Understanding key concepts of electric circuits

Students' use of mental models

Joan Borg Marks

B.Sc.(Hons.) M.A.(Loughborough) Dip.Educ.Admin.&Mgmt.

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Abstract

This study presents an action research project on the teaching and learning of fundamental ideas about electric circuits, gathering data from two cohorts. Students' ideas were probed using diagnostic test questions asked in pre-tests, post-tests and delayed post-tests. Semi-structured interviews were used with students of different abilities to indicate the mental models that students appeared to be using. Additional teaching activities were introduced with Cohort 1. The effect of these activities was reflected upon, guiding further additions to teaching activities used with Cohort 2. These activities addressed specific points that seemed to pose particular difficulties for students with the aim of improving students' qualitative understanding through guided reflection and discussion.

The performance of Cohort 2 was significantly weaker at the pre-test stage but Cohort 2 made better overall progress through the course of study when compared with Cohort 1. Both cohorts made noticeable improvement in their understanding of current conservation. However, problems with parallel circuits and with distinguishing between potential difference (p.d.) and current remained. While p.d. was described by the high ability students in terms of forces between negative charges and the battery terminals, no student referred to the electric field which exists between battery terminals even in open circuit.

In attempting to understand the behaviour of electric circuits, students appear first to construct a mental model of electric current. The data collected suggest that students start to understand p.d. when they 'see' it as some kind of difference between points. The data also suggest that the scientific model of p.d. is more difficult to visualise and use, putting p.d. at a higher level than current, in a logical hierarchy of ideas.

This study proposes a unified learning model