students observe that the bulbs are the same brightness, they infer that the currents through each bulb are equal in magnitude. By the round-trip idea, it must be the same current.

(4) Compare the current through bulb B and battery 2. This comparison is one of the key steps in forming a model for series circuits and one that students find difficult. In the context of bulb B and battery 2 only, many students rank the currents through them as equal.

(5) Compare the currents through battery 1 and battery 2. We find that many students can following the reasoning in points 1-4 correctly but still rank the currents through battery 1 and 2 as equal.

As with the resistance laboratory, students confirm their qualitative model with the use of the ammeter. This is obviously a large difference between this curriculum and that of the PbI curriculum. Students begin by measuring the current through a single bulb circuit. They predict what would happen the reading if a bulb is added in series with bulb A. Checking their prediction, students measure a smaller current through the circuit which is consistent with their model. We guide students to measure the current in-between the two bulbs in series and compare the reading to that previously. They discover that the current on each side of the bulb is the same. We hope that this reading may provide some support to the belief that current is not used up.

7.6.3 Qualitative Current: Post-Test and Analysis

Over the two years, a number of questions that examined the students' qualitative model for current were administered. Many of the questions had been given on post-tests for the pre-service teacher modules. At times, our expectations have proved a little ambitious. The analysis looks at two selected questions.

The first question was given as part of the 2008 mid term post-test. It is almost identical to the post-test given to the pre-service teachers in 2005 and 2007 which was discussed in Chapter 3. In similar fashion to the pretest on current, students were asked to determine the brightness of pairs of bulbs rather than asking them to rank the relative brightness of all the bulbs. The question is shown below.

Qualitative Current Post-Test 1

(1) *How will the brightness of bulb A compare to the brightness of bulb B? Explain your reasoning.*

(2) *How will the brightness of bulb B compare to the brightness of bulb D? Explain your reasoning.*

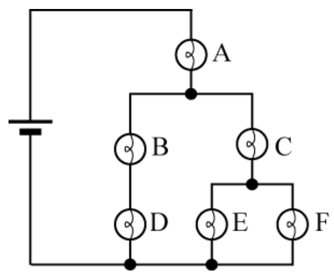


Figure 7.34: Circuit presented in Qualitative Current Post-Test 1.

(3) *Rank the brightness of bulbs C, E and F. Explain your reasoning.*

(4) *Suppose that bulb E in the circuit above is removed. Will the brightness of the following bulbs <u>increase</u>, <u>decrease</u>, or <u>stay the same</u>? Explain your reasoning.*

(a) *Bulb A*

(b) *Bulb C*

The first question asked students to rank the brightness of bulb A relative to bulb B. We expect students to reason that all the current in the circuit flows through bulb A and then splits at the node, resulting in less current through bulb B. This should lead them to rank bulb A brighter than bulb B. This question was answered particularly well with almost 100% of all students providing the correct answer.

In the second question, the students had to rank the brightness of bulb B relative to bulb D. It was hoped that students would recognise that the bulbs were connected in series and thus rank the bulbs with the same brightness. Again this question was answered well, however 30% of the JC student cohort still held on to the misconception that the first bulb in the series connection, in this case bulb B, received more current that the second bulb, bulb D.

Table 7.33: Students' answers to Qualitative Current Post-Test 1, Question 2.

Answer	**JC% (*N*=58)**	**LC% (*N*=6)**
Bulb B = Bulb D	**70 (42)**	**85 (5)**
Bulb B > Bulb D	30 (16)	15 (1)

The analysis of the reasoning used by students in stating that bulb B was brighter than bulb D is shown below in Table 7.34.

Table 7.34: Students' reasoning in response to Qualitative Post-Test 1, Question 2.

Reason	**% (*N*=17)**
As they are connected in series	45 (8)
Bulb B comes before Bulb D	30 (5)
Resistance of B causes D to be dimmer	25 (4)
Current is reduced as it flows through bulb B	10 (2)
Other	10 (2)

The third question asked students to rank the relative brightness of bulbs C, E and F. This particular arrangement of bulbs was quite similar to the arrangement which the students had seen in the laboratories and also in the pretest, as shown in Figure 7.34.

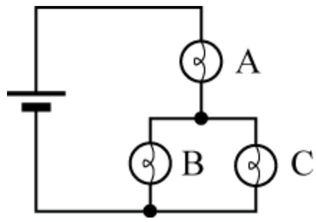


Figure 7.35: Single bulb in series with a two bulb parallel network.

Although the arrangement of bulbs A-C in Figure 7.35 is identical to bulbs C, E and F in Figure 7.34, bulbs C, E and F are contained within a more complicated circuit which makes the comparison more difficult.

The results to this question are shown in Table 7.35.

Table 7.35: Students' answers to Qualitative Current Post-Test 1, Question 3.

Answer	JC% (*N*=58)	LC% (*N*=6)
C>E=F	**80 (47)**	**85 (5)**
C=E=F	15 (8)	0 (0)
E=F>C	<5 (2)	15 (1)
C>F>C	<5 (1)	0 (0)

This question was answered very well with ~80% of each group attaining the correct answer by recognising that the current that flows through bulb C splits evenly at the node, thus less current flows through bulbs E and F. This is a considerable improvement in light of the pretest analysis.

The last question on the exam would again inspect students' understanding of resistance and circuit connections. Students are asked to comment on the change in brightness, if any, to bulb A and bulb C when bulb E is removed from the circuit. It was hoped that students would recognise that the removal of bulb E would increase the resistance of the circuit, since it is connected in parallel and thus lower the current through the battery. Consequently if the current is lowered through the battery, the brightness of bulb A should decrease since all the current that flows through the battery, also flows through bulb A. Unfortunately, many students could not recognise this line of reasoning and many stated that bulb A would not change in brightness. This highlighted that the localist or sequential approach had not been eradicated. The answers are shown in Table 7.36.

Table 7.36: Students' answers to Qualitative Current Post-Test 1, Question 4(a).

Bulb A	JC% (*N*=58)	LC% (*N*=6)
Decreases	**10 (7)**	**0 (0)**
Stays the same	70 (42)	100 (6)
Increases	15 (9)	0 (0)

Similarly, the question related to the change in brightness of bulb C was also poorly answered with only 35% of each group providing the correct answer.

Table 7.37: Students' answers to Qualitative Current Post-Test 1, Question 4(b).

Bulb C	JC% (*N*=58)	LC% (*N*=6)
Decreases	**35 (21)**	**35 (2)**
Increases	35 (20)	15 (1)
Stay the same	30 (17)	50 (3)

Qualitative Current Post-Test 2

As part of the post-test given at Ithaca College (scal and trad groups) and at Dublin City University in 2009, students were given a question which focussed on examining students' qualitative model of electric circuits. Students were asked to compare the brightness of a number of bulbs in the circuits shown in Figure 7.36 as well as commenting on how the brightness of certain bulbs would change when bulb F was removed from the circuit.

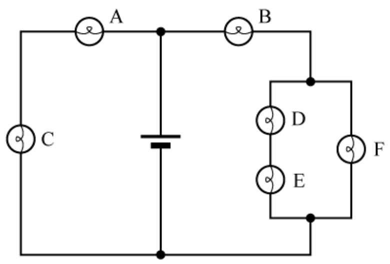


Figure 7.36: Circuit presented in Qualitative Current Post-Test 2 at Ithaca College.

However before the analysis is covered in detail, it must be noted that the post-test given at DCU was presented differently than that given at Ithaca College. The most significant changes were in the layout of the circuit diagram and the ordering of questions. In the DCU post-test the circuit diagram was presented as shown in Figure 7.37.

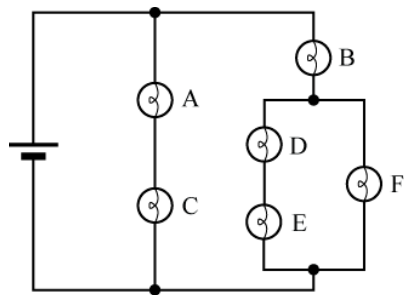


Figure 7.37: Circuit presented in Qualitative Current Post-Test 2 at DCU.

The difference in the ordering of the questions is shown below in Table 7.38.

Table 7.38: Difference in question order between Ithaca College and DCU Qualitative Current Post-Test 2.

Question	Ithaca Question Order	DCU Question Order
Compare Bulb A to Bulb B	Question A	Question D
Compare Bulb D to Bulb F	Question B	Question C
Compare Bulb B to Bulb F	Question C	Question B
What happens bulb B when bulb F is unscrewed?	Question D	Question E
Compare Bulb A to Bulb C	Not asked	Question A

The analysis of students' results follows the question order from the Ithaca College post-test. Therefore the first question deals with how students compared the brightness of bulbs A and B. The results of the analysis provided the data shown below in Table 7.39.

Table 7.39: Students' answers to Qualitative Current Post-Test 2, Question 1.

Question 1	Ithaca Scal (N=67)	Ithaca Trad (N=44)	DCU (N=61)
Bulb A is dimmer than Bulb B	**50 (32)**	**35 (16)**	**45 (27)**
Bulb A is as bright as Bulb B	40 (28)	50 (22)	50 (29)
Bulb A is brighter than Bulb B	10 (7)	15 (6)	10 (5)

In each of the questions students were asked to explain their reasoning afterwards. The reasoning used by students who provided the correct answer was categorised into groups of complete, incomplete and incorrect reasoning. The data is shown in Table 7.40.

Table 7.40: Type of reasoning used in response to Qualitative Current Post-Test 2, Question 1.

Type of Reasoning	Ithaca Scal (N=32)	Ithaca Trad (N=16)	DCU (N=27)
Complete	**40 (12)**	**45 (7)**	**30 (8)**
Incomplete	50 (16)	55 (9)	35 (10)
Incorrect	10 (3)	0 (0)	30 (8)

The answers which were categorised as complete included a reason for why the branch containing bulb A had more resistance or vice versa for bulb B. The answers categorised as incomplete, only stated that there was a difference in resistance between the two branches but did not given a reason for this difference. Examples of answers in each category are shown below.

Complete Reasoning

"Bulb A is dimmer than B b/c A is in series w/ C which increases resistance while B has a parallel circuit after it, so it decreases resistance."

Incomplete Reasoning

"Bulb A is dimmer because there is more resistance in that pathway so less current."

Incorrect Reasoning

"dimmer - bulb A's current is shared w/ bulb C's - Bulb receives all the current after it split at the node"

From Table 7.39 it can be seen that approximately half of each cohort answered the question incorrectly by stating that bulb A was as bright as bulb B. The reasoning used by these students is shown in Table 7.41.

Table 7.41: Students' reasoning used in incorrect answers to Qualitative Current Post-Test 2, Question 1.

Type of Reasoning	Ithaca Scal (*N*=28)	Ithaca Trad (*N*=22)	DCU (*N*=29)
Current splits equally between bulb A and bulb B	45 (12)	55 (12)	15 (5)
Bulbs A and B are in series	20 (5)	10 (2)	10 (3)
Bulbs A and B are in parallel	10 (3)	5 (1)	35 (10)
The have the same current	20 (5)	20 (4)	15 (5)

In the second question on the Ithaca post-test students were asked to compare the brightness of bulb D to bulb F. This is a very similar question to that shown previously where students have to understand that the current splits at the junction according to the resistance in each branch. In conjunction with this, they have to recognise that the series connection of bulbs D and E is more resistive that the single bulb F, thus students should determine that the current through bulb D is less than the current through bulb F. The results of the analysis are shown in Table 7.42.

Table 7.42: Students' answers to Qualitative Current Post-Test 2, Question 2.

Question 2	Ithaca Scal (*N*=67)	Ithaca Trad (*N*=44)	DCU (*N*=61)
Current through Bulb D is less than Bulb F	**95 (63)**	**85 (38)**	**75 (46)**
Current through Bulb D is equal than Bulb F	5 (2)	10 (5)	25 (15)
Current through Bulb D is greater than Bulb F	5 (2)	<5 (1)	0 (0)

Since this question has the potential to be answered correctly on the basis of incorrect reasoning, the reasoning used by the students was examined. The results of this analysis is shown in Table 7.43.

Table 7.43: Type of reasoning used in response to Qualitative Current Post-Test 2, Question 2.

Type of Reasoning	Ithaca Scal (*N*=63)	Ithaca Trad (*N*=38)	DCU (*N*=46)
Complete	**35 (22)**	**25 (9)**	**20 (10)**
Incomplete	60 (37)	70 (26)	15 (6)
Incorrect	10 (4)	10 (3)	65 (30)

Once again, answers which included an explicit reason for why the branch containing bulbs D and E was more resistive were categorised as complete. However, many students only stated that the branch with bulb F was less resistive or vice versa and were thus categorised incomplete. As Table 7.43 shows, there was also a large percentage of students, particularly in the DCU cohort, that used incorrect reasoning. The most common incorrect answer is for students to state that bulbs D and E share the same amount of current which bulb F receives.

For the 25% of DCU students who answered the question incorrectly by stating that bulb D was equal in brightness to bulb F, 50% of those reasoned on the basis that bulb D and F were connected in parallel with each other.

In the third question on the Ithaca exam, students were asked to compare the currents through bulb B and bulb F. From the outset this is viewed as a relatively simple question as it is expected that students recognise that the current through bulb B must split at the node before it enters bulb F, therefore the students should recognise that the current through bulb B is greater than the current through bulb F. For the students at Ithaca College, this line of reasoning was not difficult to recognise however the students at DCU did poorly with 40% of students providing an incorrect answer as shown in Table 7.44.

Table 7.44: Students' answers to Qualitative Current Post-Test 2, Question 3.

Question 3	**Ithaca Scal (*N*=67)**	**Ithaca Trad (*N*=44)**	**DCU (*N*=61)**
Current through Bulb B is greater than Bulb F	**90 (61)**	**95 (41)**	**60 (38)**
Current through Bulb B is less than Bulb F	5 (4)	5 (3)	15 (9)
Current through Bulb B is equal than Bulb F	5 (2)	0 (0)	25 (14)

The type of reasoning used by students who gave the correct answer is shown in Table 7.45.

Table 7.45: Type of reasoning used in response to Qualitative Current Post-Test 2, Question 3.

Type of Reasoning	**Ithaca Scal (*N*=61)**	**Ithaca Trad (*N*=41)**	**DCU (*N*=38)**
Complete	**80 (50)**	**95 (39)**	**70 (27)**
Incomplete	10 (6)	<5 (1)	5 (2)
Incorrect	10 (5)	<5 (1)	15 (6)

Of the 14 DCU students who stated that bulb B is equal to bulb F, a large amount of different reasons were used.

In the last question of the post-test, students had to comment on the change to the brightness of bulb B and bulb E when bulb F was unscrewed. The question is shown below.

Bulb F is unscrewed from its sockets, opening the circuit. (The socket remains in place.) Does bulb B become brighter, dimmer, or stay the same brightness? Explain

It is hoped that students recognise that a parallel branch has been removed from the right hand parallel branch thus increasing its resistance and consequently reducing the current through the branch. This is turn causes bulb B to become dimmer. The results are shown below in Table 7.46.

Table 7.46: Students' answers to Qualitative Current Post-Test 2, Question 4.

Question 4	**Ithaca Scal (*N*=67)**	**Ithaca Trad (*N*=44)**	**DCU (*N*=61)**
Bulb B gets dimmer	**90 (59)**	**75 (32)**	**30 (19)**
Bulb B gets brighter	5 (2)	5 (3)	30 (18)
Bulb B stays the same	10 (6)	20 (9)	35 (22)
Other	0 (0)	0 (0)	5 (2)

The reasoning used by students who provided the correct answer is shown below in Table 7.47.

Table 7.47: Type of reasoning used in response to Qualitative Current Post-Test 2, Question 4.

Type of Reasoning	**Ithaca Scal (*N*=59)**	**Ithaca Trad (*N*=32)**	**DCU (*N*=19)**
Complete	**60 (35)**	**55 (17)**	**40 (9)**
Incomplete	30 (18)	30 (9)	25 (5)
Incorrect	10 (6)	20 (6)	20 (4)

Examples of answers in each category are shown below.

Complete Reasoning

"Bulb B becomes dimmer because now it is in series with D and E. There are less ways for current to travel without F, so resistance increases"

Incomplete Reasoning

"Bulb B becomes dimmer since the resistance in that side of the circuit increases"

Incorrect Reasoning

"bulb B will get dimmer b/c it is now in series with bulbs D and E and so it must share current with them."

In a review of the data shown in Tables 7.39 through 7.47, it is apparent that both groups at Ithaca College performed considerably better than DCU students on the same post-test. The ability of Ithaca students to provide the correct answer supported by complete reasoning was at a level close to that of pre-service teachers who took the more intensive PbI module discussed in Chapter 3. It is also very interesting to note the large number of students in the trad cohort who provided correct answers, although they had not completed the inquiry based labs. After discovering that the scal cohort at Ithaca carried out daily online problems in addition to weekly qualitative homework questions, I felt strongly that these were significant factors in the difference between the answers. Further evidence for the difference in students understanding between Ithaca and DCU students is shown in following section.

7.7 Addressing Current Quantitatively

Although qualitative understanding of circuits is paramount in the labs, students do take quantitative measurements with an ammeter to support their qualitative model. In 2008 we decided to post-test students' ability to provide quantitative values for current through the circuits shown in Figure 7.38. The analysis identified some significant misconceptions. It is interesting to note that the same students performed satisfactorily in qualitative ranking questions. In order to provide an insight on students' ability to assign quantitative values before instruction, we decided to pretest students in 2009 with the same circuits.

7.7.1 Quantitative Current Pretest Analysis

The pretest question which was given at DCU in 2009 is shown below followed by the data analysis. It was also given at Ithaca College (scal group only).

Quantitative Current Pretest

Consider the circuits shown below

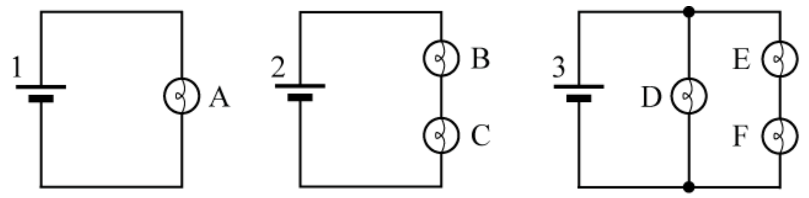


Figure 7.38: Circuits presented in Quantitative Current Pretest 1.

A student takes some measurements on the circuits shown above. She measures a current of 100 mA through bulb A and 70 mA through bulb B. Determine the current through each of the other circuit elements.

Before the results are discussed in detail for each circuit element, I present a brief analysis of the prevalence of correct answers in Table 7.48.

Table 7.48: Breakdown of correct answers to Quantitative Current Pretest.

	Circuit Element						
Correct Answer	**Battery 1**	**Battery 2**	**Battery 3**	**Bulb C**	**Bulb D**	**Bulb E**	**Bulb F**
JC % (*N*=101)	**80 (80)**	**35 (35)**	**10 (12)**	**40 (40)**	**35 (33)**	**30 (31)**	**25 (25)**
LC % (*N*=43)	**95 (41)**	**35 (15)**	**5 (2)**	**35 (16)**	**30 (14)**	**30 (13)**	**20 (8)**
Ithaca % (*N*=66)	**95 (64)**	**5 (3)**	**0 (0)**	**40 (26)**	**35 (22)**	**25 (16)**	**10 (6)**

Almost all students correctly determine the current through battery 1 since the question informs the students that 100 mA is measured through bulb A.

The current through battery 2, is the same current through bulb B, 70 mA, since the circuit contains a single loop. However as the results in Table 7.47 show, only about 35% of DCU students gave the correct answer. Notice the large percentage of students, particularly from the IC scal group who stated that the current through battery 2 was equal to 100 mA, the same value as battery 1. It can only be assumed that students are using a constant current model. This misconception was also evident in the DCU data in addition to the belief that the current is divided or shared between bulbs in series. This is evident when students state the current through battery 2 is twice the amount through bulb B.

Table 7.49: Students' answers for Battery 2 in Quantitative Current Pretest.

Battery 2 Current (mA)	JC % (*N*=101)	LC % (*N*=43)	IC Scal % (*N*=66)
70	**35 (35)**	**35 (15)**	**5 (3)**
100	20 (21)	35 (15)	65 (42)
140	15 (16)	10 (5)	25 (18)
Other	10 (9)	10 (4)	0 (0)
No answer	20 (20)	10 (4)	5 (3)

The reasoning for battery 3 is certainly the most difficult as students must consider a number of concepts. Students must first reason that bulb D is as bright as bulb A and that bulbs E and F are equal in brightness to each other and also equal in brightness to bulbs B and C. This should lead students to reason that the current through bulb D is 100 mA and the current through bulbs E and F is 70 mA, resulting in a combined current of 170 mA through battery 3. The majority of students did not recognise this line of reasoning. The results are shown in Table 7.50.

Table 7.50: Students' answers for Battery 3 in Quantitative Current Pretest.

Battery 3 Current (mA)	JC % (*N*=101)	LC % (*N*=43)	IC % Scal (*N*=66)
170	**10 (12)**	**5 (2)**	**0 (0)**
100	25 (25)	45 (20)	70 (46)
240	10 (8)	5 (2)	10 (5)
Other	20 (22)	20 (10)	10 (6)
No answer	25 (27)	20 (8)	15 (9)
I don't know	10 (7)	5 (1)	0 (0)

For bulb C, students are expected to notice that the current through bulb B is equal to the current through bulb C since they are connected in series. However, many students determine that the current through bulb C is 30 mA. This stems from the belief that the combined current through bulb B and bulb C must be equivalent to that through battery 2, which many have incorrectly determined to be 100 mA.

Table 7.51: Students' answers for Bulb C in Quantitative Current Pretest.

Bulb C Current (mA)	**JC % (*N*=101)**	**LC % (*N*=43)**	**IC Scal % (*N*=66)**
70	**40 (40)**	**35 (16)**	**40 (26)**
30	15 (15)	35 (16)	60 (39)
100	10 (11)	5 (1)	0 (0)
Other	10 (11)	10 (4)	0 (0)
No answer	25 (24)	15 (6)	<5 (1)

The results for bulbs D, E and F were also very poor. Approximately a fifth of each cohort stated that the current through bulb D was 50 mA. Many students incorrectly believe that the current splits evenly between parallel branches, regardless of their relative resistance.

For bulbs E and F, there was a large range of incorrect answers. Small percentages (5%-15%) varied between stating 100 mA, 50 mA and 25 mA. Stating that the current through bulbs E and F was 50 mA results from the misconception stated previously. There was a large variation in the values stated by students who believed that the current is shared or used up between bulbs E and F. The most common pairs were 25 mA each and 35 mA for bulb E and 15 mA for bulb F.

7.7.2 Quantitative Current: Post-Test and Analysis

As stated in the introduction, the investigation of this concept began as a post-test question in 2008. The question given in the 2008 exam was identical to the 2009 pretest question and is shown overleaf.

Quantitative Post-Test 1

Consider the circuits shown below

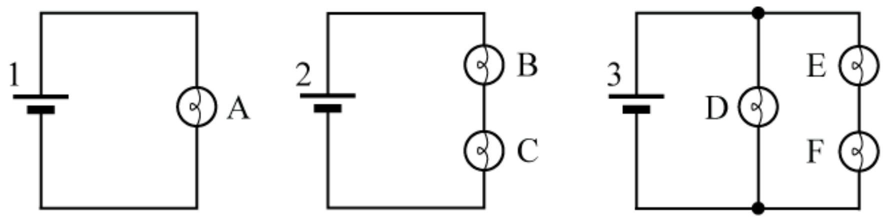


Figure 7.39: Circuits presented in Quantitative Current Post-Test 1.

A student takes some measurements on the circuits shown above. She measures 100 mA through bulb A and 70 mA through bulb B. Determine the current through each of the other elements and state your reasoning.

The breakdown of correct answers is shown in Table 7.52. The analysis shows that in some cases the results are lower than the pretest results.

Table 7.52: Breakdown of correct answers to Quantitative Current Post-Test 1.

	Circuit Element						
Correct Answer	**Battery 1**	**Battery 2**	**Battery 3**	**Bulb C**	**Bulb D**	**Bulb E**	**Bulb F**
JC % (*N*=60)	**95 (58)**	**20 (12)**	**5 (3)**	**55 (34)**	**40 (25)**	**35 (20)**	**25 (16)**
LC % (*N*=7)	**100 (7)**	**0 (0)**	**0 (0)**	**45 (3)**	**0 (0)**	**30 (2)**	**30 (2)**

Since only 20% of JC students and 0% of LC students answered the question for battery 2 correctly, I have displayed the incorrect answers in the Table 7.53.

Table 7.53: Students' answers for Battery 2 in Quantitative Current Post-Test 1.

Battery 2 (mA)	JC % (*N*=60)	LC % (*N*=7)
100	50 (30)	85 (6)
140	25 (14)	15 (1)
Other	5 (4)	0 (0)

On examining the answers of those students who stated that the current through battery 2 was equal to 100 mA, it was discovered that they also stated that the current through battery 3 was equal to 100 mA. The reasoning used in determining the current through battery 2 and battery 3 are categorised in Table 7.54.

Table 7.54: Students' reasoning given in incorrect answers for Battery 2 and 3 in Quantitative Current Post-Test 1.

Reasoning	% (*N*=34)
All batteries are identical	25 (9)
No reference to current through the battery	20 (7)
Derived from current through bulb A	20 (7)
Current through a battery is constant	10 (4)
Stated with no reason	10 (4)
Other	10 (3)

The breakdown of answers for bulb C is shown below.

Table 7.55: Students' answers for Bulb C in Quantitative Current Post-Test 1.

Bulb C (mA)	JC% (*N*=60)	LC% (*N*=7)
70	**55 (34)**	**45 (3)**
30	35 (21)	55 (4)
40	5 (2)	0 (0)
50	5 (3)	0 (0)

Although 55% of the JC students and 45% of the LC students answered the question correctly, the correlation to the current through battery 2 is interesting. The results of this correlation are shown below in Table 7.56.

Table 7.56: Correlation of answers between bulb C and battery 2 for Quantitative Post-Test 1.

Battery 2	% (*N*=37)
70 mA	25 (10)
100 mA	25 (10)
140 mA	45 (16)
Other	5 (1)

From Table 7.56 above, it can be seen that only 25% of students who chose the correct answer for bulb C followed with the correct answer for battery 2. Almost half of these students that stated that the current through bulb C was equal to 70 mA stated that battery 2 was equal to 140 mA. Some of the students' reasons are shown below.

> *"The current of the two bulbs are equal and so B and C are 70mA. When the current of B and C are added together you get the current of battery 2 which is 140."*

> *"As bulbs B and C are in series the current flowing from the battery through is halved therefore batt2 is 140 mA whereas both bulbs B and C are half this giving 70 mA."*

In a similar correlation, of the students who stated that the current through battery 2 was equal to 100 mA, 30% of those also stated that the current through bulb C was equal to 70 mA, which suggests contradictory reasoning. From the analysis of their reasoning it suggests that they completely ignored the reasoning used in determining the current through the batteries or have separate conceptions regarding the current through the bulbs and the current through the battery.

> *"The current that flows through the battery is 100 mA. This will always stay the same. In a single series the bulb has the same current flowing through it as the battery. When bulbs are in series like they are in circuit with battery 2 they will have the same current."*

Further analysis of the students' answers who stated incorrectly that the current through bulb C was 30 mA is shown in Table 7.57.

Table 7.57: Analysis of reasoning used in stating the current through bulb C was equal to 30 mA in Quantitative Current Post-Test 1.

Reasoning	**% (*N*=25)**
Bulb C = 100 mA - 70 mA = 30 mA	70 (17)
As they are in series	15 (4)
B and C in series, increase in resistance, lower current	10 (2)
Stated with no reason	5 (1)
Other	5 (1)

Bulbs D, E and F

The circuit shown on the far right of Figure 7.39 is repeated and shown in Figure 7.40. In this circuit which the students have seen in labs, we expect the students to reason that bulb D would have the same brightness as bulb A and bulbs E and F would have the same brightness as bulb B and C from Figure 7.39.

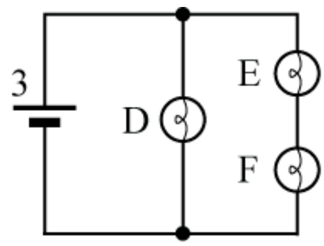


Figure 7.40: Parallel circuit consisting of a branch with a single bulb and a branch with two bulbs in series.

Thus giving them the values of 100mA for bulb D and 70 mA for bulbs E and F. The results are shown in Table 7.58.

Table 7.58: Students' answers for Bulb D in Quantitative Current Post-Test 1.

Bulb D (mA)	JC % (*N*=60)	LC % (*N*=7)
100	**40 (25)**	**0 (0)**
50	25 (16)	70 (5)
70	10 (6)	30 (2)
40	10 (5)	0 (0)
140	5 (4)	0 (0)
Other	5 (4)	0 (0)

Again the reasoning used in determining the current through battery 3 led to a large amount of incorrect answers. Only 40% of the Junior Certificate group provided the correct answer while no student from the Leaving Certificate cohort answered the question correctly.

It can also be seen that a large percentage in each group stated the current through bulb D was equal to 50 mA which although correctly states the splitting of current at the node, it highlights students' misunderstanding of resistance in parallel circuits. An example of a student's answer is shown below.

> *"D is in parallel with E and F so current through battery, 100 mA splits at node 1, 50 mA going to D and 50 mA going to E and F. E and F are in series so E will have a larger current flowing through it than F."*

The answers for bulb E and bulb F were the most inconsistent with a large invariance in current values. In trying to determine the current through these two bulbs, many misconceptions from the previous circuits had been carried through, first of which regarded the equal split of current at the node and secondly the misconception that the two bulbs in series have different amounts of current through them. Only 35% of students answered the question correctly for bulb E while a further decrease was seen for bulb F, with only 25% of students providing the correct answer. The answers can be seen in Table 7.59.

Table 7.59: Analysis of answers for Bulb E and Bulb F in Quantitative Current Post-Test 1.

Bulb E (mA)	**JC % (*N*=60)**	**LC % (*N*=7)**	**Bulb F (mA)**	**JC % (*N*=60)**	**LC % (*N*=7)**
70	**35 (20)**	**30 (2)**	**70**	**25 (16)**	**30 (2)**
30	20 (11)	15 (1)	20	15 (8)	15 (1)
50	15 (9)	0 (0)	50	15 (8)	0 (0)
25	10 (6)	45 (3)	25	10 (7)	45 (3)
40	10 (5)	0 (0)	40	10 (6)	0 (0)
15	5 (3)	0 (0)	30	10 (7)	0 (0)
100	<5 (2)	0 (0)	15	5 (4)	15 (1)
35	<5 (2)	15 (1)	Other	5 (4)	0 (0)
No answer	<5 (2)	0 (0)			

Since the analysis of the pretest and post-test given in 2008 revealed some significant findings, a different quantitative post-test was given in 2009. A small change was made to one of the circuits as shown in Figure 7.41.

Quantitative Post-Test Question 2

Consider the circuits shown below.

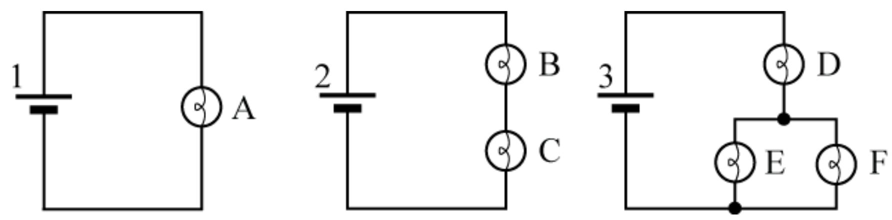


Figure 7.41: Circuits presented in Quantitative Post-Test 2.

A student measures the current through some of the elements shown above. She measures 80 mA through battery 1, 50 mA through bulb C and 60 mA through bulb D.

The reasoning for the single bulb circuit and the two bulb series circuit is identical to previous examples. However, students must use a separate line of reasoning for the circuit containing bulbs D, E and F. Since students are told that the current through bulb D is 60 mA, they are expected to reason that the current through bulbs E and F will be half this value since the current splits equally at the node below bulb D. They should also reason that the current through battery 3 is equal to 60 mA since bulb D and battery 3 are placed along a single path. The analysis of the correct results provided the data shown in Table 7.58.

Table 7.60: Breakdown of correct answers to Quantitative Current Post-Test 2.

Circuit Element	JC Correct % (*N*=44)	LC Correct % (*N*=12)	IC Trad Correct % (*N*=45)	IC Scal Correct % (*N*=71)
Battery 2	**25 (11)**	**35 (4)**	**80 (35)**	**65 (46)**
Battery 3	**15 (7)**	**50 (6)**	**85 (39)**	**70 (50)**
Bulb A	**90 (39)**	**100 (12)**	**100 (45)**	**95 (66)**
Bulb B	**70 (32)**	**75 (9)**	**100 (45)**	**95 (68)**
Bulb E	**60 (27)**	**60 (7)**	**100 (44)**	**90 (65)**
Bulb F	**60 (27)**	**60 (7)**	**100 (44)**	**90 (65)**

In a separate exam in the same year students were given the same circuits and told that the student measured 100 mA through bulb A, 70 mA through bulb B and 40 mA through bulb E. The reasoning for this question is not particularly different from the previous question, since students must follow the same line of reasoning for each of the circuit elements. Students results are shown in Table 7.61.

Table 7.61: Breakdown of correct answers to Quantitative Current Post-Test 3.

Circuit Element	JC Correct % (*N*=47)	LC Correct % (*N*=12)
Battery 1	**100 (47)**	**100 (12)**
Battery 2	**30 (13)**	**15 (2)**
Battery 3	**20 (9)**	**10 (1)**
Bulb C	**65 (31)**	**60 (7)**
Bulb D	**40 (18)**	**15 (2)**
Bulb F	**100 (47)**	**90 (11)**

It is noteworthy that only for bulb D the results are different

In the 2008 mid-term exam, an additional quantitative post-test question was given to a separate group. Instead of presenting this data along with the data relevant to Figure 7.38 on page 208, I have presented it separately here, due to the very surprising results. In this example, students were told that a student measured 140 mA through battery 3 and 80 mA through bulb A in the circuits shown in Figure 7.38.

This was obviously a very difficult question since students would have to base a large amount of their reasoning on the current through battery 3, which has shown to be difficult from previous examples. The student results are presented in Table 7.62.

Table 7.62: Breakdown of correct answers to Quantitative Current Post-Test 4.

Circuit Element	JC Correct % (*N*=49)	LC Correct % (*N*=8)
Battery 1	**60 (30)**	**75 (6)**
Battery 2	**0 (0)**	**0 (0)**
Bulb B	**0 (0)**	**0 (0)**
Bulb C	**0 (0)**	**0 (0)**
Bulb D	**20 (11)**	**40 (3)**
Bulb E	**<5 (1)**	**15 (1)**
Bulb F	**<5 (1)**	**15 (1)**

It was very surprising to see that only 60% of JC students and 75% of LC students determined the current through battery 1 currently, despite being told that the student measured 80 mA through bulb A. When compared to similar examples, this is a considerably lower success rate. Results for other circuit elements were also considerably worse.

7.8 Conclusion

The development of curriculum for the first year undergraduate laboratories at DCU was an enjoyable experience and one which was very motivating. The personal experience of the same traditional labs as an undergraduate, eight years prior to the redevelopment, was a large contributing factor for the motivation of the project.

The findings of our pretest analysis were very similar to that published in the literature and discussed in detail in Chapter 3. Misconceptions such as the belief that the battery is a constant current source and that current is used up in the circuit, were highly prevalent. We found that students' use of misconceptions was independent of the their background. Those who had taken physics at higher secondary level displayed the same difficulties as those who had not.

The development of curriculum was a difficult process. Throughout the development, I faced the challenge of producing curriculum that promotes conceptual understanding, yet adheres to the imposed time constraint. A lot has been learned through the implementations at DCU and at IC and I feel that the project has been successful. Although some of the post-test results highlight areas which the students still find difficult, they also show significant improvement in understanding of specific electric circuits concepts.

The survey carried out at the conclusion of the labs in 2008 provided a pleasing insight to students' perceptions of the labs. Some of the most relevant results are shown are shown in Table 7.63.

Table 7.63: Results to a survey on all electric circuits laboratories.

Statement (*N*=90)	**Strongly agree %**	**Agree %**	**Neutral %**	**Disagree %**	**Strongly Disagree %**
Most of the electric circuits labs were enjoyable	10 (10)	65 (59)	15 (15)	5 (5)	<5 (1)
The labs were generally pitched at too high a level	5 (3)	15 (12)	30 (26)	50 (48)	<5 (1)
I acquired some skills in the electric circuits labs that will be useful in my further studies	10 (7)	65 (59)	15 (13)	10 (9)	<5 (2)
The atmosphere in the physics lab was generally pleasant	35 (32)	55 (51)	5 (6)	0 (0)	<5 (1)

As part of the survey students were asked to make a comment on what they thought was best about the electric circuits labs. Two comments are shown in below.

> *"they made physics a bit more interesting!!"*

> *"The questions were particularly easy to follow and understand for these labs. They followed in a very logical order and made it easier understand what was going on and why."*

The contrast between data gathered at Ithaca College at the DCU was quite stark for both qualitative and quantitative questions. Students at IC performed exceptionally well on qualitative questions considering the amount of time with the concepts. They also made considerable improvements in their ability to determine quantitative values for current through a number of different circuits. We found that these improvements were not as evident in the data gathered at DCU. We intend to implement at DCU online problems and qualitative homework questions similar to those implemented at IC to determine if these are significant factors in the difference in students' answers.

References

1. R. J. Beichner, J. M. Saul, *Introduction to the SCALE-UP (Student-Centered Activities for Large Enrollment Undergraduate Programs) Project*, Paper submitted to the Proceedings of the International School of Physics (Enrico Fermi), Varenna, Italy, 2003.
2. A. H. Johnstone, A. Watt, T. U. Zaman, The student's attitude and cognition change to a physics laboratory, Phys. Educ. **33** (1) 1998.
3. D. M. Shipstone, (1985). 'Electricity in simple circuits' In R Driver, E Guesne & A Tiberghien (Eds.), *Children's ideas in science* (pp. 291-316). Milton Keynes: Open University Press.
4. L. C. McDermott, P. S. Shaffer, *Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding,* Am. J. Phys. **60** (11), 994-1003, 1992.
5. L. Liégeois, G. Chasseigne, S. Papin, E. Mullet, *Improving high school students' understanding of potential difference in simple electric circuits*, Int. J. Sci. Educ. **25** (9) 1129-1145, 2003.

3. L. C. McDermott and the Physics Education Group at the University of Washington, *Physics by Inquiry vol II*, 397 - 405, Wiley, New York 1996.

6. Private communication with Andrew Crouse, Ithaca College.

Chapter 8

First Year Voltage Laboratory

8.1 Introduction

The last concept which is covered by students in the first year laboratories is the concept of voltage. Just as in the traditional PbI course this concept is covered following the concepts of current and resistance. Since the concept takes considerable time to carry out in depth such as that detailed in Chapter 4, a large amount of compromises were made in order to adapt the PbI curriculum to the first year laboratory. The most significant of these compromises was a large dependence on the voltmeter which we felt was necessary in helping form the key rules of the students' model of electric circuits.

8.2 Voltage: Pretest and Analysis

In the two years which the labs were carried out students completed an online pre-test. In the 2008 pre-test we asked students three questions on the concept of voltage, the first of which asked them to describe in their own words, the difference between current and voltage. The analysis revealed that some students provided a description of one concept only while some provided descriptions of both.

When analysing students' descriptions on current it was noticed that almost all students described current as a flow, but answers varied when describing the nature of the flow. It was not surprising to see that approximately half of the students described current as the flow of electricity or the flow of charged particles since this is how current is defined in many secondary school textbooks and in the Junior and Leaving Certificate syllabi[1,2,3].

Table 8.1: Students' descriptions of the concept of current.

Description	**JC % (*N*=65)**	**LC % (*N*=24)**
Current is the flow of charged particles/ charge/electrons	25 (16)	45 (11)
Current is the flow of electricity/ measure of electricity	30 (19)	20 (5)
Current is the flow of power	10 (8)	5 (1)
Current is flow/measure of flow	10 (5)	5 (1)
Energy flowing thru battery/Energy Flow	15 (10)	15 (3)
Relates current to rate/speed/direction	5 (3)	0 (0)
Other	5 (4)	15 (3)

Although there was some form of unity in describing the concept of current, there was a large spectrum of descriptions in describing the concept of voltage. This is not surprising since it is the most intangible and abstract concept. The analysis revealed that many students described voltage as some property of current rather than using the textbook definition as the potential difference between two points or the work done in bringing a charge from point to the other. These findings have been documented by others [4,5,6]. Students' descriptions are shown in Table 8.2.

Table 8.2: Students' descriptions of the concept of voltage.

Descriptions	**JC % (*N*=76)**	**LC % (*N*=27)**
Voltage is related to power/Watts	25 (20)	15 (4)
Voltage is the strength of the current	10 (7)	5 (1)
Measurement of electrical energy/ amount of energy/Strength of energy	10 (8)	15 (4)
Difference in Electric Potential/potential difference	10 (8)	10 (3)
Amount of amps flowing/current/ electrons	5 (5)	0 (0)
Makes current flow	5 (3)	0 (0)
Potential Energy	5 (2)	0 (0)
Drives current through the circuit/Force which pushes current around	5 (2)	15 (4)
Strength of energy in the battery/ strength provided	5 (2)	0 (0)
Electrical Energy per unit charge	5 (2)	0 (0)
Work done in bringing a charge from one point to another	0 (0)	5 (2)
Other	25 (17)	35 (9)

In the second question of the 2008 pre-test, students were asked to rank the values of a number of voltmeters attached across bulbs connected in three different circuits. The question is shown overleaf.

Voltage Pretest 1, Question 2

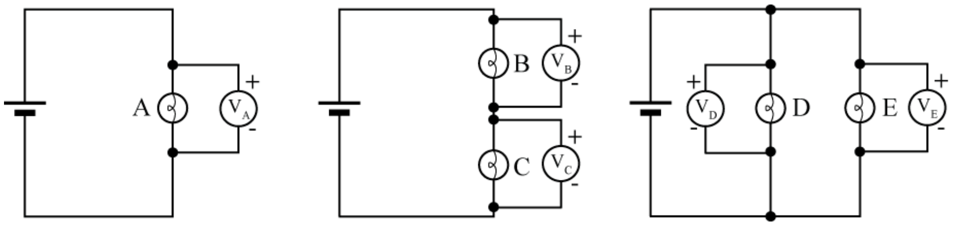


Figure 8.1: Circuit diagrams presented in Voltage Pretest 1, Question 3.

(a) Is the reading on V_A greater than, less than or equal to the reading on V_B?
(b) Is the reading on V_B greater than, less than or equal to the reading on V_C?
(c) Is the reading on V_D greater than, less than or equal to the reading on V_E?
(d) Is the reading on V_A greater than, less than or equal to the reading on V_E?

The first part of the second post-test question asked students to compare the reading on the voltmeter connected across bulb A to the reading on the voltmeter connected across bulb B. The answers for both groups are shown in Table 8.3.

Table 8.3: Students' answers to Voltage Pretest 1, Question 2(a).

Answer	JC % (*N*=89)	LC % (*N*=30)
$V_A > V_B$	**45 (38)**	**55 (17)**
$V_A = V_B$	30 (27)	35 (10)
$V_B > V_A$	10 (10)	5 (2)
I don't know	10 (9)	0 (0)
No answer	5 (5)	5 (1)

It was surprising to see that only half of each group answered the question correctly since the majority of students ranked bulb A brighter than bulb B in the pretest given in the current laboratory. A large number of students also stated in a question, not analysed here, that when voltage of the battery increased, the brightness of the bulb increased. This hints at a sense of ambiguity to students' understanding.

In the second part to the question, students had to compare the reading on the voltmeter connected across bulb B to the reading on the voltmeter connected across bulb C. The results are shown in Table 8.4.

Table 8.4: Students' answers to Voltage Pretest 1, Question 2(b).

Answer	**JC % (*N*=89)**	**LC % (*N*=30)**
$V_B = V_C$	**70 (62)**	**70 (21)**
$V_B > V_C$	10 (8)	15 (5)
$V_B > V_C$	5 (4)	10 (3)
I don't know	10 (10)	0 (0)
No answer	5 (5)	5 (1)

These results shown in Table 8.4 are similar to how students rank the brightness of bulbs in series. Similar results were also revealed for the question on ranking the readings on the voltmeters connected across bulbs in parallel. These are shown in Table 8.5.

Table 8.5: Students' answers to Voltage Pretest 1, Question 2(c).

Answer	**JC % (*N*=89)**	**LC % (*N*=30)**
$V_D = V_E$	**60 (52)**	**80 (24)**
$V_D > V_E$	15 (14)	5 (2)
$V_E > V_D$	10 (7)	5 (2)
I don't know	10 (11)	5 (1)
No answer	5 (5)	5 (1)

In the last question, students had to compare the reading on the voltmeter connected across bulb A to the reading on the voltmeter connected across bulb D. Although students have seen that a single bulb is as bright as a bulb in a parallel branch connected across the battery, only a small percentage of students ranked the readings on the voltmeter equal to each other, as shown in Table 8.6.

Table 8.6: Students' answers to Voltage Pretest 1, Question 2(d).

Answer	JC % (*N*=89)	LC % (*N*=30)
$V_A = V_E$	**30 (27)**	**25 (8)**
$V_A > V_E$	45 (40)	50 (15)
$V_E > V_A$	5 (5)	15 (4)
I don't know	15 (12)	5 (1)
No answer	5 (5)	5 (2)

In the first question on the 2009 voltage pretest students were asked to consider the following student statements in relation to the circuit shown in Figure 8.2.

Voltage Pretest 2, Question 1†

Four students give explanations for the relative brightness of the bulbs in the circuit at right.

Student 1: *"B and C are equally bright but dimmer than A. B and C share the current, but A gets all of it. So A is brighter than B and C."*

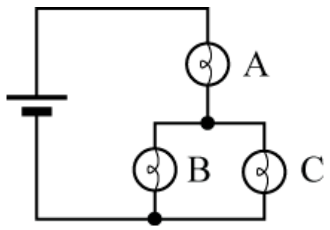


Figure 8.2: Single bulb in series with a two bulb parallel network.

Student 2: *"Bulb A has more resistance than the B-and-C network so bulb A has more voltage across it. Therefore A is brighter than B or C."*

Student 3: *"Bulb A uses up most of the current so less is left for B and C. A is therefore brighter than B or C."*

Student 4: *"After bulb A, the voltage divides into two paths with the result that B and C each get less voltage than A. Therefore A is brighter than B or C."*

With which student(s) do you agree? You may tick more than one box

It is clear from the analysis of students' statements to see that student 1 and student 2 use correct current and voltage reasoning respectively. Since the concepts of current and resistance have been covered prior to this pretest it would be expected that the majority of students would agree with student 1. However since the concept of

† This pretest is adapted from an exercise in the published PbI curriculum.

voltage had not been covered, I did not expect many students to agree with student 2. Student 3 still applies the 'used up' current model which can still be prevalent among some students while student 4 confuses the concept of voltage with current, stating that the voltage divides into two paths. The analysis of students' answers provided the data shown in Table 8.7.

Table 8.7: Students' answers to Voltage Pretest 2, Question 1.

Answer	JC % (*N*=99)	LC % (*N*=47)
Student 1 & 2	**5 (5)**	**10 (5)**
Student 1	30 (28)	25 (11)
Student 1 & 4	20 (22)	35 (16)
Student 4	20 (21)	10 (4)
Student 2	5 (4)	5 (2)
Student 3	5 (4)	0 (0)
Student 3 & 4	5 (4)	<5 (1)
Other	10 (11)	15 (8)

Considering the students inability to differentiate between the concepts of current and voltage, it was not surprising to see that a large number of students agreed with students 1 and 4.

In the second question of the 2009 pretest, students were asked to determine quantitative values of voltages across a number of bulbs in three different circuits in a similar fashion to the quantitative current questions covered in the previous chapter. The question is shown overleaf.

Voltage Pretest 2, Question 2

In the circuits below, all batteries are ideal and identical, and all bulbs are identical.
A student measures a voltage of 10 V across bulb A.
Determine the voltage across the other circuit elements.

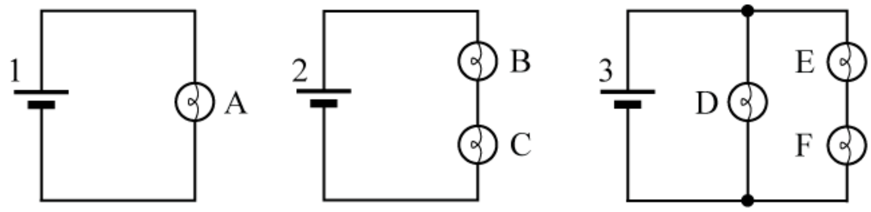


Figure 8.3: Circuit diagrams presented in Voltage Pretest 2, Question 2.

The correct results for each circuit element are shown in Table 8.8.

Table 8.8: Students' answers to Voltage Pretest 2, Question 2.

Circuit Element	**JC % Correct (*N*=99)**	**LC % Correct (*N*=47)**
Battery 1	**95 (94)**	**95 (45)**
Battery 2	**60 (61)**	**65 (30)**
Battery 3	**60 (60)**	**55 (27)**
Bulb B	**50 (49)**	**55 (25)**
Bulb C	**50 (49)**	**55 (27)**
Bulb D	**60 (60)**	**55 (27)**
Bulb E	**50 (47)**	**45 (22)**
Bulb F	**50 (50)**	**50 (24)**

The results show that many students do not recognise that since the batteries are identical, the voltage across the terminals is the same for each battery. The most common incorrect answers for battery 2 and battery 3 were either half or double the value of battery 1, 5 V and 20 V respectively. The failure to determine the voltages across bulbs B-F highlights a lack of understanding of Kirchhoff's loop rule.

8.3 Voltage: Curriculum Discussion

Due to the considerable time constraints imposed by the traditional lab setting, the voltage curriculum for the first year laboratories is vastly different to that discussed in Chapter 4. However, a large effort was made to include as many of the key concepts addressed in the PbI voltage curriculum, as possible. The main concepts which I was focussed on are bulleted below:

- If the voltage across a bulb is increased, the brightness increases. Thus, brightness is an indicator of voltage.
- The voltage across the battery remains constant, regardless of what circuit it is connected to.
- Algebraic rule for voltages in series circuit: $V_{\text{battery}} = V_A + V_B + V_C$
- Algebraic rule for voltages in parallel circuits: $V_{\text{battery}} = V_A = V_B = V_C$
- Kirchhoff's Loop Rule
- Relationship between voltage and resistance

The introduction of the concepts is carried out in a similar fashion to the PbI module where students examine the change in bulb brightness when the voltage across the bulb is changed. Students observe that the brightness of the bulb increases when the voltage across the bulb increases which is what many students would expect considering their pretest results.

Rather than concluding the experiment with this observation, I wanted students to compare the changes in this experiment to the changes in previous experiments. It is hoped that students recognise that this change is different, since they have changed the bulb brightness without adding any bulbs to the circuit. This may help to stimulate thought on the difference between voltage, current and resistance.

Following on from previous experiments, students investigate one of the main concepts in the PbI curriculum which is that voltage of the battery remains constant regardless to any changes made in the circuit. This is obviously a key experiment as it may help some students to overcome the misconception related to the constant current model. We guide students to measure the voltage across the power supply when its connected to a single bulb circuit, a two bulb series circuit and a two bulb parallel circuit. Students discover that the voltage reading on the voltmeter remains constant and are guided to the conclusion that the voltage across the battery remains constant. Upon reflection of this experiment, I realise that although it serves a key purpose, it may not be effective for students who find it difficult to distinguish the difference between voltage and current and in some cases may reinforce the misconception of a constant current model.

Once students have formed a basis for voltage, they investigate voltages in series circuits with the aim of determining a relationship between the voltage across each of the circuit elements. The investigation is carried out in a two-part process where students first investigate a two bulb series circuit and then a three bulb series circuit. In the first of these circuits, students measure the voltage across each of the two bulbs and discover that the voltmeter readings and bulb brightness are equal. Although the curriculum does not explicitly ask students to compare the voltages across the bulbs to the voltage across the battery, at this stage, a small number of students recognise that the values across the bulbs are approximately half of that across the battery. They thus determine that the sum of the voltages across the bulbs equals the voltage across the battery.

For the three-bulb series circuit, we first ask students to predict the voltage across each of the bulbs which although can be done logically from the previous experiment we find that a large number of students make incorrect predictions. This may highlight that, at this stage in the experiment and in spite of the students pretest results on the relationship of voltage and bulb brightness, many students are still uncomfortable with the concept of voltage and thus unable to make educated predictions.

Once students have carried out the experiment correctly, they notice that the voltage across each of the bulbs is approximately equal and a third of the value of the voltage across the battery. Considering student’s difficulty with the concept, we asked them a series of questions which helps them process their observations and data. The first of these questions asks them to determine an algebraic equation between the voltage across the battery and the voltage across each of the bulbs. We find that students generally do not find it difficult to formulate the equation.

To provide some more structure to the students' investigation, we also ask them to complete the table shown in Figure 8.9, where they comment on the effect to the current through each element and the voltage across each element when a third bulb, bulb C was added to the two bulb series circuit. Bulb A and bulb B represent the two bulbs in series.

Table 8.9: Extract of a table that summarises the students' observations for voltages and current in series circuits.

Circuit element	Current through element	Voltage across element
Battery		
Bulb A		
Bulb B		

Although most students do not find it difficult to determine that both the current through and the voltage across bulb A and B decreases, some students still believe that the current through the battery remains the same, which is one of many indicators of how strong some misconceptions are ingrained in students' understanding.

On completion of the investigation of series circuits, students continue with an investigation of voltages in parallel circuits. This section is considerably shorter than that of the series circuit section, however students carry out further investigations in later sections. The sole purpose of the section is to guide students to formulate an algebraic equation for the voltage across a battery connected to two bulbs in parallel. As with the algebraic equation in the series section, students do not find it difficult to formulate.

The penultimate section of the laboratory looks at investigating Kirchhoff's loop rule using the circuit shown in Figure 8.4. At first we ask students to make a prediction of the voltage they should measure across each circuit element. At this stage in the lab students should be able to make an educated prediction of the voltage across the battery and that across bulbs A, B and C, reasoned on the basis that bulb brightness is an indicator of voltage.

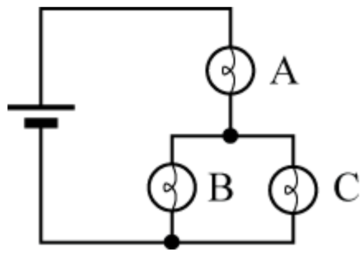


Figure 8.4: Single bulb in series with a two bulb parallel network.

When students make their measurements, they find that the voltage across bulb A is considerably larger than bulbs B and C, which are equal to each other. By guiding students to add the voltages across bulb A and bulb B and bulb A and bulb C, they discover that these values are consistent with Kirchhoff's loop rule.

The last section of the laboratory guides students to investigate the relationship between voltage and resistance by first asking them to rank the relative resistance of each box in the Figure 8.5.

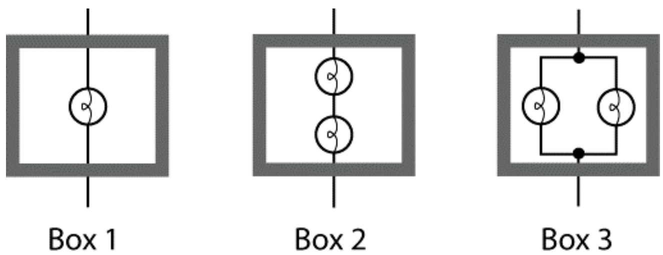


Figure 8.5: Three boxes containing a single bulb, two bulbs in series and two bulbs in parallel.

Although students struggle at this exercise at first, with some guidance they can determine that the resistance of box 2 is greatest, and box 1 is greater than box 3. We then ask them to recall the voltages they have measured across each of the boxes in the circuits shown in Figure 8.6.

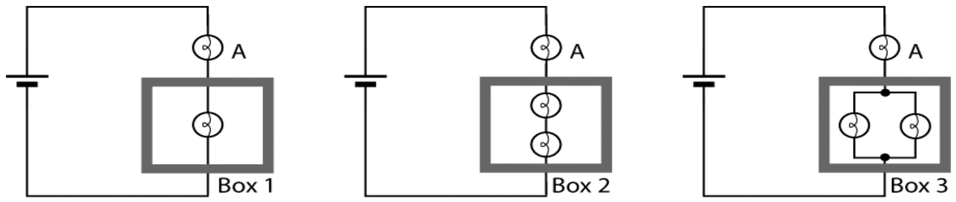


Figure 8.6: Circuit diagrams with the boxes from Figure 8.5 connected in series with a single bulb.

They then rank the relative voltages across the boxes which they discover is the same as the resistance ranking and finally comment on the student conversation shown below.

> ***Student 1:*** *" The voltage across the box increases when the resistance of the box increases"*
> ***Student 2:*** *"When the voltage across a bulb is decreased, the brightness of the bulb decreases."*

To broaden this relationship of resistance and voltage we allow students to investigate the voltage across the bulbs in the circuit shown in Figure 8.7.

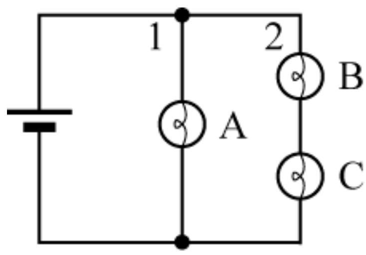


Figure 8.7: Parallel circuit with a single bulb connected across a two bulb series network.

Students discover that changing the resistance of a branch connected across the battery does not effect the voltage across that branch or any other branch connected across the circuit.

The laboratory is concluded with a section that guides students to apply their voltage model in making predictions when a bulb is added in parallel across the battery in Figure 8.8. They also make predictions for when a bulb is added in series with bulb C.

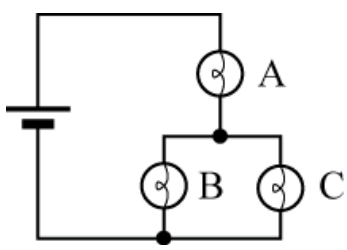


Figure 8.8: Single bulb in series with a two bulb parallel network

8.4 Voltage: Post-Test and Analysis

The post-test questions presented here came from a mix of mid-term and final exams. Two qualitative questions and two quantitative questions are discussed. The first quantitative voltage post-test question was given in 2008 mid-term exam and is identical to the 2009 pretest shown previously.

Quantitative Voltage Post-Test 1

In the circuits below, all batteries are ideal and identical, and all bulbs are identical. A student measures a voltage of 10 V across bulb A. Determine the voltage across each of the other circuit elements.

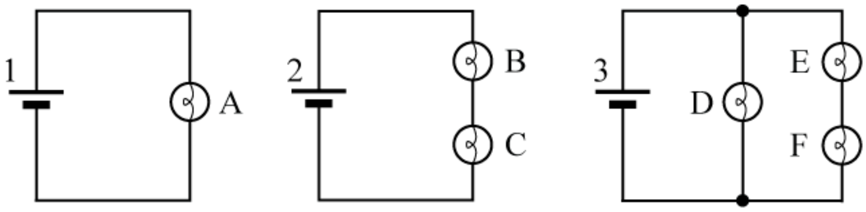


Figure 8.9: Circuit diagrams presented in Quantitative Voltage Post-Test 1.

The analysis of students' answers in Table 8.10 shows an improvement in determining the voltage across each of the three batteries. This improvement is likely to be linked to the investigation where students discover that the voltage across identical batteries is the same, regardless of the type of circuit the batteries are connected to. Similar improvements are also seen in determining the voltage across bulbs B and C.

Table 8.10: Breakdown of correct answers to Quantitative Voltage Post-Test 1.

Circuit Element	JC % Correct (*N*=53)	LC % Correct (*N*=10)
Battery 1	**95 (51)**	**100 (10)**
Battery 2	**85 (44)**	**100 (10)**
Battery 3	**90 (47)**	**90 (9)**
Bulb B	**75 (40)**	**100 (10)**
Bulb C	**75 (40)**	**100 (10)**
Bulb D	**50 (26)**	**80 (8)**
Bulb E	**45 (25)**	**80 (8)**
Bulb F	**45 (24)**	**80 (8)**

Although the results for bulbs B and C are answered reasonably successfully, the results for bulbs D, E and F were answered poorly. We find that approximately 50% of students state that the voltage across bulb D is 5 V and the voltage across bulbs E and F is 2.5 V. These answers hint at the idea that students incorrectly believe that the voltage across the battery is split between the two parallel branches, however correctly state that the voltage is split between bulbs E and F. This also suggests that these students may not differentiate between the concepts of current and voltage and are applying a 'used up' current model.

Similar to the quantitative current questions in 2009, students were also asked an additional quantitative voltage question. The question is shown below.

Quantitative Voltage Post-Test 2

A student measures the voltage across bulbs B and E and measures a value of 5V and 3V respectively. Determine the voltage across each of the other circuits elements.

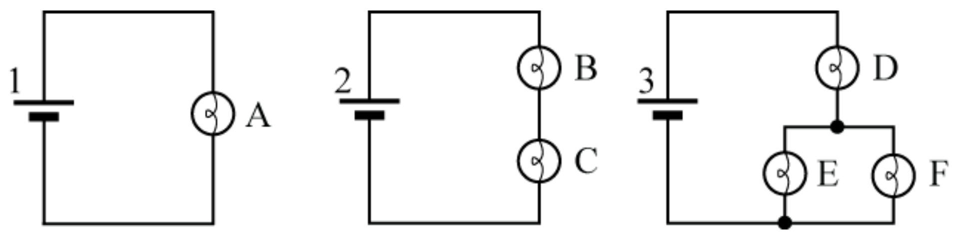


Figure 8.10: Circuit diagrams presented in Quantitative Voltage Post-Test 2.

Unfortunately the results for this post-test question were below the expected level with approximately half of the students determining the correct values. Considering the values presented in the question, it is slightly more difficult than the question presented in 2008. The results are shown in Table 8.11.

Table 8.11: Breakdown of correct answers to Quantitative Voltage Post-Test 2.

Circuit Element	JC % Correct (N=39)	LC % Correct (N=20)
Battery 1	**55 (21)**	**50 (10)**
Battery 2	**55 (21)**	**55 (11)**
Battery 3	**50 (19)**	**45 (9)**
Bulb A	**55 (21)**	**50 (10)**
Bulb C	**70 (27)**	**60 (12)**
Bulb D	**20 (7)**	**30 (6)**
Bulb F	**100 (39)**	**90 (18)**

In analysing the incorrect values for the voltages across each of the batteries, no significant value was dominant. The analysis finds that values of 6 V, 8 V and 9 V were common in similar percentages. One can imagine that some students have added the values provided in the question to yield 8 V. Similarly no dominant incorrect answer was prevalent in the analysis of the voltages across bulbs A, C and D. For bulb A, 20% of students stated the voltage across it was equal to 8 V and 15% stated the value of 6 V, which stem from the incorrect determination of the voltage across battery 1.

The last two voltage post-test which feature in the analysis focussed on students' qualitative understanding of voltage. The first question was asked during the final exam of 2008 which took place eight weeks after students had completed the laboratories. The second question was asked in both years.

The first post-test to be discussed consisted of five short questions and asked students explicitly about the voltage across certain circuit elements. The question is shown overleaf.

Qualitative Voltage Post-Test 1, Part I

(1) How does the voltage across bulb A compare to the voltage across bulb B? Explain your reasoning.

(2) How does the voltage across bulb B compare to the voltage across bulb D? Explain your reasoning

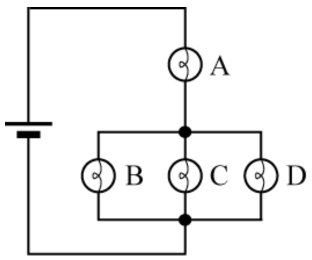


Figure 8.11: Single bulb in series with a three bulb parallel network.

In the first question students were asked to compare the voltage across bulb A to the voltage across bulb B in the circuit shown in Figure 8.11. Examining the circuit, students should be able to determine that the current through bulb A is greater than that through bulb B. Thus they can determine that the voltage across bulb A is greater than that across bulb B since they have seen that bulb brightness is an indicator of voltage. They could also base their reasoning on resistance, where they can determine that the resistance of bulb A is greater than that of bulb B, since bulb B is connected in a parallel network. They have seen that in series circuits the greater the resistance of the element, the greater the voltage across it. Although many of the students provided the correct answer as shown in Table 8.12, the reasoning used was very poor with many students treating voltage in the same manner as current.

Table 8.12: Students answers to Qualitative Voltage Post-Test 1, Question 1.

Ranking	JC % (*N*=42)	LC % (*N*=13)
$V_A > V_B$	**70 (29)**	**75 (10)**
$V_A = V_B$	10 (5)	15 (2)
$V_B > V_A$	10 (4)	10 (1)
Other	10 (4)	0 (0)

In the second question students were asked to compare the voltage across bulb C to bulb D. The analysis of students' answers in Table 8.13 shows that the large majority of students ranked the voltages equal to each other, on the basis that the two bulbs are connected in parallel to each other.

Table 8.13: Students answers to Qualitative Voltage Post-Test 1, Question 2.

Ranking	JC % (*N*=42)	LC % (*N*=13)
$V_C = V_D$	**80 (33)**	**100 (13)**
$V_C > V_D$	10 (4)	0 (0)
$V_D > V_C$	5 (2)	0 (0)
Other	5 (3)	0 (0)

In the second part of the post-test, students were asked three questions which referred to a new circuit.

Qualitative Voltage Post-Test 1, Part II

(3) Is bulb E added to the circuit in series or in parallel to bulb C? How will the addition of bulb E affect the resistance of the circuit? Explain.

(4) Will the voltage across bulb A increase, decrease or stay the same when bulb E is added? Explain.

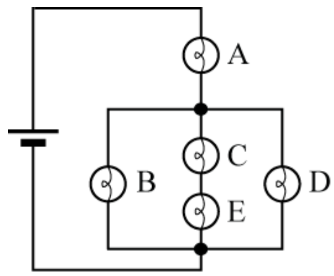


Figure 8.12: Second circuit presented in Qualitative Voltage Post-Test 1.

(5) Will the voltage across bulb B increase, decrease or stay the same? Explain.

The analysis of third question of the post-test highlighted that the majority of students recognised that bulb E was added in series to bulb C. The breakdown of the analysis is shown in Table 8.14.

Table 8.14: Students' answers to Qualitative Voltage Post-Test 1, Question 3.

Answer	2008 JC % (*N*=42)	2008 LC % (*N*=13)
Series	**85 (35)**	**100 (13)**
Parallel	10 (4)	0 (0)
Other	5 (3)	0 (0)

In contrast to the pretest results on the concept of resistance, discussed in Chapter 7, the majority of students recognised that the series connection of bulb E to bulb C increased the resistance of the circuit. The analysis of the students' answers are shown in Table 8.15.

Table 8.15: Students' answers to Qualitative Voltage Post-Test 1, Question 3.

Answer	2008 JC % (*N*=42)	2008 LC % (*N*=13)
Increases	**75 (32)**	**85 (11)**
Decreases	10 (4)	0 (0)
Stays the same	5 (2)	10 (1)
Other	10 (4)	10 (1)

Unfortunately the success in determining how bulb E affects the resistance of the circuit, did not translate to the determining how it would affect the voltage across bulb A. The analysis shown in Table 8.16 highlights that many students apply a localist approach by failing to recognise that a change to one part of the circuit affects the entire circuit. This leads them to state that the voltage across bulb A remains the same.

Table 8.16: Students' answers to Qualitative Voltage Post-Test 1, Question 4.

Answer	2008 JC % (*N*=42)	2008 LC % (*N*=13)
Decreases	**30 (12)**	**25 (3)**
Increases	5 (3)	10 (1)
Stays the same	60 (25)	70 (9)
Other	5 (2)	0 (0)

Similarly, the majority of students failed to determine correctly the change in voltage across bulb B when bulb E was added. Again, a large number of students state that the voltage remains the same which stems from an incorrect generalisation of independent parallel branches. The analysis of students' answers is shown in Table 8.17.

Table 8.17: Students' answers to Qualitative Voltage Post-Test 1, Question 5.

Answer	**2008 JC % (*N*=42)**	**2008 LC % (*N*=13)**
Increases	**15 (6)**	**15 (2)**
Decreases	30 (13)	30 (4)
Stays the same	50 (22)	55 (7)
Other	<5 (1)	0 (0)

In light of the analysis, it must be noted that this post-test question was quite ambitious in the fact that it requires a competent understanding of the use of voltage in modelling circuits. Although the laboratory curriculum covers the concepts addressed in this question, it maybe unreasonable to expect students to fully grasp the concepts, considering their minimal experience and time in the laboratory.

The second qualitative question that is addressed here was presented in an easier setting, however still required a particular level of understanding of the concepts.

Qualitative Voltage Post-Test 2, Question 1

When a student sets up the circuits shown below, she observes that bulb A is brighter than bulb B.

(1) Considering the student's observations, what can you conclude about the voltage across bulb A to the voltage across bulb B? Explain.

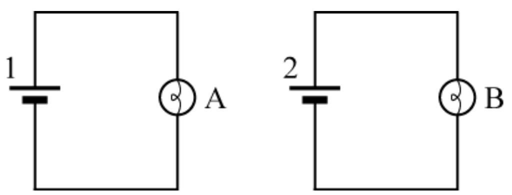


Figure 8.13: Two single bulb circuits with non-identical batteries.

The analysis of students' results show that almost 100% of each cohort answered the question correctly by stating that the voltage across bulb A was greater than the voltage across bulb B. The majority of students' referred to the observation that if the voltage across a bulb is increased, its brightness increases also. The second question of the post-test referred to the addition of a bulb to both circuits as shown in Figure 8.14.

Qualitative Voltage Post-Test 2, Question 2

(2) A second bulb is added to each circuit as shown in the diagram at right. The student notices that bulb A is now equal in brightness to bulb B.

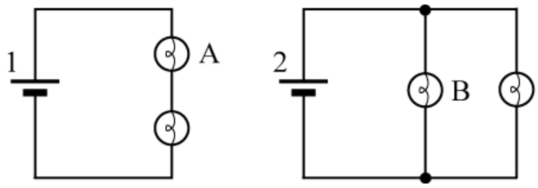


Figure 8.14: A two bulb series circuit and a two bulb parallel circuit with non-identical batteries.

What can you conclude about the voltage of battery 1 in comparison to the voltage of battery 2? Explain.

For this question students are expected to recognise that since the two bulbs are the same brightness, they must have the same voltage across them. Since the voltage across battery 1 is V_0, the voltage across bulb A must be equal to $^1/_2V_0$, as it is connected in series to another bulb. Since bulb B is connected across battery 2, it must have the same voltage as battery 2. Thus the voltage across battery 2 must also be $^1/_2V_0$ since bulb B and bulb A have the same brightness. The analysis of students' answers shows that approximately 40% of each cohort answered the question correctly. A small number of students also stated correctly that the voltage across battery 2 was less than V_0, although this can be derived from the first question.

Table 8.18: Students' answers to Qualitative Voltage Post-Test 2, Question 2.

Answer	2008 JC % (N=69)	2009 JC % (N=45)	2009 LC % (N=11)
$^1/_2V_0$	**35 (23)**	**55 (25)**	**35 (4)**
V_0	25 (16)	15 (6)	10 (1)
$2V_0$	5 (4)	10 (5)	10 (1)
Less than V_0	5 (4)	<5 (1)	20 (2)
Other	30 (21)	20 (8)	25 (3)

In the last part of the question, students had to compare the brightness bulbs A and B when the batteries were placed in opposite circuits.

Qualitative Voltage Post-Test 2, Question 3

(3) *The batteries are now placed in the opposite circuits. How would the brightness of bulb A compare to bulb B? Explain.*

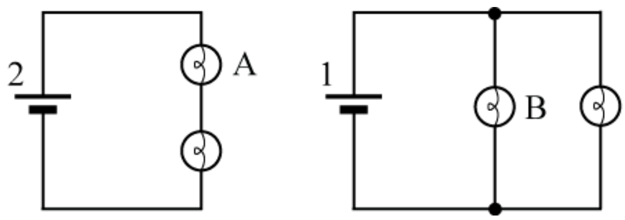


Figure 8.15: A two bulb series circuit and a two bulb parallel circuit with non-identical batteries.

If students have comprehended the information presented throughout the question, they should recognise that bulb A is dimmer than bulb B, as the voltage across bulb A is less than that across bulb B. The analysis of the students' answers revealed that many students make this recognition.

Table 8.19: Students' answers to Qualitative Voltage Post-Test 2, Question 3.

Answer	2008 JC % (*N*=69)	2009 JC % (*N*=45)	2009 LC % (*N*=11)
Bulb B > Bulb A	**70 (47)**	**85 (39)**	**100 (11)**
Bulb A > Bulb B	10 (8)	0 (0)	0 (0)
Bulb A = Bulb B	10 (8)	10 (4)	0 (0)
Other	5 (5)	5 (2)	0 (0)

Similarly to the previous qualitative post-test question, these results are below our expected level. Although when one considers students' backgrounds and the expressed difficulty with the curriculum, some success can be drawn from the results.

8.5 Conclusion

The examination of students' understanding of the concept of voltage before instruction proved fruitful in that it highlighted students' conceptual difficulties. The majority of students found if difficult to differentiate between the concepts of current and voltage which has been noted in other studies. Although students could provide an adequate description of current, very few could provide a conceptual description of voltage. In addition to these findings, many students could not make accurate predictions for voltages across bulbs in simple circuits, which highlighted a poor understanding of Kirchhoff's loop rule.

The process of writing curriculum to overcome these difficulties proved the most difficult task in this part of the project. To comply with the imposed time constraints, many comprises had to be made at the expense of developing students' conceptual understanding of voltage. In each section of the curriculum, a large effort was made to address the key issues that would improve students' ability in applying the use voltage in modelling circuits. The present effort has made some large strides towards an effective curriculum, however further developments are needed.

Evidence to support the redevelopment are found in the unsatisfactory post-test results. In many cases, students have not reached a level where they can reason on the basis of voltage. To address this issue, it has been proposed to extend the curriculum to two laboratory sessions. The difficulty with the curriculum has been expressed by fellow instructors and students. In spite of these findings, at the conclusion of the laboratory, a large number of students stated that they had learnt something and only 15% stated that they did not enjoy the laboratory. The analysis of the survey is shown in Table 8.20.

Table 8:20: Analysis of students' answers in response to a survey given at the end of the Voltage laboratory.

Statement (*N*=275)	**Strongly disagree %**	**Disagree %**	**Neutral %**	**Agree %**	**Strongly agree %**
I enjoyed the Voltage Laboratory	5 (10)	10 (28)	30 (85)	50 (137)	5 (15)
I found the Voltage Laboratory too hard	5 (14)	40 (114)	40 (103)	15 (34)	5 (7)
I learnt something from the Voltage Laboratory	< 5 (5)	5 (12)	15 (46)	70 (186)	10 (25)

Through further revisions, it is hoped that the level of expressed enjoyment in the labs can be matched with a similar level of improvement in students' understanding.

References

1. R. Henly, M. Quirke, *Science Today - Junior Certificate Ordinary and Higher Levels*, CJ Fallon, Dublin, 2007.
2. *Junior Certificate Science Syllabus*, Department of Education and Science, Ireland, online:http://www.education.ie/servlet/blobservlet/jc_science_sy_rev.pdf?language=EN
3. *Leaving Certificate Science Syllabus*, Department of Education and Science, Ireland, online http://www.eduaction.ie/servlet/blobservlet/lc_physics_sy.pdf?language=EN
4. L. C. McDermott, P. S. Shaffer, *Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of student understanding*, Am. J. Phys. **60** (11), 1992.
5. D. Psillos, P. Koumaras, A. Tiberghien, *Voltage presented as a primary concept in an introductory teaching sequence on DC circuits*, Int. J. Sci. Educ. **10** (1), 1988.
6. L. Liegeois, G. Chasseigne, S. Papin, *Improving high school students' understanding of potential difference in simple electric circuits*, Int. J. Sci. Educ. **25** (9) 2003.

Chapter 9

Conclusion

Research has shown that many students fail to form a conceptual model for electric circuits through traditional instruction. The analysis of our pretest data shows that this is true in an Irish context. Physics courses at both secondary and tertiary level in Ireland fail to go beyond providing a superficial understanding of physics. Many students, although competent in memorising physical laws and answering quantitative problems, struggle with the most simplistic qualitative questions on the same topic. With compounding evidence from many different countries, the need for the improvement of physics teaching becomes evident.

This research project centres its focus on the improvement of teacher preparation in the domain of electric circuits. In achieving this objective, much of the work carried out over the last four years has involved the inclusion and revision of Physics by Inquiry modules as part of the pre-service teacher degree programme at Dublin City University. Research has shown that providing a specialised module in which scientific reasoning is addressed in the same context as educational training, improves the effectiveness of teacher training. This research project was concerned with two PbI electric circuits modules, one which addressed the concepts of current and resistance, the other addressed the concept of voltage.

The PbI module on the concepts of current and resistance has proven to been a large success throughout the three years of its implementation. This was the pioneer module of the research project and provided a real insight to the potential that could be attained in providing specialised teacher training modules. The use of inquiry based learning in the area of electric circuits was the first of its kind in the Science Education degree programme at DCU. The investigation of student's understanding through written pretests revealed the majority of misconceptions as outlined in the literature. This highlights that physics modules at second level and at tertiary level in Ireland have failed to address the development of students' conceptual understanding.

Allowing students to work through a process of inquiry where they address each concept in a structured and sequential manner, encourages the development of a coherent understanding of the concepts. Our post-tests analysis has shown considerable improvements in students' understanding with many gaining an expert knowledge of the topics. It is only through this detailed process, that we find that students can grapple with their difficulties and eventually overcome them. Rather than curtailing student's development with the concepts of current and resistance, we also introduced a PbI module on the concept of voltage.

The development of inquiry based curriculum for the concept of voltage formed the largest part of the research project. The first iterations of the curriculum were carried out in the summer of 2006 and it was implemented for the first time as part of the electric circuits module for third year pre-service teachers at DCU. The curriculum proved to be somewhat successful in providing a more qualitative treatment of the concept of voltage but was flawed in some areas. Subsequent revisions in 2007 and 2008 have led to a curriculum which is vastly improved on the original version. By working through the curriculum students discover that the product of current and resistance yields a constant related to the number of batteries, which is later defined as voltage. This investigation encourages students to relate the concept of voltage with the battery. It also leads to two significant conclusions: (1) students discover that the voltage and not current is associated with the battery; this helps students resolve the incorrect belief that a battery supplies current. (2) By developing the concept of voltage in conjunction with the concepts of current and resistance, students can differentiate between current and voltage, which is an ability that many students lack before and after traditional instruction. The implementation of the curriculum at UW and at the University of Maine has supported the effectiveness of the early development.

The investigation of students' understanding of voltage revealed that many students failed to reason correctly on the basis of voltage and relied largely on their understanding of current and resistance. This likely stems from the comprehensive treatment of current and resistance in the module carried out prior to the module on voltage.

The post-tests show that approximately 30% of students who have taken the course gain a complete understanding of the concept. We find that the large majority of the remaining students have overcome many of the difficulties identified in the pretest analysis but fail in linking the concepts together. It is intended that further developments are carried out on the curriculum in the aim to build upon the incremental successes that have been made thus far.

The redevelopment of the first year labs for non-physics undergraduates at DCU formed the second part to the research project. I am very passionate about this redevelopment as I had personally experienced the failings of traditional labs to provide a clear perspective and complete understanding of physics concepts. The focus of the redevelopment was placed on providing labs that cater for the students' background in physics and to also develop them in such a way that students could enjoy carrying out the practicals.

Our research of students' backgrounds highlighted that 75% participating in labs had very minimal experience in physics. Their knowledge of physics concepts was derived from their Junior Certificate Science course taking between the ages of 12 and 15. Due to the large amount of content on the syllabus and the assessment format, emphasis is placed on rote learning rather than conceptual understanding. Physics courses at higher secondary level also display the same traits.

The development of three labs on the concepts of current, resistance and voltage proved to be a success. Within the time constraints of the traditional lab, many of the key concepts dealt with in the PbI modules were addressed in each laboratory. They have been successful in eradicating some student misconceptions and the large majority of students have expressed that they have both enjoyed and learnt something from the labs. This is quite a breakthrough in the light of the views held by students on the traditional labs where many felt that they were too difficult and were not enjoyable. Of course, there were some areas that still needed some improvement. We found that for difficult post-test questions, many students reverted to old misconceptions to answer the questions, a common trait also seen in some post-test questions from the PbI modules.

It is foreseen that future developments will take place on each of the laboratories in addition to tutor training and the introduction of homework problems. The data which was gathered at Ithaca College was remarkable and achieved many of our initial ambitions. It is suggested that the use of qualitative homework problems was significant factor in these results.

The research project has made some large strides towards the development of effective voltage curriculum. It has shown to be successful in addressing voltage in a more qualitative manner and has highlighted an alternative method for the treatment of the concept. It is with much confidence, that I believe subsequent developments will further enhance students' ability to model circuits on the basis of voltage, leading to a complete curriculum for the concept.

Appendix A

Voltage Curriculum for Pre-service Teacher Module

This Appendix contains the curriculum on the concept of voltage and the topics of multiple batteries in multiple loops and RC circuits.

Part C: Voltage

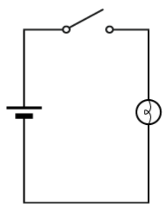
In Parts A and B we developed a number of rules that allow us to make predictions for a number of circuits based on the concepts of current and resistance. However, in a number of circuits we could not predict the bulb brightness. In the following sections we extend the model by adding further rules that allow us to make more complete predictions about simple electric circuits.

Section 7: Circuits with multiple batteries

The next three experiments involve the addition of a battery to an existing circuit.

Experiment 7.1

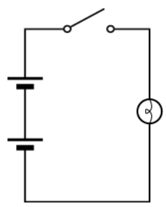
A. Set up a circuit with a switch, a bulb and a battery as shown in the circuit at right. Briefly close the switch and note the bulb brightness.



Insert a second battery into the circuit such that the negative terminal of one battery is connected to the positive terminal of the other as shown in the circuit below.

The second battery is said to be connected *in series*. Is the way is the batteries are connected in series similar to the series connection of two bulbs?

Is this definition consistent with the definition of series connections of bulbs given in Section 4? Explain.



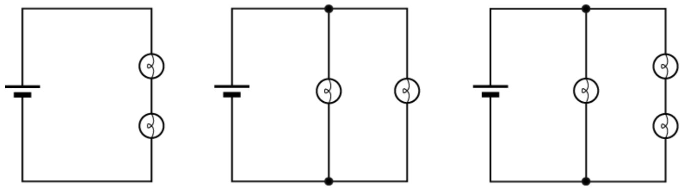
B. Close the switch, and take note of any significant changes in bulb brightness.

Note: Do not leave the switch closed any longer than necessary to make your observation.

Did adding the second battery cause the current through the bulb to increase, decrease, or remain the same? Explain.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

B. Set up each of the circuits below, one at a time. Add a second battery in series with the first battery in each of the circuits below. In each case, take note of any significant changes in bulb brightness when the second battery is added.



C. Consider the following student statements:

Student 1: *"I think that when the second battery is added, the current through the first battery does not change. Each bulb gets the extra current from the second battery, that's why they get brighter."*

Student 2: *"The bulbs get twice as bright, so I think the current through the first battery has doubled."*

Do you agree with any of these students? Discuss with your partner why you agree or disagree with each student. Explain.

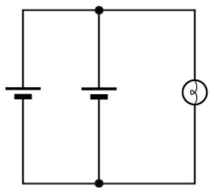
D. Formulate a rule that allows you to predict the change in bulb brightness when a second battery is added in series with another battery.

E. Investigate whether the rules for independent branches we developed in Section 3 for single-battery circuits hold for circuits that contain two batteries in series. Describe the investigation as well as its results.

Experiment 7.2

A. Set up a single-bulb, single-battery circuit.

What do you think will happen when a second battery is added to the circuit such that the positive terminal of one battery is connected to the positive terminal of the other battery and the negative terminal of one battery is connected to the negative terminal of the other, as shown in the circuit at right?



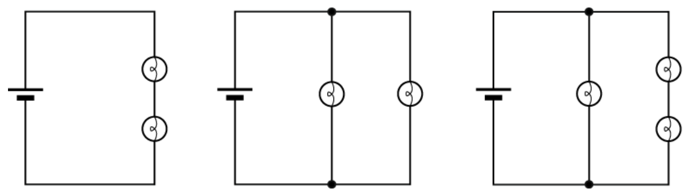
Add the second battery to the circuit. Observe and make note of any significant changes in bulb brightness.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

B. The second battery is said to be connected *in parallel*. Is the way is the batteries are connected in parallel similar to the parallel connection of two bulbs?

Is this definition consistent with the definition of parallel connections of bulbs given in Section 4? Explain.

C. Add a second battery in parallel to the first battery in the circuits below. Take note of any significant changes in bulb brightness.



Do you think the current through the first battery increased, decreased or remained the same when you added the second battery in parallel? Explain.

D. Formulate a rule that allows you to predict the change in bulb brightness when a second battery is added in parallel to another battery.

Do you expect the rules for independent branches to hold when a second battery is added in parallel to another battery?

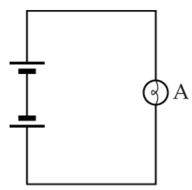
✓ Explain your reasoning to a staff member.

Experiment 7.3

In the circuits shown below, one of the batteries is said to be in *opposite orientation* to the other batteries. When setting up two batteries in opposite orientation make sure that the negative terminal of one battery is connected to the negative terminal of the other.

A. Do you think bulb A in the circuit at right will light?

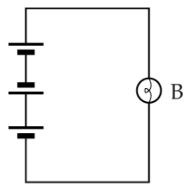
Set up the circuit and check if you were right.



Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

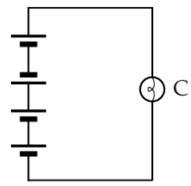
B. Do you think bulb B in the circuit at right will light?

Set up the circuit and check if you were right.



C. Predict if bulb C in the circuit at right will light. If so, how bright do you expect the bulb to be?

Set up the circuit and check your prediction.



D. Formulate a rule that allows you to predict the change in bulb brightness when a battery is added in opposite orientation to another battery or batteries.

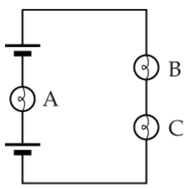
Use this rule to predict how you could connect a single bulb to five batteries in series, including opposite orientation connections, so that the brightness of the bulb is the same as when the bulb is connected to:

- a single battery
- two batteries in series (in the same orientation)

✓ Explain your reasoning to a staff member.

Experiment 7.4

A. Predict the relative brightness of the three bulbs in the circuit at right. Do not set up the circuit yet.



B. Consider the following student dialogue.

Student 1: *"Bulbs B and C are in a parallel branch, and bulb A is in a branch on its own, so bulb A will be brighter."*

Student 2: *"Bulb A gets the current from the bottom battery, and bulbs B and C get the current from the top battery, so bulb A is brighter."*

Do you agree with either student? Explain.

C. Set up the circuit and make note of your observations. Did your prediction match your observation?

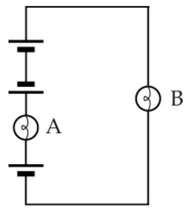
D. Predict what would happen to the brightness of bulb A if bulb C were removed and replaced with a wire.

Check your prediction.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

EC 434 *§7 Circuits with multiple batteries*

Experiment 7.5



A. Predict the brightness of the bulbs in the circuit shown at right. Explain your reasoning. *Do not set up the circuit yet.*

B. Three students are discussing their predictions for the circuit.

Student 1: *"Bulb A will not light. It is connected only to positive battery terminals, so it is not in a complete circuit."*

Student 2: *"I agree. Bulb B is the only one that will light, and it will have the same brightness as a single bulb in a one bulb, one battery circuit."*

Student 3: *"Neither bulb will light since one battery is backwards. Current can't go backwards through a battery."*

Student 4: *"Bulb A is connected in series with bulb B. So A and B are equally bright and as bright as the bulb in a single bulb, single battery circuit."*

Do you agree with any of these students? Discuss with your partners why you agree or disagree with each student. Explain.

C. Set up the circuit and check your prediction. Resolve any conflict between your observations and your predictions.

D. In Section 4 you observed that the order of bulbs or networks of bulbs in a series circuit does not affect the current through the circuit. What do your observations in this experiment suggest about whether or not the way bulbs and batteries are arranged in series affects the current in the circuit? Assume that the orientation of the batteries does not change when circuit elements are rearranged.

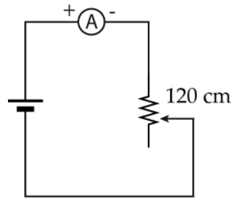
✓ Explain your reasoning to a staff member.

In Experiments 7.1–7.5, we developed a number of rules regarding the addition of batteries to a circuit. We have observed that, when we add a second battery in series to another battery, the bulb brightness increases. We also observed that adding batteries in parallel does not affect bulb brightness. Finally we examined circuits with more than two batteries and observed that when a battery is added in opposite orientation bulb brightness decreases, and that the effect of one battery is effectively cancelled.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

Experiment 7.6

A. Set up a circuit with a battery, a piece of nichrome wire just over 120 cm long, and an ammeter in series as shown at right.



Record the reading on the ammeter when 120 cm of the nichrome wire is in the circuit.

B. Reduce the length of nichrome in steps of 30 cm and record the reading on the ammeter for each decrease in nichrome wire. You should have four readings. Copy the table below into your notebook and fill in your results.

single battery circuit	
length of nichrome wire (cm)	**ammeter reading (mA)**
120	
90	
60	
30	

C. In an experiment similar to that of part B, a student obtains the following results.

single battery circuit	
length of nichrome wire (cm)	**ammeter reading (mA)**
60	200
40	300
30	400
20	600

From this data, infer a relationship between the length of the nichrome wire and the current through it. Express this relationship in the form of an equation.

B. Check if a similar relationship holds (or nearly holds) for the measurements you made on nichrome wire in Experiment 7.6.

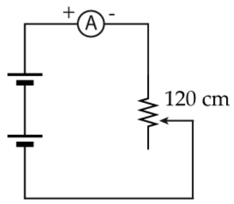
✓ Discuss your answers with a staff member.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

EC 436 *§7 Circuits with multiple batteries*

Experiment 7.7

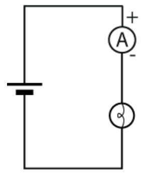
A. Repeat Experiment 7.6, but add a second battery in series as shown in the diagram at right. Make a table as in Experiment 7.6 and enter your results.



B. Does the relationship between the length of nichrome wire and the current through it you found in Exercise 7.6 still hold? If not, how is it different?

Experiment 7.8

Try to make all measurements in this experiment in the same class.



A. Set up the circuit shown at right, and measure the current through the ammeter.

Copy the table below into your notebook and fill in your results. Keep some space to add a third column later on.

single battery circuit		
number of bulbs	**ammeter reading (mA)**	
1 bulb		
2 bulbs in series		
3 bulbs in series		

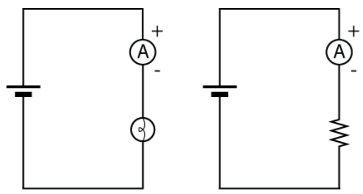
B. Predict the ammeter reading you would expect if you were to add a second bulb in series with the first.

Check your prediction, and add your results in the table.

Replace the two bulbs in series by three bulbs in series and repeat the procedure described above.

C. Consider the two circuits shown at right.

What can you infer about the resistance of each circuit if the two ammeter readings are equal? Explain.



Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

D. Set up Experiment 7.6 again. Find the length of nichrome wire for which the same current flows through the battery as in the single bulb circuit of part A. Add this length to the table above.

What is the resistance of a single bulb? Explain.

What units do you measure this resistance in?

E. Is it possible to predict the resistance of two and three bulbs in series? If so, make your predictions. If not, explain why not.

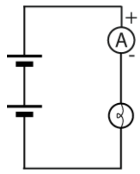
Find the resistance of two and three bulbs in series.

F. Does the relationship between current and resistance you found in Exercise 7.6 hold for bulbs? Explain your answer carefully.

✓ Check your answers with a staff member.

Experiment 7.9

Repeat Experiment 7.8 with two batteries in series instead of one.



Note: Do not leave the bulbs lit any longer than you need to make your observation.

Make a table as in part A of Experiment 7.8 and enter your results.

Are your findings consistent with what you found when you added a second battery to the nichrome wire circuit in Experiment 7.7?

Experiment 7.10

A. In the mathematical relationship you found in Exercise 7.6, a constant should have appeared.

Does the value of the constant seem to depend on the number of batteries in the circuit?

Does the value of the constant seem to depend on any other circuit elements?

What part of the circuit or circuit element do you think this constant is related to? Explain.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

B. Justify the following statement:

"The product of the current through a network connected to a battery and its equivalent resistance appears to be constant."

✓ Explain your reasoning to a staff member.

The data you have tabulated follows a particular pattern. We have noticed that the product of the resistance and ammeter reading is constant as long as the number of batteries is unchanged, and that the constant for the two-battery circuit is about twice that of the single-battery circuit. This seems to suggest that this constant is associated with the battery. The constant is important enough to be given its own name; it is known as the battery's *voltage*. We will use the symbol V_{batt} for the voltage of one or more batteries added in series.

Exercise 7.11

A. Use the information in the paragraph above to determine a mathematical relationship that relates voltage to current and resistance in the circuit.

B. Consider the following student conversation.

Student 1: *"From my observations I can conclude that when I add a second battery in series in the same orientation, the current always doubles."*

Student 2: *"After examining circuits in which a second battery was added in series in the same orientation, I conclude that the voltage always doubles."*

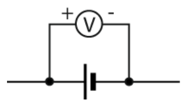
Do you agree with student 1, student 2, neither, or both?

C. If you have not already done so, use your answers to parts A and B above to show that the resistance of a circuit element is not necessarily constant.

✓ Explain your reasoning to a staff member.

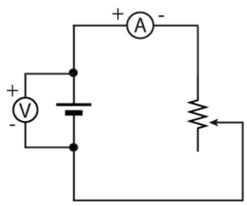
Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

Section 8: Measurement of voltage



We can measure voltage by using an instrument called a *voltmeter*. A voltmeter can be connected as shown in the diagram at right. When the terminals of a voltmeter (usually marked positive and negative) are connected to the corresponding terminals of a battery, a needle on a scale deflects from its zero position. The number obtained from this measurement is expressed in *volts* (V) and is commonly referred to as the voltage of the battery, or more precisely, as the "voltage *across* the battery," or "the *magnitude* of the voltage across the battery."

Experiment 8.1



A. Set up the circuit shown at right. Connect the nichrome wire in such a way that about half of it is in the circuit. To measure the voltage across the battery, connect the positive terminal of the voltmeter to the positive terminal of the battery and the negative terminal of the voltmeter to the negative terminal of the battery.

   Compare the voltage measurement with the voltage rating indicated on the battery. Are these numbers equal or almost equal, or do they differ significantly?

B. Predict what would happen to the ammeter reading and the voltmeter reading if the length of nichrome wire that is in the circuit were increased.

   Check your prediction, and resolves any inconsistencies.

C. Disconnect the voltmeter, and add a second battery in series with the first.

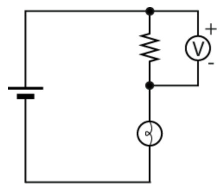
   How would you connect the voltmeter so it will measure the voltage across two batteries connected in series? Check with a staff member before setting up your circuit.

   Connect the voltmeter so that it measures the voltage across the two batteries. How does the number your read on the voltmeter compare with the voltage indicated on the batteries?

   Are your measurements thus far consistent with the properties of the battery voltage you found in Experiment 7.6? Explain.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

EC 440 *§8 Measurement of voltage*



A voltmeter will indicate a voltage not only when it is connected across a battery, but also when it is connected across any circuit element that has current through it.
To measure the voltage across a circuit element, the voltmeter is connected in parallel with it. In the diagram at right, the reading on the voltmeter indicates the voltage across the resistor. When using a voltmeter to measure voltages, we must take certain precautions. A common type of damage results from connecting the leads "backwards" so that the needle is forced downward past zero. Good meters are able to withstand a certain amount of this kind of abuse, but they will eventually be damaged. The positive terminal of a voltmeter should be connected to the terminal of the circuit element that is electrically closest to the positive terminal of the battery. When it is not clear which way to connect the voltmeter leads, connect just one lead, then tap the second lead in place to make a fleeting contact while you are watching the meter. If the needle jumps the wrong way, reverse the leads.

A voltmeter can also be damaged by trying to measure a voltage greater than the meter can indicate. If the maximum voltage on the meter scale is 5 volts and we attempt to measure a voltage of 100 volts, the meter is likely to be irreparably damaged. Just like when you are using an ammeter, it is a good habit always to use the highest voltage scale on the voltmeter first; then, if necessary, to switch to lower voltage scales.

Experiment 8.2

A. Consider a circuit with a bulb, a piece of nichrome wire, and a length of connecting wire all attached in series across the battery. Draw four separate diagrams to show how you would connect a voltmeter to measure:

- the voltage across the battery
- the voltage across the nichrome wire
- the voltage across the connecting wire
- the voltage across the bulb

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

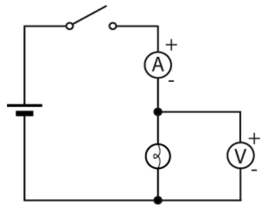
Check with a staff member to be sure that you are planning a procedure that will not damage the voltmeter.

B. Set up the circuit, and make the measurements.

   Does the voltage across some of the elements change when they are placed in a complete circuit? If so, does the voltage increase or decrease?

✓ Explain your reasoning to a staff member.

Experiment 8.3



Set up a circuit with a battery, a bulb, an open switch and an ammeter connected in series. Then connect a voltmeter across the bulb as shown. Before closing the switch, be sure to take necessary precautions to protect the meters.

A. Close the switch. Read the ammeter and voltmeter. Now, remove the ammeter from the circuit. Is the reading on the voltmeter significantly different? Does the brightness of the bulb change significantly?

   What do you infer about the resistance of the ammeter? Is it relatively large or small?

   Explain why it is reasonable to say that, in this circuit, the ammeter measures the current through the bulb.

B. Place the ammeter back in the circuit, and remove the voltmeter. Is the reading on the ammeter significantly different? Does the brightness of the bulb change significantly?

   What do you infer about the resistance of the voltmeter? Is it relatively large or small?

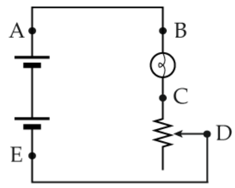
C. Does the presence of the voltmeter or the ammeter, when properly connected to a circuit, significantly affect the conditions in the circuit?

✓ Explain your reasoning to a staff member.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

EC 442 *§8 Measurement of voltage*

Experiment 8.4



Obtain a 60 cm length of nichrome wire and set up the circuit shown.

A. Predict what would happen to the brightness of the bulb when the length of the nichrome wire in the circuit is increased.

Check your prediction.

B. Measure the voltage across AB, BC, CD, DE and AE when there is 20 cm length of nichrome wire in the circuit. What relationships can you find among the voltages?

C. With the voltmeter connected across the batteries (at points A and E), vary the current in the circuit by decreasing the length of nichrome wire in the circuit from 60 cm to 0 cm in steps of 20 cm. Record the voltage at each step in a table like the one below.

Length of nichrome wire	Voltage across batteries	Voltage across bulb	Voltage across nichrome wire
60 cm			
40 cm			
20 cm			
0 cm			

How does the voltage across the batteries vary with increasing current?

What do you observe about the voltage across the batteries as resistance in the circuit is changed?

D. With the voltmeter connected across the bulb, vary the current through the bulb by the method of part B. Record your measurements for the voltage across the bulb in your table.

How does the current through the bulb vary when the voltage across the bulb increases?

E. Repeat the same experiment as in parts B and C, but this time measure the voltage across the nichrome wire. How does the voltage across the nichrome wire vary with increasing resistance in the nichrome wire?

What happens to the voltage across the bulb as the resistance in the rest of the circuit increases?

Hoe does the voltage across the bulb compare with the voltage across the nichrome wire as more resistance is added to the circuit?

How would you summarise the relationships among the voltages in the circuit?

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

F. Formulate an algebraic equation which relates the battery voltage ($V_{battery}$) to the voltages across the bulb (V_{bulb}) and nichrome wire ($V_{nichrome}$).

Does the equation hold for all lengths of nichrome wire you tested?

Formulate an algebraic equation which relates the battery current ($i_{battery}$) to the currents through the bulb (i_{bulb}) and nichrome wire ($i_{nichrome}$).

Does this equation hold for all lengths of nichrome wire you tested?

G. In Section 2, we assumed that we could use bulb brightness as an indicator for current.

Based on your observations so far, does it seem possible that bulb brightness could also be used as an indicator for voltage? Justify your answer.

✓ Discuss your answers with a staff member.

Experiment 8.5

A. Set up a single battery, single bulb circuit, and measure the voltage across the bulb.

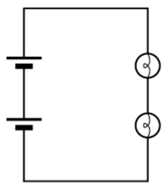
B. Consider the following student statement:

"When a second bulb is added in series, the resistance increases, so the voltage across the two bulbs increases. Therefore, the voltage across each bulb increases, too."

Do you agree with this statement?

Add the second bulb to the circuit, and measure what happens to the voltage across the bulb. Resolve any inconsistencies.

C. Suppose a second battery were added in series to the circuit. Predict how the brightness of the bulbs would compare to the brightness of the single bulb in the single battery circuit of part A. Explain your reasoning.



Check your prediction.

D. How does the current through the bulbs of parts A and C compare? Explain how you can tell.

How do you think the current in a three battery, three bulb series circuit would compare to that of a single battery, single bulb circuit? Explain.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

E. Consider the following statement:

"To predict the brightness of the two bulbs in this circuit compared to the single-bulb single-battery circuit, I don't need to think about voltage. When the second bulb was added, resistance increased, so the current decreased. When the second battery was added, the current increased. The two effects cancel, so the bulbs are equally bright."

Comment on this statement.

✓ Check your results with a staff member.

Exercise 8.6

Two students discuss Experiment 8.5.

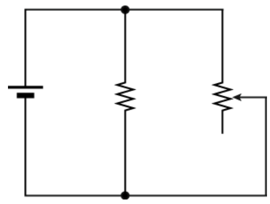
Student 1: *"When the second battery and the second bulb were added, the resistance doubled. That's why the current stayed the same."*

Student 2: *"I disagree. We saw in an earlier experiment that when a second bulb is added in series, the resistance in the circuit increases, but it doesn't double."*

Comment on these statements.

Experiment 8.7

Obtain a 30 cm piece of nichrome wire, and a 40 cm piece that can serve as a variable resistor.



A. Set up the circuit shown at right. Adjust the variable resistor so there is 20 cm of nichrome wire in that branch.

How do you think the voltage across the battery will compare to the voltage across each piece of nichrome wire. Explain your reasoning.

Make the measurements and compare with your predictions.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

B. Move the lead of the variable resistor so there is 40 cm of nichrome wire in the circuit. Predict how the voltage across the battery will compare to the voltage across each piece of nichrome wire in the circuit. Explain.

Make the measurements and compare with your predictions.

How do the voltages across the two nichrome wires in the circuit compare to each other and to the voltage across the battery?

Does changing the resistance of a branch connected directly across a battery significantly affect the voltage across that branch?

Does changing the resistance of a branch connected directly across a battery significantly affect the voltage across another branch?

Is the voltage across the battery significantly affected by changing the resistance of any branch connected directly across it?

C. Insert an ammeter in the branch that contains the 30 cm piece of nichrome wire, and take down the ammeter reading.

Predict what reading you would expect to get if you moved the ammeter to the branch containing the 40 cm wire. Carefully explain your reasoning.

Check your prediction.

D. Predict what reading you would expect to get if you moved the ammeter to the branch containing the battery. Carefully explain your reasoning.

Check your prediction.

E. Use the mathematical relationship you found in Exercise 7.11 to determine the equivalent resistance of the two wires.

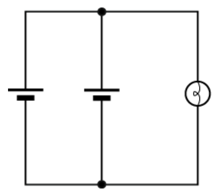
Determine the equivalent resistance of the two wires using the technique you developed in Section 5.

Make sure the two answers in agreement which each other.

✓ Check your answers with a staff member.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

Experiment 8.8



A. Set up a circuit consisting of one battery and one bulb. Measure the voltage across the bulb.

B. Add a second battery in parallel with the first battery as shown in the diagram at right. Measure the voltage across the bulb.

Are your measurements in agreement with the idea that adding a battery in parallel does not affect bulb brightness?

C. Consider the following conversation between two students.

Student 1: *"The brightness of the bulb did not change when I closed the switch, so the same current flows through the bulb as before. Obviously, nothing changed, so there is no current through the second battery."*

Student 2: *"Both batteries are identical and are connected to the circuit in the same way. Therefore the current through both batteries is the same."*

Do you agree with either student? Explain your reasoning.

✓ Check your results with a staff member.

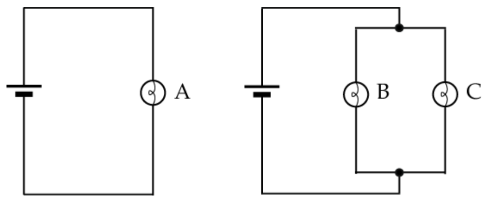
Exercise 8.9

In Exercise 3.8, you modeled electric circuits by formulating a qualitative rule for electric current in terms of the total resistance of a circuit. Extend your model with a rule for voltage in terms of the resistance of two networks within a circuit. Specify how the voltage depends on the arrangement of the networks and on the number of batteries present. Combine all your rules for current, resistance and voltage into one self-contained qualitative model.

✓ Check your model with a staff member.

Exercise 8.10

In this exercise, three students predict and explain the relative brightness of bulbs A, B and C.



Identify which of the students, if any, are reasoning incorrectly, and determine what is wrong with their reasoning. State how you used your model of Exercise 8.9 when finding your answer.

Student 1: *"B and C will be dimmer than A. Bulb A gets all the current from the battery but B and C have to share it."*

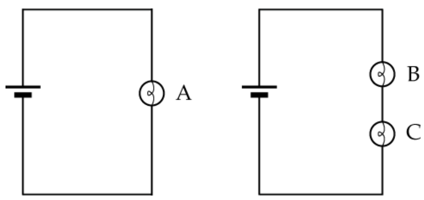
Student 2: *"A, B, and C will all be equally bright. They each have the same voltage across them."*

Student 3: *"Bulbs A, B, and C will all be equally bright. Each bulb has the same resistance, and each is connected directly across the battery, so each bulb has the same amount of current through it. So they are equally bright."*

✓ Check your reasoning with a staff member.

Exercise 8.11

In this exercise, three students predict and explain the relative brightness of bulbs A, B and C.



Identify which of the students, if any, are reasoning incorrectly, and determine what is wrong with their reasoning. State how you used your model of Exercise 8.9 when finding your answer.

Student 1: *"B and C are equally bright but dimmer than A. Bulb A gets all the current but B and C have to share it."*

Student 2: *"B and C are equally bright but dimmer than A. Bulb A gets all the battery voltage but B and C have to share it."*

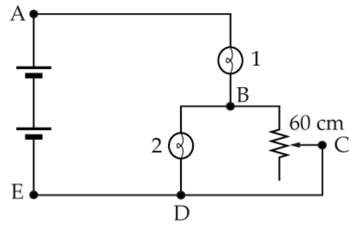
Student 3: *"A is brighter than B, and B is brighter than C. B uses up some of the current so less gets through to C. A gets all the current so it is the brightest."*

✓ Explain your reasoning to a staff member.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

Experiment 8.12

A. Set up the circuit shown at right.



Vary the length of nichrome wire in the circuit, and note how the brightness of each bulb changes.

Based on your observations, how does the voltage across each bulb change when the length of nichrome wire in the circuit increases? Explain.

B. Measure the voltage across AE, AB, BD, and BC with lengths of 0, 20, 40, and 60 cm of nichrome wire in the circuit. Record your measurements in a table like the one below.

Length of nichrome wire	Voltage across batteries	Voltage across bulb 1	Voltage across bulb 2	Voltage across nichrome wire
0 cm				
20 cm				
40 cm				
60 cm				

B. How does the brightness of bulb 1 vary as the voltage across it increases?

C. For each length of wire, can you find a mathematical relationship between the voltages in the circuit?

D. What happens to the resistance of the network of bulb 2 and the wire as the length of nichrome wire in the circuit is increased? What happens to the voltage across this network as its resistance is increased?

E. What happens to the voltage across bulb 1 as the length of nichrome wire in the circuit is increased?

F. Compare your results in this experiment to those you got in Experiment 8.4. Are the results from the two experiments consistent with each other? Explain.

✓ Discuss your results with a staff member.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

We see from Experiments 8.4 and 8.12 how voltages across series and parallel networks are related. If several elements are connected in series to form a network, the voltage across the network is just the sum of all the voltages across the individual elements. If several elements are connected in parallel to form a network, the voltage across each element and the voltage across the network are the same.

These observations lead to a rule for the sum of the voltages across the elements that lie between two nodes in a circuit. This rule is known as Kirchhoff's second rule:

The sum of the voltages across all of the elements along any path is the same for all paths between two nodes.

In the circuit for Experiment 8.12, for example, the voltage across bulb 2 is equal to the voltage across the nichrome wire. Furthermore, the sum of voltages across bulb 1 and bulb 2 is equal to the sum of voltages across bulb 1 and the nichrome wire.

Note that each of these paths can be considered to be in a loop with the battery and that the voltage across each path equals the voltage across the battery. This suggests another way of stating Kirchhoff's second rule:

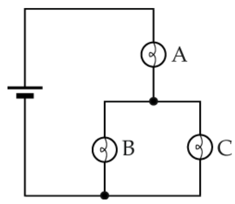
The voltage across the battery or batteries in a current loop is equal to the sum of the voltages across the other elements.

For example, the voltage across the batteries in Experiment 8.12 is equal to the sum of the voltages across bulbs 1 and 2 in loop ABDEA, and also to the sum of the voltages across bulb 1 and the nichrome wire in loop ABCDEA. The two forms of Kirchhoff's second rule that appear above are equivalent. (Kirchhoff's first rule was discussed in Section 5).

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

EC 450 *§8 Measurement of voltage*

Exercise 8.13



In this exercise, four students give explanations for the relative brightness of the bulbs in the circuit at right.

Student 1: *"B and C are equally bright but dimmer than A. B and C share the current, but A gets all of it. So A is brighter than B and C."*

Student 2: *"Bulb A has more resistance than the B-and-C network so bulb A has more voltage across it. Therefore A is brighter than B or C."*

Student 3: *"Bulb A uses up most of the current so less is left for B and C. A is therefore brighter than B or C."*

Student 4: *"After bulb A, the voltage divides into two paths with the result that B and C each get less voltage than A. Therefore A is brighter than B or C."*

Identify which of the students, if any, are reasoning incorrectly, and determine what is wrong with their reasoning.

Exercise 8.14

In Experiment 3.10, you examined the circuit of Exercise 8.13 and were asked to consider how the bulbs would be affected when bulb C is unscrewed.

A. Describe the difficulties you encounter when trying to predict how bulb B is affected using only the model for electric circuits of Exercise 3.8.

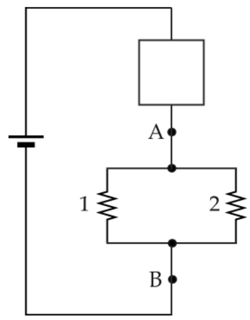
B. Consider how the following quantities change when bulb C is unscrewed and explain your reasoning.
   - the current through bulb A
   - the voltage across bulb A
   - the voltage across bulb B
   - the current through bulb B

C. Explain how your voltage model can be used to predict how the brightness of bulb B changes when bulb C is unscrewed.

✓ Check your results with a staff member.

Exercise 8.15

The diagram at right shows a parallel network in series with a black box that allows current to flow through the circuit.

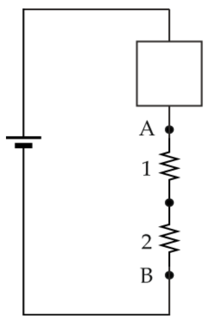


A. For the parallel network shown, let V_1 be the voltage across resistor 1, let V_2 be the voltage across resistor 2, and let V_0 be the voltage across the whole network (from A to B). Write equations to express the relations among these three voltages.

B. For the parallel network shown let i_1 be the current through resistor 1, let i_2 be the current through resistor 2 and let i_0 be the current through the whole network (entering at A and leaving at B). Write equations to express the relations among these three currents.

Exercise 8.16

The diagram at right shows a series network in series with a black box that allows current to flow through the circuit.



A. For the series network shown, let V_1 be the voltage across resistor 1, let V_2 be the voltage across resistor 2, and let V_0 be the voltage across the whole network (from A to B). Write equations to express the relations among these three voltages.

B. For the series network shown, let i_1 be the current through resistor 1, let i_2 be the current through resistor 2 and let i_0 be the current through the whole network (entering at A and leaving at B). Write equations to express the relations among these three currents.

Exercise 8.17

A. Refer to the definitions for series and parallel connections of circuit elements given in Section 4. The definition for a series connection of elements was given in terms of the current passing through the elements. In Exercise 8.16, we found that this definition leads to a simple mathematical relationship between the current through each element. What is this relationship?

B. In Exercise 8.15, we found that a simple mathematical relationship exists between the voltages across elements connected in parallel. What is this relationship?

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

EC
452 *§8 Measurement of voltage*

C. Consider the following statement:

> *"When the voltage across two circuit elements is the same, they must be connected in parallel."*

Do you agree? If not, give an example where the voltages across two circuit elements that are not connected in series are the same.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

Section 9: Ohm's Law

In this section, we examine quantitatively how current, voltage and resistance are related to one another. Specifically, we will find how much voltage is required for a unit of current to flow through a circuit element of a given resistance.

Experiment 9.1

A. Set up a circuit with a single battery and a 60 cm piece of nichrome wire in series with an open switch. Draw a circuit diagram that shows how you would connect an ammeter to measure the current, *i*, through the nichrome wire and a voltmeter to measure the voltage, *V*, across the nichrome wire. Check your diagram with a staff member.

   Measure the current and voltage. Make sure to take the necessary precautions to protect the meters (see Sections 5 and 8.)

B. Make a table for recording measurements for the current through the nichrome wire as the voltage across it is varied (by adding batteries in series). Record your measurements from part A in the table.

   Add a second battery in series with the first. Record the values for the voltage and the current in the table.

   Add a third battery in series with the first two. Record your measurements in the table.

C. Plot the data from your table in a graph of voltage versus current. Label the vertical axis voltage, *V*, and the horizontal axis current, *i*.

   Is the graph straight or curved?

   How would you characterize the relationship between the voltage and current for the nichrome wire?

   Are the voltage and current proportional, inversely proportional, or neither?

   Interpret the slope of your graph.

D. Predict how the graph in part C would look if you had used a 40 cm piece of nichrome wire instead of a 60 cm piece.

   How would the graph have looked if you had used an 80 cm piece instead?

   Check your predictions.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

EC 454 *§9 Ohm's Law*

Experiment 9.2

A. Repeat Experiment 9.1 using a bulb instead of a nichrome wire. Plot the data for the bulb in a separate graph.

B. Contrast the behaviour of the nichrome wire with that of the bulb as the current in the circuit varies.

In Experiments 7.7 and 7.10 you examined how adding bulbs in series affects the equivalent resistance of a network. Are your observations from these experiments consistent with your results from part A above? Explain.

C. Explain why nichrome wire can properly be called a linear resistor.

✓ Check your results with a staff member.

In Experiment 9.1, we found that for nichrome wire the ratio V/i is constant. This ratio is approximately constant for any linear resistor over a wide range of currents and voltages. In Experiment 9.2, we found that for bulbs this ratio is not constant but increases as the voltage across the element is increased.

We have thought of bulbs and nichrome wire as presenting an obstacle, or resistance, to current. We can now make this idea more precise. For nichrome wire and other linear resistors, we can define the resistance R as the constant ratio of voltage across the resistor to the current through the resistor (V/i). This relationship is referred to as *Ohm's Law*. Ohm's Law can be expressed in the form of an equation as follows:

$$V=iR$$

Ohm's Law is fundamentally different from Kirchhoff's rules. Kirchhoff's rules are fundamental statements about the nature of current and voltage. These rules are believed to be exactly true. Ohm's Law, however, is never exactly true and is not viewed as a fundamental relation.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

Exercise 9.3

A commonly used unit for resistance is the ohm (Ω). One ohm is defined as the electric resistance that allows 1 ampere of current to flow when there is a voltage of 1 volt across that resistance.

How many centimetres of nichrome wire correspond to a resistance of 1 Ω? Show your work.

Exercise 9.4

When a certain linear resistor has 90 V across it, there are 15 A through it.

A. How many volts are required for 10 A to flow through the same resistor?

B. What is the current through the resistor if the voltage across it is changed to 33 V?

C. If the voltage across the resistor is doubled, what happens to the current through it?

Explain your reasoning in each case.

Exercise 9.5

In Sections 7, 8 and 9, you have encountered the relationship $V=iR$ several times.

A. What is the meaning of the symbols in $V=iR$ as it applies to a battery (see Exercise 7.11)?

   How do you interpret the formula?

B. What is the meaning of the symbols in $V=iR$ as it applies to a bulb (see Exercise 8.3)?

   How do you interpret the formula in this case?

C. What is the meaning of the symbols in $V=iR$ as it applies to a nichrome wire (see Exercise 9.3)?

   How do you interpret the formula in this case?

✓ Discuss your answers with a staff member.

Part D: Resistors and Capacitors

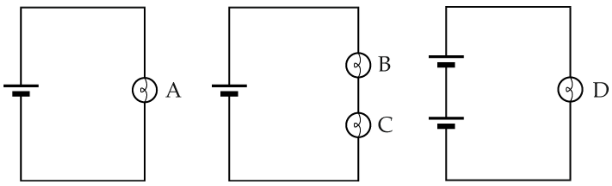
Section 10: Multiple Batteries in Multiple Loops

In Sections 7–9 we examined circuits with multiple batteries that were placed in a single loop.

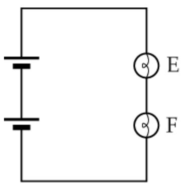
In this section we examine circuits with multiple batteries placed in more than one loop.

Exercise 10.1

A. Consider the three circuits shown below.



How does the brightness of bulbs E and F in the circuit at right compare to the brightness of bulbs A–D in the circuits above? Explain your reasoning.



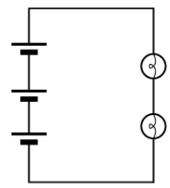
Rank the bulbs A–F according to brightness from brightest to dimmest.

Rank the bulbs A–F according to the voltage across them from highest to lowest. Explain your reasoning.

Experiment 10.2

A. Measure the voltage across each of the batteries and bulbs in the circuit at right.

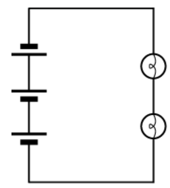
   Check that Kirchhoff's loop rule holds for this circuit.



B. Measure the voltage across each of the circuit elements in the circuit at right.

   Caution: Be sure to connect the leads of the voltmeter correctly for each circuit element.

   What is the sum of the voltages across the bulbs in this circuit?



C. Use Kirchhoff's loop rule to determine how to add voltages of batteries in opposite orientation. Explain your reasoning.

   In Experiment 7.3 you found that when a battery is added in opposite orientation to a battery or number of batteries it effectively cancels one of the batteries. Use your results from this experiment to state this result in terms of voltage.

✓ Discuss your answers with a staff member.

To help us examine circuits with more than one loop, we introduce two new ideas. First, we adopt the convention that current *inside a battery* flows from the negative to the positive terminal *in a single battery* circuit.

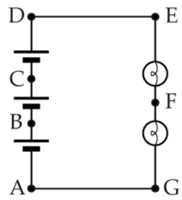
We also introduce a new quantity called *potential*. At each point in a circuit, potential has a certain value. The absolute value of potential is unimportant; what matters is that the *difference* in potential between two points is equal to the voltage measured between these two points. For this reason, the voltage between two points is often called the potential difference. For convenience, one point is often arbitrarily chosen where the potential is set to zero.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

EC
458 *§10 Multiple batteries in multiple loops*

Exercise 10.3

A. The circuit of part A of Experiment 10.2 is shown again at right.



In which direction does the current flow in each of the batteries? Explain your reasoning.

B. A student chooses the potential to be zero at point A. Does this student find that the potential at B is *greater than, less than,* or *equal to* the potential at point A? Explain.

Use your measurements from Experiment 10.2 to calculate the potential at points B, C and D.

C. Use your knowledge of the voltage between points D and E to determine whether the potential at point E is *greater than, less than,* or *equal to* the potential at point D. Explain.

Calculate the potential at point G. Explain your reasoning.

D. Because the potential at any point has a single value, the potential at the starting point must be equal to the potential at the end point when we go around a loop. Considering this, determine the potential at point F. Explain your reasoning.

E. Consider the following student conversation:

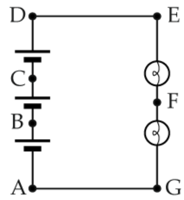
Student 1: *"Current flows from the negative to the positive terminal, so the current flows through both bulbs in the upward direction."*

Student 2: *"Current flows from the negative to the positive terminal inside the battery, so the current flows through both bulbs in the downward direction."*

Do you agree with either student? Explain your reasoning.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

Exercise 10.4



The circuit of Exercise 10.3 is shown again at right.

Choose the potential to be zero at point B.

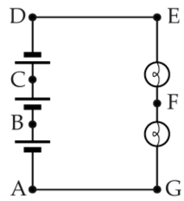
How, if at all, do the values of the potential difference between consecutive points compare to the values you found in Exercise 10.3?

Traverse the loop in the direction of the current, and find the potential at each of the points C, D, E, F, G, and A.

How, if at all, do the values of the potential change at each of the points when the potential is set to zero at point B instead of point A?

✓ Discuss your answers with a staff member.

Exercise 10.5



A. In which direction do you think the current flows through the circuit of part B of Experiment 10.2, shown at right? Explain.

From which terminal to which terminal does the current flow through each of the batteries?

B. Choose the potential at point A to be zero. Determine the potential at each of the points B–G.

C. In order for the potential to return to zero at point A, does the potential *increase, decrease* or *stay the same* when you cross the battery that is connected in opposite orientation? Explain.

Is your answer consistent with your answer to part D of Exercise 10.3? Explain.

D. Consider the following student conversation:

Student 1: *"Based on what I have seen so far, the current inside a battery always flows from the side of lower potential to the side of higher potential."*

Student 2: *"Based on what I have seen so far, the current through a bulb always flows from the side of higher potential to the side of lower potential."*

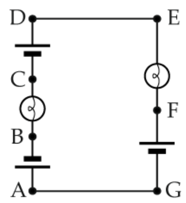
Do you agree with either student? If you disagree with either statement, give an example that shows the statement is false.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

EC 460 *§10 Multiple batteries in multiple loops*

Exercise 10.6

Consider the circuit shown at right in which the voltage of each battery is equal to V_0.



A. In which direction does the current flow through the circuit? Explain.

B. A student chooses the potential at point A to be zero. What value of potential would the student find at points G and F?

Determine the voltage across each of the bulbs and hence determine the potential at point E.

Determine the voltage across each of the bulbs and hence determine the potential at points D, C and B.

✓ Discuss your answers with a staff member.

Exercise 10.7

Write a set of rules that allow you to determine the potential at each point of a single loop circuit, and the direction of the current. Your rules should allow for any ordering of any number of bulbs and batteries, and for both possible orientations of some of the batteries.

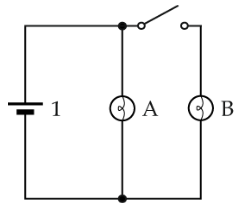
✓ Discuss your answers with a staff member.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

Experiment 10.8

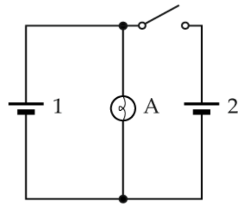
A. In the circuit at right, compare the current through battery 1 and the current through bulb A:

- when the switch is open;
- when the switch is closed.



Which, if any, of the elements in the circuit at right are unaffected by the addition of bulb B? Explain.

B. Bulb B is replaced by battery 2, as shown at right. Two students predict what will happen to bulb A when the switch is closed.



Student 1: *"The potential difference across bulb A will stay the same, so its brightness will not change."*

Student 2: *"I disagree. The outer loop has two batteries in opposite orientation, so there will be no current at all. Bulb A will go out."*

Comment on each statement.

C. Set up the circuit, and check the brightness of bulb A before and after the switch is closed.

Based on your observation, does it appear to be possible to make predictions about multiple loop circuits by considering individual loops? Explain.

Exercise 10.9

Three students discuss Part B of Experiment 10.8.

Student 1: *"When the switch was closed, the current through battery 1 remained the same."*

Student 2: *"When the switch was closed, an extra pathway opened up, so the current through battery 1 increased."*

Student 3: *"I think the current through battery 1 halved. Batteries 1 and 2 were connected to bulb A in the same way, so the same current should flow through each of them."*

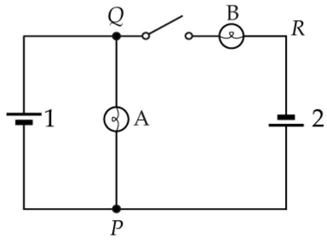
With which student, if any, do you agree? Explain.

✓ Discuss your answers with a staff member.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

EC
462
§10 Multiple batteries in multiple loops

Experiment 10.10



A. Two students predict the relative brightness of the two bulbs in the circuit at right if the switch were closed.

Student 1: *"There is one battery across bulb A, but bulb B has two batteries acting on it. So bulb B will be brighter than bulb A."*

Student 2: *"I don't think so. Bulbs A and B are in series with battery 2, so each bulb gets half the voltage. They will be equally bright."*

Do you agree with either student? Explain.

B. Predict how, if at all, the brightness of bulb A would change when the switch is closed.

Also predict how the brightness of bulb A would compare to the brightness of bulb B.

Set up the circuit to check your predictions.

C. Choose the potential to be zero at one of the three points, *P*, *Q* and *R*. Use your rules from Exercise 10.7 to calculate the potential at each of the other points.

Determine the potential difference across each bulb to explain the relative brightness of the bulbs.

D. Use your rules from Exercise 10.7 to determine whether the current through bulb A flows from top to bottom, or from bottom to top.

Does the current through bulb B flow from left to right, or from right to left?

E. Use Kirchhoff's junction rule to determine the direction of the current through battery 1.

Is the current through battery 1 greater than, less than, or equal to the current through battery 2?

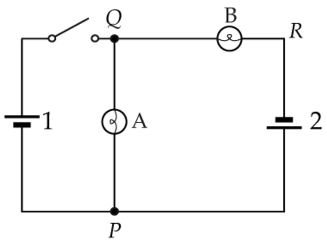
Does the current through battery 1 increase, decrease, or remain the same when the switch is closed?

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

F. In Section 3, you formulated rules for dependent and independent branches.

Based on what you have seen in this experiment, do these rules appear to hold when a battery is included in an *independent* branch? If so, rewrite your rules so that they include the possibility of adding a battery in a branch. If not, explain why not.

Experiment 10.11



A. The switch in the circuit of Experiment 10.10 is moved so that it connects battery 1 to the remainder of the circuit as shown at right.

Predict the relative brightness of bulbs A and B:

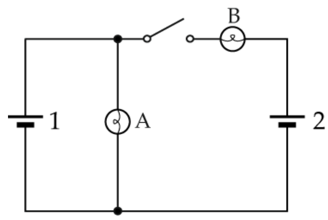
- when the switch is open;
- when the switch is closed.

B. Set up the circuit, and check your predictions.

In Section 3, you found rules for dependent and independent branches. Based on what you have seen in this experiment, do these rules appear to hold when a battery is included in a *dependent* branch? If so, rewrite your rules so that they include the possibility of adding a battery in a branch. If not, explain why not.

✓ Discuss your answers with a staff member.

Experiment 10.12



A. In the circuit of Experiment 10.10, the orientation of battery 2 is reversed as shown at right.

Predict the change in brightness of bulb A and bulb B when the switch is closed.

B. Set up the circuit to check your predictions.

If you have not done so already, apply your rules for potential to explain the observed brightness of the bulbs when the switch is closed.

C. Based on your observations thus far, how does adding a branch consisting of bulbs, batteries or both, in parallel across a single bulb and a battery affect the current through the single bulb?

Does adding the branch affect the current through battery 1?

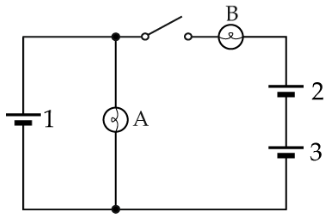
EC 464 *§10 Multiple batteries in multiple loops*

Exercise 10.13

If necessary, adapt your rules for determining the potential and the direction of current to include multiple loop circuits. If not, explain why you don't need to adapt your rules.

✓ Discuss your answers with a staff member.

Experiment 10.14



A. Consider the circuit at right. Predict the relative brightness of the bulbs both when the switch is open and when it is closed.

   Set up the circuit, and check your predictions.

   Does current flow through bulb A from top to bottom or from bottom to top? Explain.

B. Use your knowledge of potential to determine whether the current flows through bulb B to the left or to the right when the switch is closed.

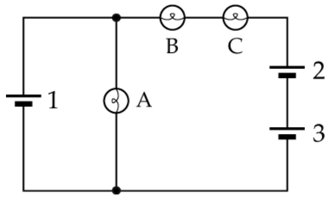
   Through which, if any, of the batteries would the current be from the negative to the positive terminal?

   Through which, if any, of the batteries would the current be from the positive to the negative terminal?

C. Show that your observations, combined with Kirchhoff's junction rule, require that the current though battery 1 be equal to zero.

✓ Discuss your answers with a staff member.

Experiment 10.15



A. Predict the brightness of all three bulbs in the circuit shown at right.

   Set up the circuit and check your predictions.

   Is the current through battery 1 in the upward direction, in the downward direction, or zero?

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

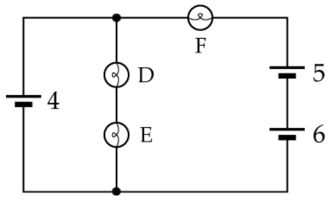
B. Predict what would happen to the brightness of each of the bulbs if battery 3 was placed in the same orientation between the two bulbs in the right branch.

Check your predictions.

C. Predict what would happen to the brightness of each bulb in the original circuit if the orientation of battery 3 were reversed.

Check your predictions.

D. Predict the brightness of all three bulbs in the circuit at right.



Set up the circuit and check your predictions.

Is the current through battery 4 in the upward direction, in the downward direction, or zero? Explain how you can tell from Kirchhoff's junction rule.

E. State a rule that allows you to predict the effect on the voltage across various circuit elements in the circuit of adding in parallel to a battery, a network consisting of a number of bulbs and two batteries in series (in the orientation of the three circuits of Experiments 10.14 and 10.15). Explain your reasoning.

Exercise 10.16

Consider the following conversation between two students.

Student 1: *"When I add a second battery in series with another battery and both have the same orientation, the current through the circuit increases. If I add it in opposite orientation to the first battery, it cancels out one of the batteries."*

Student 2: *"That only seems to work for batteries in circuits within a single loop. When I put a battery across a circuit element, it sometimes no longer appears to increase the current in the circuit. The behaviour of batteries in such circuits is impossible to predict."*

Do you agree with either student? Explain your reasoning.

✓ Discuss your answers with a staff member.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

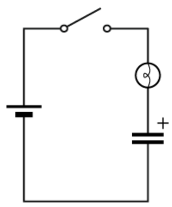
Section 11:Capacitors in single loop circuits

In Section 10, we familiarised ourselves with some of the properties of batteries and bulbs in various circuits. We now encounter a new circuit element, the capacitor, and see how it behaves in a circuit. In circuit diagrams, the symbol we will use for a capacitor is:

Note: Some capacitors have one terminal designated by a "+" or a "–" symbol. The other terminal may or may not have a symbol marked on it. These capacitors may be damaged if they are not connected so that the terminal marked "+" is electrically closer to the positive terminal of the battery than the other terminal.

Experiment 11.1

A. Set up the circuit shown at right.



Before proceeding, check with a staff member that the capacitor is connected correctly.

Close the switch. Describe the behaviour of the bulb immediately after the switch is closed, and during the next few seconds.

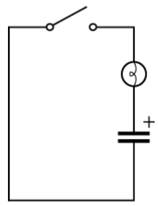
What does this behaviour suggest about the voltage across the bulb after the switch is closed?

What does this suggest about the voltage across the capacitor after the switch is closed?

B. *Just after* the switch is closed in the circuit above, does the capacitor behave like a copper wire, an insulator, an open switch, or a battery? (More than one answer is possible.) Explain your reasoning.

A long time after the switch is closed, does the capacitor behave like a copper wire, an insulator, an open switch, or a battery? Explain your reasoning.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.



C. Open the switch in your circuit, remove the battery and set up the circuit shown at right.

   Based on your previous observations of circuits without a battery, what, if anything, do you expect to happen when the switch is closed? Explain.

D. Close the switch. Describe the behaviour of the bulb immediately after the switch is closed and during the next few seconds.

   What does the behaviour of the bulb imply about the voltage across the bulb after the switch is closed?

   What does this imply about the voltage across the capacitor after the switch is closed?

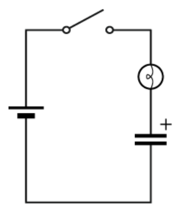
E. *Just after* the switch is closed in this circuit above, does the capacitor behave like a copper wire, an insulator, an open switch, or a battery? (More than one answer is possible.) Explain your reasoning.

   Based on your answer above, revise your answer to part B if necessary.

   A long time after the switch is closed, does the capacitor behave like a copper wire, an insulator, an open switch, or a battery? Explain your reasoning.

✓ Discuss your answers with a staff member.

Experiment 11.2



Set up the circuit at right again. Read all of part A below before carrying out the experiment.

A. Close the switch, and open it again when the bulb's glow becomes too dim to be seen. Record the approximate amount of time that elapses between closing and opening the switch.

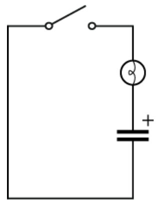
   Wait a little while.

   What do you expect to happen when the switch is again closed? Explain your reasoning.

   Close the switch again and describe the behaviour of the bulb.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

EC 468 *§11 Capacitors in single loop circuits*



Open the switch and remove the battery to construct the circuit at right. Read all of part B before carrying out the experiment.

B. Close the switch and observe the behaviour of the bulb. How does the time it takes for the bulb to go out compare with the corresponding time in the previous circuit?

Open the switch, and wait a little while. What do you expect to happen when the switch is again closed?

Close the switch again and describe the behaviour of the bulb.

C. In what ways does the capacitor in these two circuits behave like a battery? In what ways does it behave differently from a battery?

The process you observed in part A of Experiment 11.2 is called *charging* the capacitor. The process you observed in part B of Experiment 11.2 is called *discharging* the capacitor. A capacitor that behaves like battery in opposite orientation is said to be *charged*; a capacitor that behaves like a wire is said to be *discharged*.

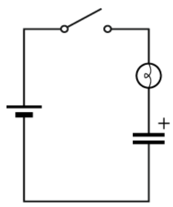
Exercise 11.3

Imagine that you are handed a capacitor without being told whether it is charged or discharged. Devise a test to determine whether the capacitor is charged or discharged.

Is your test destructive? (In other words, does your test change whether the capacitor is charged or discharged? It is OK if it does.)

✓ Discuss your answers with a staff member.

Experiment 11.4

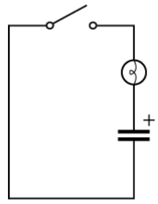


A. Construct the circuit at right. Leave the switch open and the capacitor discharged.

With the switch open, use the voltmeter to measure the voltages across the battery, the capacitor, the bulb, and the switch.

Are your measurements consistent with Kirchhoff's loop rule for this circuit?

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.



B. Close the switch and wait at least twice the time it takes for the bulb to go out. Leave the switch closed. Predict the values you expect to measure for the voltages across each of the four circuit elements.

Measure the four voltages again. Are your measurements consistent with Kirchhoff's loop rule for this circuit?

How does the voltage of the charged capacitor compare with the battery voltage?

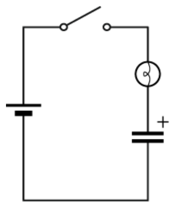
C. Open the switch and wait the same length of time as in part B. Measure the four voltages again.

Are your voltage measurements consistent with Kirchhoff's loop rule?

D. Are your measurements of the voltage across the bulb in parts A, B, and C all consistent with the bulb not being lit?

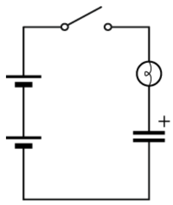
E. Devise a new test to determine whether or not a capacitor is charged. Your test should be nondestructive.

Experiment 11.5



A. Construct the circuit at right. Close the switch to charge the capacitor. Wait at least twice the time it takes for the bulb to go out.

Open the switch; leave the capacitor charged.



In part B, you will add another battery to construct the circuit shown at right. Before doing so, consider the following conversation between three students predicting the behaviour of the bulb in the circuit when the switch is closed.

Student 1: *"I don't think anything will happen, because the capacitor is already charged. We saw before that once a capacitor has been charged, the battery can't push any more current through the bulb."*

Student 2: *"The bulb will do the same thing as in the circuit with one battery. The capacitor acts like one battery in opposite orientation, so the capacitor will be charged again."*

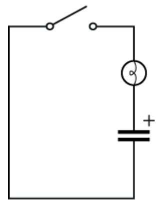
Student 3: *"We saw that a bulb with two batteries is brighter than a bulb with one, so the bulb should start out brighter than it did in the one-battery circuit, and then fade."*

Do you agree with any of these students? Explain your reasoning.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

B. Add a battery to set up the two-battery circuit shown above. Close the switch and describe the behaviour of the bulb. Is its behaviour consistent with your discussion of the three students' statements? If not, resolve any inconsistencies.

C. Open the switch. Remove the batteries from the circuit to construct the circuit at right, with the charged capacitor and the bulb in series with the open switch.



Predict the behaviour of the bulb once the switch is closed. Will the bulb light? If so, will its initial brightness be like a bulb connected to two batteries or like a bulb connected to one battery? Explain.

Close the switch and check your answer.

D. Now construct the two-battery circuit of part A. Make sure that initially, the switch is open and the capacitor is discharged.

Predict the behaviour of the bulb after the switch is closed. In particular, predict how the initial brightness of the bulb will compare to that of a bulb in a circuit with one or two batteries.

Close the switch and check your prediction.

Exercise 11.6

A. Compare the behaviour of a capacitor with that of a battery. Expand your earlier comparison to incorporate the results of Experiments 11.4 and 11.5.

B. Experiment 11.5 suggests that the statement "this capacitor is charged" is incomplete. What additional information should be given to specify the state of charge of a capacitor?

C. Extend your voltage model with a set of rules that describe how a capacitor behaves in a single loop circuit.

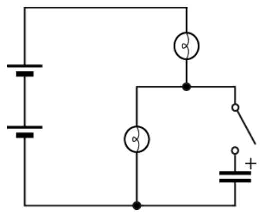
✓ Discuss your answers with a staff member.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

Section 12: Capacitors in parallel circuits

In the previous section we investigated how capacitors behave in series circuits. In this section, we will use this knowledge to predict how capacitors will behave in slightly more complex circuits.

Experiment 12.1



A. Consider the following conversation between three students predicting the voltage across the capacitor in the circuit shown at right, *a long time after* the switch is closed.

Student 1: *"There are two batteries in this circuit, so the voltage across the charged capacitor will be twice the battery voltage."*

Student 2: *"A charged capacitor is not only like a battery in opposite orientation; it is also like an insulator. So the total battery voltage will be divided equally between the two bulbs, and the voltage across the charged capacitor will be the same as that of a single battery."*

Student 3: *"The voltage across the charged capacitor will be the same as that of a single battery, because you can't charge a capacitor any more than that."*

Comment on each of these statements.

B. Set up the circuit. Leave the switch open. Predict what will happen to the brightness of each bulb when the switch is closed.

Close the switch, and check your predictions.

Are any of the student statements in agreement with your observations?

C. Describe how the voltage across the capacitor changes after you close the switch. Explain how you can tell without using a voltmeter.

D. Explain the brightness of the two bulbs a long time after the switch is closed in terms of potential.

✓ Discuss your answers with a staff member.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

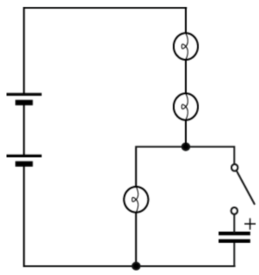
EC 472 *§12 Capacitors in parallel circuits*

Experiment 12.2

A. Set up the circuit shown at right. Leave the switch open.

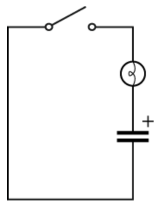
Predict what will happen to the brightness of the three bulbs when you close the switch. Explain your reasoning.

Close the switch, and check your predictions.



B. Open the switch, and remove the left loop to set up the circuit at right. Predict what will happen to the brightness of the bulb when the switch is closed.

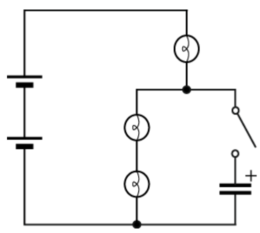
Check your prediction.



C. Set up the circuit shown at right, leaving the switch open.

Predict what will happen to the brightness of the three bulbs when you first close, and then open the switch. Explain your reasoning.

Close the switch, and check your predictions.



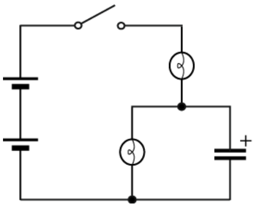
D. Extend your model of Exercise 11.6 to incorporate the behaviour of capacitors in multiple loop circuits.

✓ Discuss your answers with a staff member.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

Experiment 12.3

A. Set up the circuit at right with a discharged capacitor. Leave the switch open.

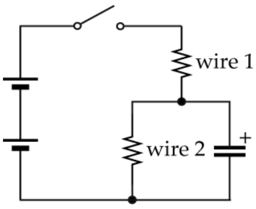


Obtain a voltmeter, and measure the total battery voltage (in other words, the voltage across the network of the two batteries).

Predict what will happen to the voltage across the capacitor when you close the switch, and when you open it again after the capacitor is charged. Explain your reasoning.

Check your predictions.

B. Set up the circuit shown at right. Make sure the capacitor is discharged and the switch is open. Use two 60 cm long pieces of nichrome wire.



Predict what will happen to the voltage across the capacitor when you close and then open the switch. Check your predictions.

Take note of the approximate amount of time it takes for the capacitor to discharge.

C. Replace wire 1 with a 20 cm long piece of nichrome wire.

Predict what will happen to the voltage across the capacitor when you close and then open the switch. Indicate what you think will be the same, and what will be different, from charging and discharging the capacitor in part B.

Check your predictions.

Compare the time it took the capacitor to discharge to your answer in part B.

D. Could you use the circuit of part B to investigate how the discharging time of a capacitor varies with the initial voltage across it? If so, state how you would do this. If not, explain why it is not possible.

✓ Discuss your answers with a staff member.

Developed by the Physics Education Group at CASTeL, Dublin City University, 2005–2008.
Based on: Lillian C. McDermott and the Physics Education Group, *Physics by Inquiry,* John Wiley & Sons, 1996.

Appendix B

Curriculum for First Year Undergraduate Physics Laboratories

This Appendix contains the curriculum developed for first year undergraduate physics laboratories. It includes three separate laboratories on the concepts of current, resistance and voltage.

Name: ______________________________________ **Class:** ______

Experiment 1: Current

In the next four experiments, you will develop a model for electric circuits. The development of your model will always be guided by the observations you make. All reasoning you do to make predictions should be based on your model only, not on prior knowledge of electric circuits.

In today's experiment you will begin your investigation of electric circuits and some of their properties. The experiment will begin with the basics of electric circuits and through investigations you will begin to develop your understanding of simple resistive circuits.

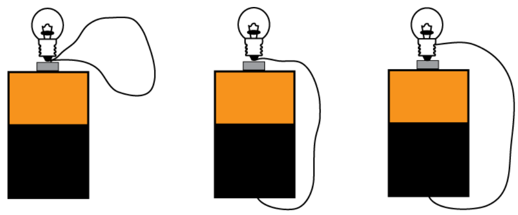
Make sure you check your answer with a tutor when asked to do so.

Equipment/Apparatus check

Check that you have at your disposal: a battery, a bulb and a single wire.

Section 1: Complete Circuits

i. Consider the three arrangements of a battery, a bulb and a wire in Figure 1.1 below. Predict if the bulb will light in which, if any, of the arrangements. Enter your predictions in the middle column of Table 1.1 below.



(1) (2) (3)

Figure 1.1: Arrangements of a battery, a bulb and a wire.

Table 1.1: ____

Arrangement	Prediction: (on/off)	Observation (on/off)
1		
2		
3		

ii. Connect the battery, bulb and wire as shown in the diagrams above, and verify your predictions. Enter your observations in Table 1.1 above.

WARNING: Some arrangements may cause the wire to get hot.

iii. Comment on the differences between your predictions and your observations, if any.

____

____

____

____

iv. There are three other arrangements of a single battery, bulb and wire in which the bulb lights. Focussing on the arrangement in Figure 1.1 that allows the bulb to light, find three other arrangements in which the bulb lights and sketch these in the space below.

v. How do the arrangements in which the bulb lights differ from those in which the bulb fails to light? How are they similar?

Hint: Consider the parts of the bulb, wire and battery which are used in the arrangements which allow the bulb to light and the ones which don't.

____

____

____

____

The arrangements of a battery, a bulb, and a wire in which the bulb lights is said to be a **closed electric circuit.** This arrangement can also be referred to as a **complete circuit,** or just a **circuit.**

vi. Explain in your own words why this is a sensible name. Refer to the arrangements in which the bulbs lit, and to those in which the bulb did not light.

____

____

____

____

Section 2: Conductors and Insulators

In the previous experiment you arranged a battery, bulb and wire in such a way that the bulb lights. In the next experiment we will investigate the effects that different materials have on an electric circuit.

Equipment/Apparatus check

Retain the equipment from Section 1 and obtain a small bag of equipment from a tutor that contains a battery holder, two bulb holders, three extra wires, an extra bulb, a small piece of paper, an elastic band, a crocodile clip and a Fahnstock clip.

i. Use the battery, battery holder, bulb, bulb holder and two wires to set up the circuit shown in Figure 2.1a below. This we will call a **single bulb circuit.**

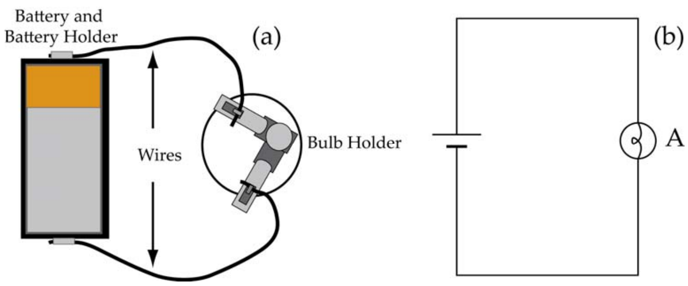


Figure 2.1: (a) Single bulb circuit and (b) corresponding circuit diagram.

Tip: To place the wire on the battery and bulb holder, press down on the inner end of the Fahnstock clip, place the wire through the gap and then release.

Throughout your work in electric circuits you will encounter many circuit diagrams. The circuit diagram for the single bulb circuit is shown in Figure 2.1b above. This circuit diagram contains two symbols, one for the battery and another for the bulb.

Circuit diagrams do **not** represent the physical layout of a circuit.
The lines in the circuit diagram represent contact by wire or direct contact.

ii. Insert each of the objects (paper, elastic band, crocodile clip and Fahnstock clip) individually into the circuit as shown in the diagram to the right and note any effects on the brightness of the bulb. Consider large differences only.

____

____

____

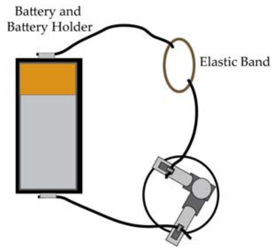


Figure 2.2: Circuit with bulb and elastic band.

Categorise the materials according to how they affect the brightness of the bulb. Make a table with an appropriate caption in the space below, and enter your results.

The objects that allow the bulb to glow are called **conductors.** Objects that cause the bulb to go out are called **insulators.**

iii. Using circuits like that of Figure 2.3 below, determine whether each part shown in the Figure 2.4 below is a conductor or an insulator. Record your observations in a table in the space below.

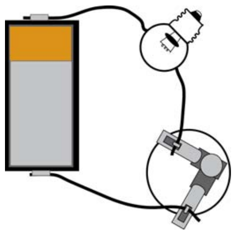


Figure 2.3: Investigating the properties of a bulb.

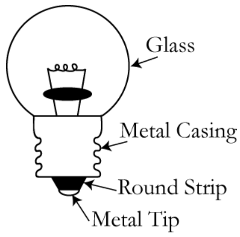


Figure 2.4: A bulb.

iv. Carry out the same investigation for a bulb holder by identifying the materials which are conductors and insulators. Why do you think the bulb holder is designed the way it is? (**Hint:** Think of the arrangements of bulb, wire and battery that did and did not make the bulb light).

____

____

____

Which of the following diagrams do you think best represents the connections of the filament inside a bulb? Explain.

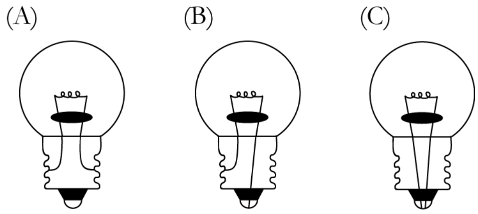


Figure 2.5: Filament arrangement inside a bulb.

____

____

____

Considering your results from the previous two questions, what do you feel is the purpose of the round black strip at the base of the bulb?

____

____

____

Discuss your answers to part iv with a tutor.

v. In previous experiments you have observed that a circuit must be complete in order for the bulb to light. The diagram to the right shows an incomplete circuit.

Explain why the bulb doesn't light. Use the terms "insulator" and "conductor" in your answer.

____

____

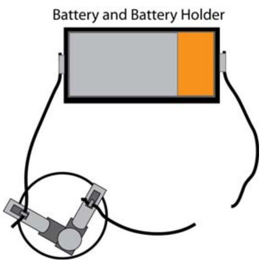


Figure 2.6: An incomplete circuit.

vi. A student is testing a bulb with a broken filament. She connects a battery, a small bulb, and two connecting wires as shown below in Figure 2.7. The small bulb lights.

What can you conclude about the connections in the broken bulb? To what part of the bulb is the left filament connected? Explain.

____

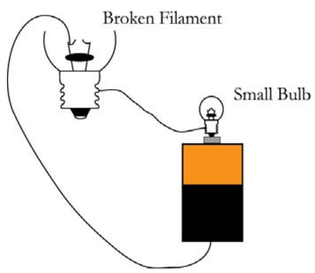


Figure 2.7: Arrangement of a small bulb and a broken bulb.

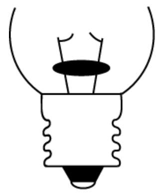


Figure 2.8: A broken bulb.

Draw the connections inside the metal casing in Figure 2.8.

vii. The wire connecting the battery and the broken filament is now moved so that it connects the same side of the battery with the other filament post, as shown.

Do you think the small bulb will light? If so, will it light with greater, less, or equal brightness? Explain.

____

____

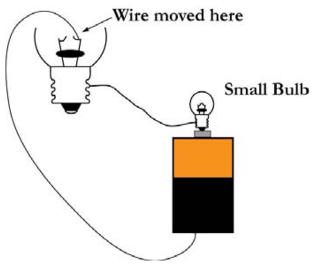


Figure 2.9: New arrangement of the small bulb and the broken bulb.

Section 3: Current

While you carry out the following experiments it is helpful to make the following two assumptions.

1. There is a flow around a circuit; we will call this flow **current.**
2. Bulb brightness indicates the amount of **current,** an increase in brightness indicates an increase in **current.**

These assumptions form the base of our **model** for electric circuits. As we continue our experiments, we will check whether the model holds, and expand it to gain a deeper understanding of electric circuits.

Take the above information into consideration when answering the following questions:

i. Explain how the first assumption is consistent with the idea that a complete circuit is needed for a bulb to light.

____

____

____

Can you tell **from your observations** in which direction current flows? Explain.

____

____

____

ii. If you were to connect a wire across the terminals of the battery, you would notice that the wire and battery gets hotter in such a way that points 1, 2, and 3 and are always equally hot, and the hotter they get the hotter the battery gets.

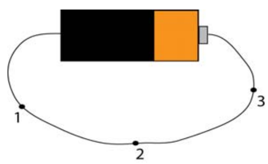
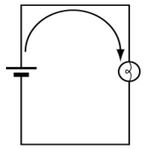


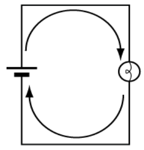
Figure 3.1: Hypothetical set-up of a battery and wire.

Note: Do **not** carry out this experiment.

Consider the following student statements:



Student 1: *"I think the current starts at one end of the battery and goes to the bulb, and stops there. I know this because a battery can light a bulb, but a bulb can't do anything without a battery."*



Student 2: *"I think there is a flow from one end of the battery to the bulb and there is also an equal flow from the bulb back to other end of the battery. The current stops there."*

Student 3: *"I think there is a current inside the battery as well, because in the circuit we just looked at, the battery gets hot, too."*

Comment on these statements.

____

____

____

____

____

____

iii. Base your answers to the next two questions on the model given at the start of this section.

If two identical bulbs are equally bright, what does this indicate about the current through them?

____

If one bulb is brighter than another identical bulb, what does this indicate about the current through the brighter bulb?

____

Check your answers with a tutor before proceeding.

Section 4: Series Circuits

i. Before you construct the circuit shown in Figure 4.1a below, predict how the brightness of bulb B will compare to that of bulb C.

____

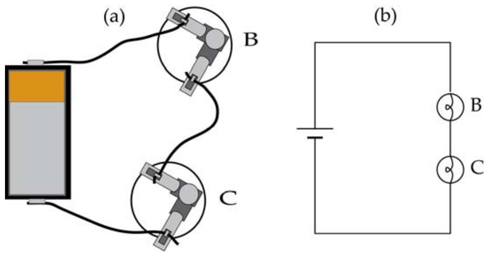


Figure 4.1: (a) A two-bulb series circuit and (b) corresponding circuit diagram.

Also predict how the brightness of bulbs B and C will compare to that of a bulb in a single bulb circuit.

____

ii. Construct the circuit shown above and compare your predictions with your observations. This circuit is called a **series circuit.** The corresponding circuit diagram is shown in Figure 4.1b.

____

____

iii. How does the current through battery 1 compare to the current through bulb A?

____

____

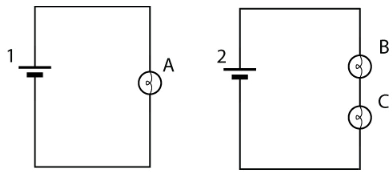


Figure 4.2: Single-bulb and two-bulb series circuits.

How does the brightness of bulb A compare to the brightness of bulb B? What can you can conclude about the current through bulb A in comparison to the current through bulb B?

____

How does the current through bulb B compare to the current through bulb C?

____

How does the current through bulb B compare to the current through battery 2? Make sure you use your model to answer this question.

____

____

____

Finally, considering your answers to the previous questions how does the current through battery 1 compare to the current through battery 2?

____

iv. Summarise your answers to part iii by ranking the currents i_1, i_2, i_A, i_B, and i_C in Figure 4.3 from greatest to least. If any currents are equal, state this explicitly.

- i_1: Current through battery 1
- i_2: Current through battery 2
- i_A: Current through bulb A
- i_B: Current through bulb B
- i_C: Current through bulb C

Explain your reasoning.

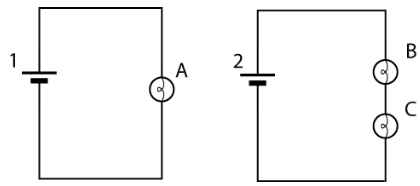


Figure 4.3: Single-bulb and two-bulb series circuits.

____

____

____

____

____

____

v. The following statement about the circuit of Figure 4.3 is **incorrect:**

> *"I know that the batteries are identical so the current through them must be the same. The bulbs in the series circuit have the same brightness because the current is shared equally between them."*

Use your model to show why the statement is incorrect.

____

____

____

____

Based on your observations, is the current "used up" in bulb B?

____

____

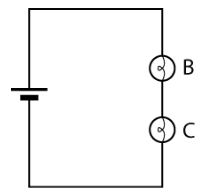


Figure 4.4: Circuit diagram for a two-bulb series circuit.

If a third bulb were placed in series with bulbs B and C, do you think it would light? Do you think the current through bulbs B and C would increase, decrease, or remain the same?

____

____

Section 5: Current Measurement

In this section, we introduce an instrument called an **ammeter** that allows us to measure current. An ammeter must be connected in series in the circuit. The ammeter used in this experiment measures the current through the circuit in **milliampere** (mA), which is $^{1}/_{1000}$ of an ampere.

Figure 5.1: Ammeter circuit symbol.

Notice that one terminal of the ammeter is marked positive and the other negative. The positive terminal of the ammeter must be connected to the positive terminal of the battery.

> **Warning:** If the needle on the ammeter is deflected backward, reverse the leads connected to the ammeter.

i. Connect an ammeter in series with a bulb in a single bulb circuit as shown in Figure 5.2 below where the positive terminal (gold end) of the battery is connected to the red terminal of the ammeter. Connect the black terminal of the ammeter to the bulb.

   Write down the ammeter reading: ____________________________________

Compare the circuit diagram to the circuit layout. How can you tell from the circuit diagram which battery terminal is positive?

___

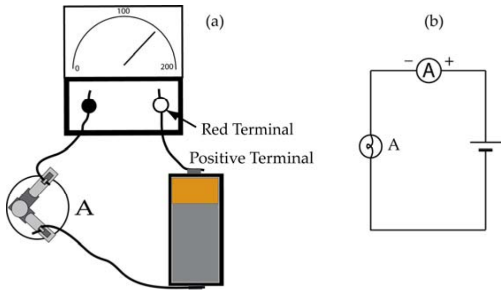


Figure 5.2: (a) Ammeter in a single bulb circuit and (b) corresponding circuit diagram.

ii. Predict what would happen to the reading on the ammeter if you added a second bulb in series with bulb A.

___

iii. Connect a second bulb in series to form the circuit shown at right, and note the reading on the ammeter. Compare your prediction to your observation. Is the reading on the ammeter consistent with your observations in the previous section?

___

___

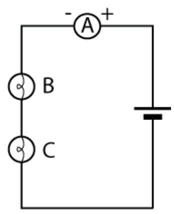


Figure 5.3: Circuit diagram for a two-bulb series circuit with ammeter.

Now place the ammeter in between bulbs B and C as shown in Figure 5.4. How does the reading compare to the reading above?

___

___

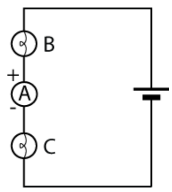


Figure 5.4: Ammeter between two bulbs in series.

How does the current on one side of bulb B compare to the current on the other side of bulb B?

___

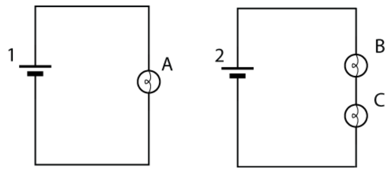
iv. In Section 4 you were asked whether current is used up in bulb B. If necessary, adjust your answer in Section 4.

____

v. Which of the following student statements agree with your model? Explain your answer in some detail.

Note: The question is **not** whether the statements are correct.

Student 1: *"The electric charge is shared between bulbs B and C, unlike in the case of bulb A. Therefore bulb A would be a brighter light source than B."*



Student 2: *"Even though bulb A is closer to the energy source, bulb A has the same brightness as bulb B as they still have the same amount of energy passing through them."*

Student 3: *"Bulb B is dimmer than bulb A because the current flowing through bulb B is less than the current flowing through bulb A."*

____

____

____

____

____

____

____

____

Check your answers with a tutor before you leave the lab.

Name: ______________________________________ **Class:** ______

Experiment 2: Resistance

In Experiment 1 we discovered some properties of simple electric circuits and laid the foundations for a model for electric circuits. In today's experiment we will expand our knowledge of electric circuits by investigating other types of circuits and comparing our observations to those from Experiment 1.

Equipment/Apparatus Check

Check to make sure you have a power supply, an ammeter, five pieces of wire, four bulb holders, four bulbs and two crocodile clips.

Section 1: Power Supply

In Experiment 1 you worked solely with batteries, bulbs and wires. In this experiment we will use a new component called a power supply.

i. Attach two crocodile clips to the leads of the power supply and set up a single bulb circuit as shown in the diagram at right. The switch on the power supply should be set to 9 V.

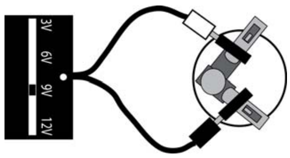


Figure 1.1: A single bulb connected to a power supply.

> **WARNING: The two leads of the power supply should not touch each other directly or be connected through a wire only.**

ii. Predict the change in brightness of the bulb if any, if another bulb were added in series to the circuit as shown below.

____

____

Set up the circuit shown at right and verify your prediction. What did you observe?

____

____

____

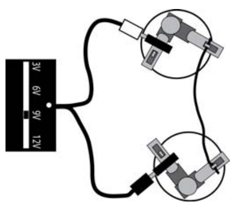


Figure 1.2: Two bulbs in series connected to a power supply.

iii. How do your observations compare to your observations from last week's experiment? Do the circuits containing a battery behave differently to circuits containing a power supply or do they behave the same?

____

____

Section 2: Resistance in Series Circuits

In what follows, you may assume that a power supply and a battery behave identically.

In Experiment 1 we observed that when a bulb was added in series, the bulbs in the circuit dimmed. We took this as evidence that the current in the circuit decreased. We now try to incorporate this finding into our model for electric circuits.

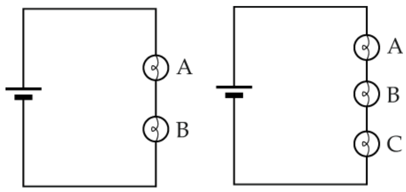


Figure 2.1: Adding a third bulb in series.

i. Consider the two bulb series circuit which you have set up in Section 1. We label the bulbs A and B. Predict what would happen to the brightness of bulb A if a third bulb were added in series to the circuit as shown in Figure 2.1 above.

____

____

ii. Set up the circuit and verify your prediction.

____

____

To explain why the brightness of bulbs and consequently the current through the battery is different in different circuits, it is helpful to think of the bulbs as providing an obstacle or a **resistance** to the current where an increase in resistance causes a decrease in current and vice versa.

iii. What can you infer about the total resistance of a circuit as more bulbs are added in series?

____

____

____

iv. Formulate a rule which allows you to predict how the current through the battery would be affected as the number of bulbs added in series were increased or decreased. Include the concept of resistance in your rule. **This rule forms the third part of our model.**

____

____

____

Discuss your answers with a tutor.

Section 3: Parallel Circuits

We have seen how adding bulbs in series affects the current through the battery and how it affects the brightness of the bulbs in the circuit. We now look at a different circuit and compare its properties to the circuits we have seen previously.

The circuit shown in Figure 3.1 at right is called a **parallel circuit**.

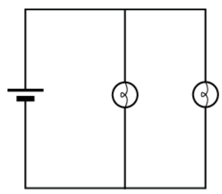


Figure 3.1: Two bulbs in parallel.

i. Compare the circuit diagram of the parallel circuit above to a single that of a single bulb circuit shown in Figure 3.2 at right. What are the similarities and differences between the two circuits? How many complete conducting routes/pathways exist in each circuit?

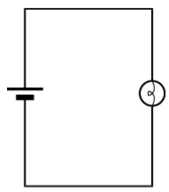


Figure 3.2: Single bulb circuit.

____

____

____

ii. How do you think the brightness of each bulb in a parallel circuit will compare to that of a bulb in a single bulb circuit?

____

Set up the parallel circuit as shown below in Figure 3.3. Compare the brightness of the bulbs in the parallel circuit to that of a bulb in a single bulb circuit. Write down your observations below.

____

____

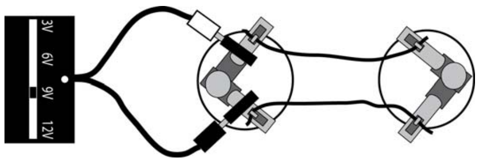


Figure 3.3: Parallel circuit set-up.

Compare the brightness of each of the bulbs in parallel. How do the currents through the bulbs compare to each other?

____

In a parallel circuit we often think of the current splitting and recombining at junctions or nodes in the circuit. A junction or node can be defined as an electrical connection between more than two components.

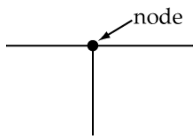


Figure 3.4: A node.

iii. Insert nodes (black dots) into Figure 3.5 where appropriate.

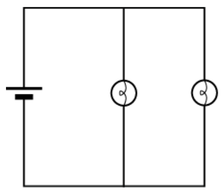
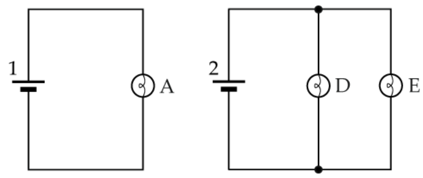


Figure 3.5: Circuit diagram without nodes.

iv. Consider the following student statements about the circuits at right.



Student 1: *"I think the current splits evenly when it reaches the first node. I know that the bulbs are equal in brightness to a single bulb and they are also equal in brightness to each other. Therefore the current through battery 2 must be double the amount of current through battery 1."*

Student 2: *"I disagree. I know that all batteries have the same current and all bulbs are the same brightness, so the same current flows through each bulb."*

Which of the students, if any do you agree with? Explain.

____

____

____

Section 4: Measurement of current

i. Use an ammeter to measure the current through a bulb in a single bulb circuit. The set-up of the circuit is given in Figure 4.1 at right. Write down your measurement below.

____

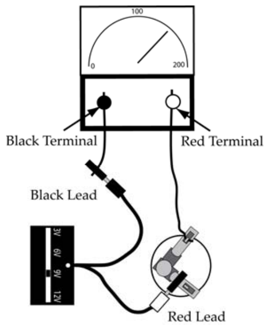


Figure 4.1: Circuit with single bulb and ammeter.

ii. **Predict** the reading on the ammeter in the circuit shown in Figure 4.2 below.

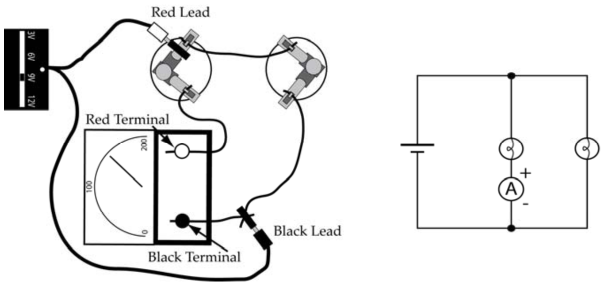


Figure 4.2: Parallel circuit with ammeter in one of the branches.

Set up the circuit and verify your prediction.

How does the current through each individual bulb compare to the current through the battery?

Which of the student statements on the previous page is your measurement consistent with?

iii. Predict the reading on the ammeter when it is connected to read the current through the battery in a parallel circuit as shown at right.

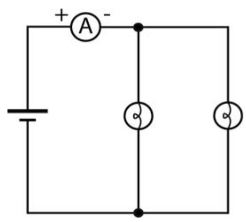


Figure 4.3: Parallel circuit with ammeter.

Set up the circuit shown at right which measures the current through the battery in a parallel circuit. How does your observation compare to your prediction?

____

____

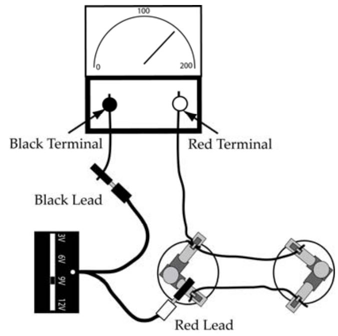


Figure 4.4: Parallel circuit with ammeter.

iv. Compare the current through the battery in the parallel circuit to the current through the battery in the single bulb circuit. Can the current through a battery change?

____

What can you infer about the resistance of a parallel circuit as compared to that of a single bulb circuit?

____

v. Formulate a rule that allows you to predict what happens to the current through the battery and a bulb, and to the resistance of a circuit, when a second bulb is added in parallel to a single bulb circuit. **This rule is the fourth part of our model.**

Discuss your answers with a tutor.

Section 5: Resistance in parallel circuits

In the previous section we have seen that when we add a bulb in parallel to a single bulb the current through the battery increases. We now carry out more experiments to investigate the properties of parallel circuits.

i. Consider the circuit shown at right. The black box represents an arrangement of circuit elements. A change is made within the black box and the brightness of the indicator bulb A increases. What can you infer about the change in resistance of the circuit after the connections in the box have been changed?

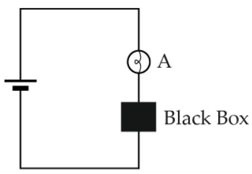


Figure 5.1: A black box circuit.

ii. Set up a two bulb series circuit as shown. We call bulb A an **indicator bulb** as it indicates the current through the battery.

Suppose you added a third bulb, C, in parallel to bulb B as shown in Figure 5.3 below.

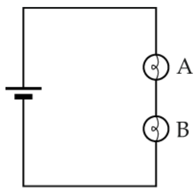


Figure 5.2: A two-bulb series circuit.

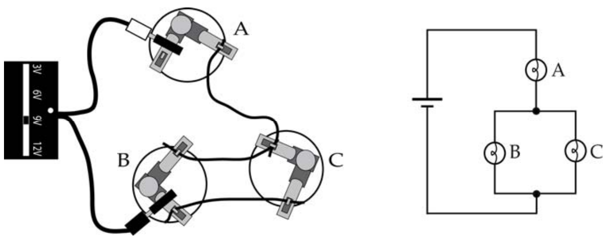


Figure 5.3: A three bulb circuit.

Predict how the brightness of the bulbs in the diagram of Figure 5.3 would rank from greatest to least. Carefully explain how you used your model to make your prediction.

Do you expect the brightness of bulb A to change when bulb C is added?

____

iii. Now add bulb C in parallel to bulb B as shown in Figure 5.3. How does the brightness of the indicator bulb A change?

____

iv. Using the reasoning of question ii, what can you infer about the change in the resistance of the circuit as bulb C is added in parallel to bulb B?

____

Is your answer consistent with what you found in Section 3 when you added a bulb in parallel with a single bulb? Explain briefly.

____

____

v. Formulate a rule which describes how the current through the battery changes when a bulb is added in parallel to another bulb. Include the concept of resistance in your rule. **This is the fifth rule of our model.**

____

____

Check your rule with a tutor.

Through the investigations carried out in the previous sections and Experiment 1, you have developed a large portion of your model on electric circuits. To help you summarise some of the major concepts, complete Table 5.1 below.

Table 5.1: ______________________________

Change to circuit	**Change in resistance of the circuit**	**Change in current through battery**
Adding a bulb in series		
Adding a bulb in parallel		

vi. Using your observations from previous experiments, consider the following arguments:

Student 1: *"Circuit 2 has more resistance than circuit 1 because adding bulbs to a circuit always increases the total resistance so it decreases the current through the battery. Circuit 1 has fewer bulbs so it has less resistance."*

Student 2: *"Circuit 2 has less resistance than circuit 1 because bulb C is added in parallel. When bulbs are added in parallel the total resistance decreases."*

Do you agree with student 1, student 2, or neither? Explain.

____

____

Section 6: Applying your model

i. Consider the three bulb circuit of Section 5. **Suppose** a fourth bulb is added as shown in Figure 6.1 below.

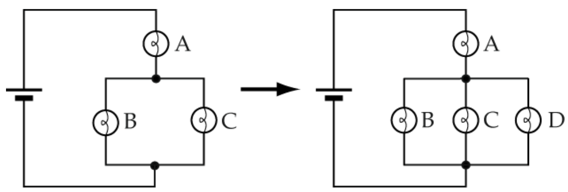


Figure 6.1: Adding a fourth bulb to a three-bulb circuit.

Is bulb D added to the circuit in series or in parallel? Explain carefully.

____

____

How would the addition of bulb D affect the resistance of the circuit? Explain.

____

How would the addition of bulb D affect the current through the battery? Explain.

____

Finally, predict the change in brightness of bulb A on the addition of bulb D to the circuit.

____

ii. Set up the circuit and verify your prediction. A possible layout is shown in Figure 6.2. Were there any inconsistencies between your prediction and observation? If so, resolve these.

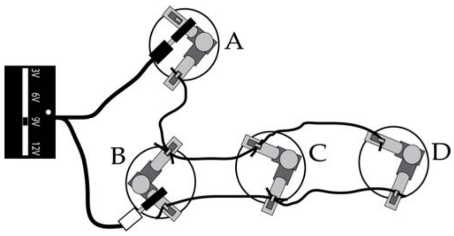


Figure 6.2: The circuit of Figure 6.1.

iii. Insert the ammeter into the circuit as shown in Figure 6.3 at right.

Predict whether the ammeter reading would increase, decrease, or remain the same if you were to unscrew bulb D. Explain briefly.

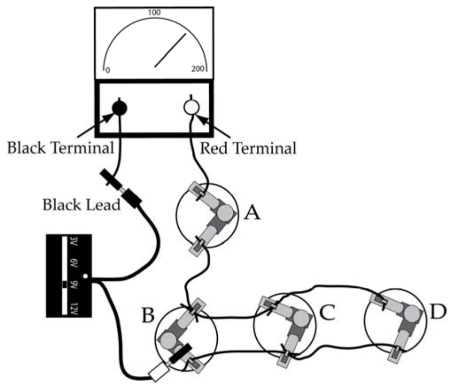


Figure 6.3: The circuit of Figure 6.1, with ammeter added.

Verify your prediction. Was it correct?

Are your observations consistent with your model? If not, adjust your model so that all your observations thus far are dealt with.

Check your answers with a tutor.

iv. Again consider the three bulb circuit shown in Figure 6.4 below. If we were to add bulb D to the circuit as shown, would we be adding bulb D in series or in parallel to the circuit?

____

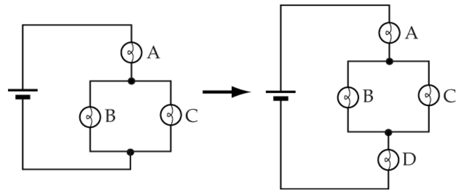


Figure 6.4: Adding a fourth bulb to a three-bulb circuit.

When bulb D is added, does the resistance of the circuit increase, decrease or stay the same? Explain.

____

How does the addition of bulb D affect the amount of current through the battery? Explain.

____

Predict the change in brightness of bulb A, if any, on the addition of bulb D.

____

v. Set up the circuit and verify your prediction. Were there any inconsistencies between your prediction and observation?

____

____

____

____

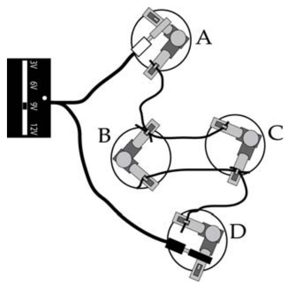


Figure 6.5: The circuit of Figure 6.4.

Are your observations consistent with your model? If not, adjust your model so that all your observations thus far are dealt with.

____

Check your answers with a tutor.

Name: ______________________________________ **Class:** ______

Experiment 3: Voltage

In Experiments 1 and 2 we started to build a model for electric circuits. Thus far we have covered the concepts of current and resistance in relation to series and parallel circuits. In today's experiment we investigate more complicated circuits and introduce the third and final concept to our model.

Equipment/Apparatus Check

Check to make sure you have a power supply, two crocodile clips, five pieces of wire, four bulb holders, four bulbs and a voltmeter.

Section 1: Voltage

i. Set up a single bulb circuit with the power supply switch at 3 V, 6 V and 9 V, and describe any changes in bulb brightness.

   ____

   ____

   ____

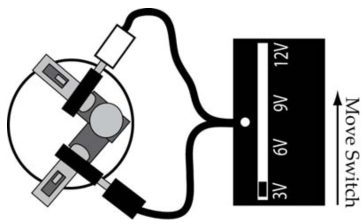


Figure 1.1: Single bulb circuit.

In Experiments 1 and 2, the brightness of bulbs changed when you added bulbs to the circuit. Is there a difference in the way you changed the brightness in this experiment? Explain briefly.

____

____

Section 2: Power Supply

In the previous section we saw that a change in the set-up of the power supply affected bulb brightness. The following experiments will investigate this change in the power supply and help determine how it affects the circuit.

We introduce another circuit element, called a **voltmeter**. A voltmeter measures a quantity known as **voltage** which is related to the ability of a battery or power supply to push/drive current around the circuit. The voltmeter must be connected in parallel to the element which you are measuring as shown in the diagram at right.

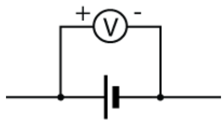


Figure 2.1: Circuit diagram for connecting a voltmeter to a battery.

WARNING: When it is not clear which way to connect the voltmeter leads, connect just one lead, then tap the second lead in place to make a fleeting contact while you are watching the meter. If the needle jumps the wrong way, reverse the leads.

i. Set up a single bulb circuit with the switch on the power supply at 9 V. From now on, we will refer to the power supply as "the battery".

   Connect the voltmeter across the battery as shown in the diagram at right. Note the reading on the voltmeter.

   ____

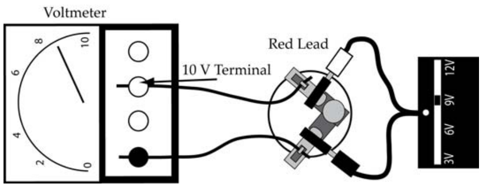


Figure 2.2: Circuit lay-out for measuring battery voltage in a single-bulb circuit.

ii. Disconnect the voltmeter and then add a second bulb in series to the circuit. Re-connect the voltmeter across the battery as shown at right and write down the voltmeter reading.

   ____

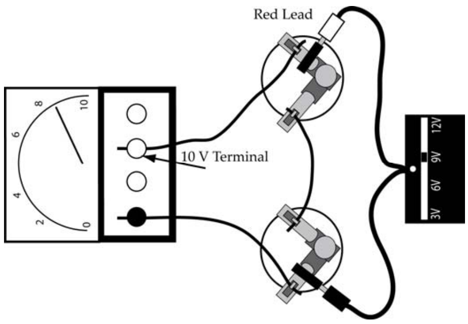


Figure 2.3: Circuit lay-out for measuring battery voltage in a two-bulb series circuit.

iii. Disconnect the voltmeter. Remove the bulb in series and connect it in parallel as shown in the diagram below. Re-connect the voltmeter across the battery and note the reading on the voltmeter.

____

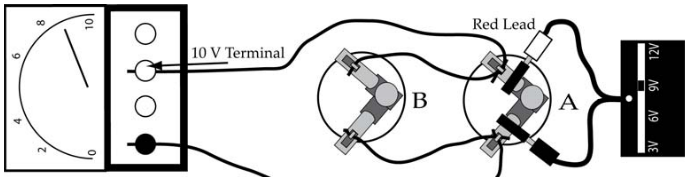


Figure 2.4: Circuit lay-out for measuring battery voltage in a two-bulb parallel circuit.

iv. How do your measurements for the voltage across the battery compare for each of the three circuits?

____

Section 3: Voltages in series circuits

A voltmeter will indicate a voltage not only when it is connected across a battery, but also when it is connected across any circuit element that has current through it.

To measure the voltage across a circuit element, the voltmeter is connected in parallel with it as shown in the diagram at right. The positive (red) terminal of a voltmeter should be electrically closest to the positive terminal of the battery, just like an ammeter.

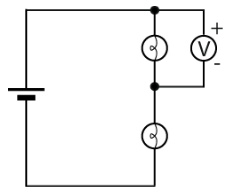


Figure 3.1: Circuit diagram for voltmeter across one of two bulbs in series.

i. Set up a two bulb series circuit with a voltmeter as shown in Figure 3.2 at right. Note the voltmeter reading across the battery, and across bulb A.

____

____

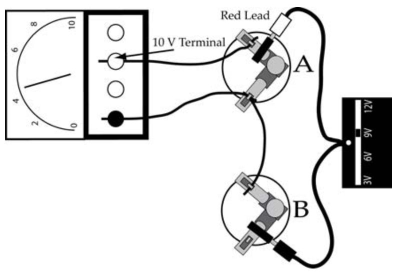


Figure 3.2: Circuit lay-out with voltmeter across one of two bulbs in series.

Connect the voltmeter across bulb B in the same way as bulb A and note the reading on the voltmeter.

____

How does the voltage across bulb A compare to that across bulb B? Only pay attention to differences greater than about 1 V.

____

How does the brightness of bulb A compare to the brightness of bulb B?

____

ii. If a third bulb were added to the circuit in series, predict the voltage across each of the bulbs. Enter your predictions in the table below.

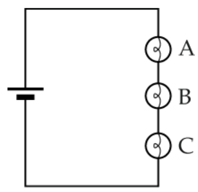


Figure 3.3: Circuit diagram for a three-bulb series circuit.

Table 3.1: ____________________________

Circuit element	Voltage prediction (V)	Voltage measurement (V)
Battery		
Bulb A		
Bulb B		
Bulb C		

Connect the third bulb, C, in series and re-measure the voltage across bulbs A and B. Also measure the voltage across bulb C and the battery. Add your results to the table above.

Resolve any differences between your predictions and measurements.

____

____

iii. Formulate a rule for how the voltage across a battery and across a bulb changes when a second bulb is added, both in series and in parallel. **This is the sixth rule of the model.**

____

____

iv. Can you determine a mathematical relationship between the voltage across the battery (V_{bat}) to the voltage across each bulb (V_A, V_B, V_C)?

____

____

____

____

Predict what voltage you would measure if you put the voltmeter leads across bulbs B and C as shown in Figure 3.4.

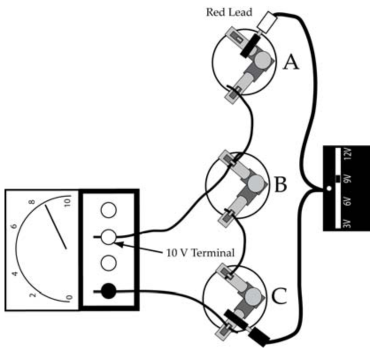


Figure 3.4: Measuring voltage across bulbs B and C simultaneously.

____

Verify your prediction, and resolve any inconsistencies.

____

v. Enter in the table below the effect on the current through and the voltage across each element when bulb C was added to the circuit. Did these quantities increase, decrease, or remain the same?

Table 3.2: ____________________________

Circuit element	Current through element	Voltage across element
Battery		
Bulb A		
Bulb B		

When the voltage across a bulb decreases, how is its brightness affected, if at all?

____

____

Check your answers with a tutor.

Section 4: Voltages in parallel circuits

i. Set up a two bulb parallel circuit with the power supply switch at 9 V.

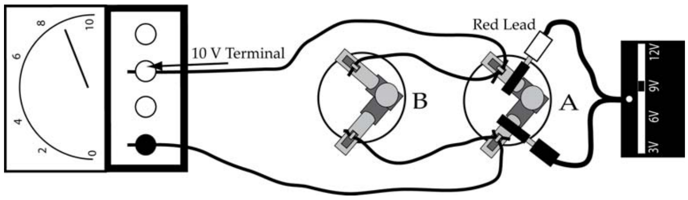


Figure 4.1: Measuring the voltage across one of two bulbs in parallel.

Connect the voltmeter across bulb A as shown in the diagram above. Note the reading on the voltmeter.

____

ii. Predict the voltage across bulb B. How will it compare to the voltage across bulb A?

____

Move the voltmeter so that it measures the voltage across bulb B. Write down the reading of the voltmeter.

____

iii. How does the voltage across bulb A compare to bulb B? How does the voltage across the bulbs compare to the voltage across the battery?

____

____

Find a mathematical relationship that relates the voltage of the battery (V_{bat}) to the voltage across bulbs A and B (V_A, V_B).

____

____

Check your answers with a tutor.

Section 5: Kirchhoff's Loop Rule

i. **Before** you set up the circuit shown at right predict how the voltages across each of the elements compare, and rank them accordingly. Enter your predictions in Table 5.1 below.

Hint: Use your prediction of bulb brightness to make predictions for voltage.

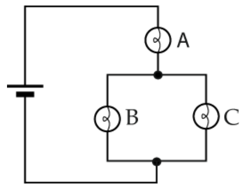


Figure 5.1: Circuit diagram for three-bulb circuit.

Table 5.1: ___________________________

Circuit element	Voltage prediction (V)	Voltage measurement (V)
Battery		
Bulb A		
Bulb B		
Bulb C		

Set up the circuit and measure the voltage across the battery and each of the bulbs. Enter your values in the table above.

ii. How does the voltage across bulb B compare to bulb C?

____

Are your measurements consistent with the mathematical relationship for voltages in parallel in question iii of Section 4?

____

iii. Add the voltages across bulb A and bulb B and compare this value to the voltage across the battery. Also add the voltage across bulb A and bulb C and again compare to the voltage across the battery.

____

____

Consider the circuit of Figure 5.1 once again. Trace the current around the circuit. How many paths are in the circuit for the current to follow?

____

iv. Kirchhoff's Loop Rule states that the sum of the voltages across all of the elements along any path is the same as the voltage across the battery. Are your measurements consistent with this rule?

____

____

____

Section 6: Voltage and resistance

i. Rank the boxes below in terms of resistance from greatest to least. Explain.

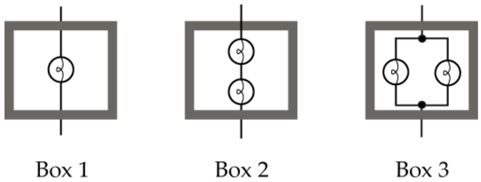


Figure 6.1: Arrangements of bulbs inside boxes 1-3.

____

____

____

____

Discuss your answers with a tutor before proceeding.

ii. Consider the circuits in Figure 6.2 below where each box has been added in series with bulb A.

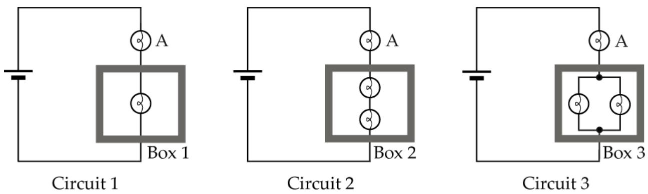


Figure 6.2: Circuit diagrams of boxes 1-3 connected in series with bulb A.

Use your earlier measurements to complete Table 6.1 below.

Table 6.1: ______________________________

Circuit element	Voltage across A (V)	Voltage across box (V)
1		
2		
3		

iii. Rank the voltages across each of the boxes from greatest to least. How does this ranking compare to your ranking of the resistance for each box?

____

____

Consider the following student statements.

Student 1: *"The voltage across the box increases when the resistance of the box increases."*

Student 2: *"When the voltage across a bulb is decreased, the brightness of the bulb decreases".*

Comment on each statement.

____

____

____

____

iv. In Section 4 you set up a parallel circuit and measured the voltage across each bulb. The measurements indicated that the voltage across each bulb was the same as the battery voltage.

If a third bulb were added as shown at right, predict the voltage across each of the branches 1 and 2.

____

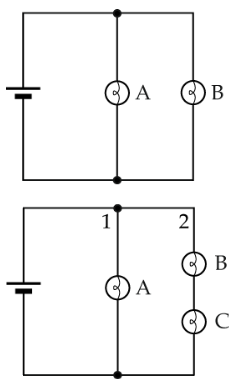


Figure 6.3: Circuit diagrams of parallel circuits.

Set up the circuit as shown in Figure 6.4 and measure the voltage across each branch. Enter the results in Table 6.2 below. How do your measurements compare to your predictions?

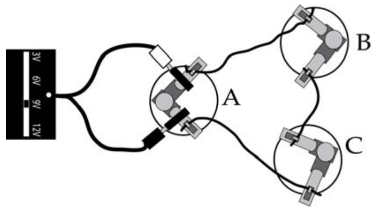


Figure 6.4: Circuit of Figure 6.3.

Table 6.2: ____

Branch	Voltage measurement (V)
1	
2	

v. Does changing the resistance in branch 2 affect the voltage across branch 2?

Does changing the resistance in branch 2 affect the voltage across branch 1?

vi. Formulate a rule that states how brightness and voltage are related.

Formulate a rule that states how the voltage across a bulb in a branch changes when the resistance within that branch is changed.

These rules complete your model for electric circuits.

Discuss your answers with a tutor.

Section 7: Application of your model

i. Consider the circuits below. To form circuit 2, must bulb D be connected in series or parallel to circuit 1?

____

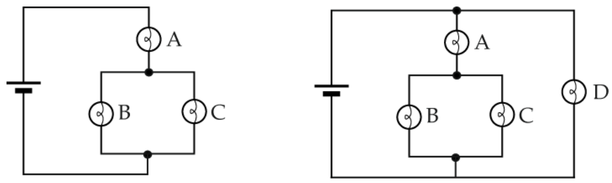


Figure 7.1: Circuit diagram showing the addition of bulb D.

ii. Do you think the addition of bulb D will affect the voltage across the battery? Explain.

____

____

Considering your rule for voltages across parallel branches, will the addition of bulb D affect the voltage across the branch containing bulbs A, B and C?

____

____

Enter your predictions for how each of the quantities in Table 7.1 would change on the addition of bulb D.

Table 7.1:______________________________________

Quantity	Prediction	Measurement
Voltage across battery		
Voltage across bulb A		
Voltage across bulb B		
Brightness of bulb A		
Brightness of bulb B		

iii. Connect bulb D as shown and enter your measurements in Table 7.1. Resolve any inconsistencies between your predictions and measurements.

____

____

____

____

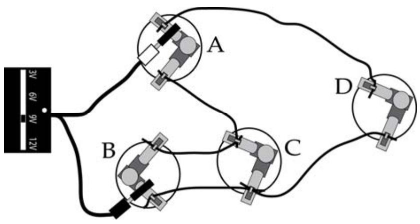


Figure 7.2: Circuit layout on addition of bulb D.

Check your answers with a tutor.

Section 8: Application of your model II

i. Consider the circuit shown below. Suppose a fourth bulb, D, were added to the circuit as shown below. Is bulb D connected in series or parallel to bulb C?

____

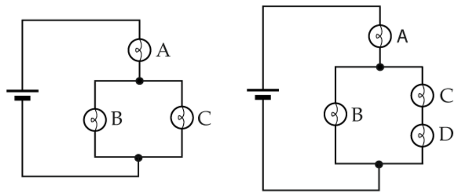


Figure 8.1: Circuit diagrams showing the addition of bulb D.

Predict the change in voltage across the battery, if any, if bulb D were added as shown.

____

ii. How would the addition of bulb D affect the resistance of the circuit?

____

How will the brightness of bulb A be affected?

____

How will the voltage across bulb A be affected?

____

iii. Use Kirchhoff's loop rule to find an equation relating V_{bat}, V_A and V_B.

____

Use your prediction of how the addition of bulb D will affect the voltage across bulb A to predict how the voltage across bulb B and its brightness will change.

____

____

iv. Enter all of your predictions in Table 8.1 below.

Table 8.1: ______________________________________

Quantity	Prediction	Measurement
Voltage across battery		
Voltage across bulb A		
Voltage across bulb B		
Brightness of bulb A		
Brightness of bulb B		

v. Connect bulb D as shown in Figure 8.2 and verify your predictions. Note any inconsistencies and try to resolve these.

____

____

____

____

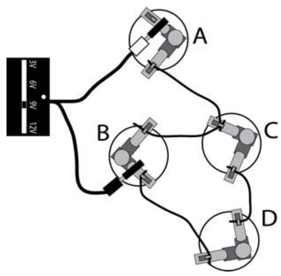


Figure 8.2: Circuit layout showing the addition of bulb D.

Check your answers with a tutor.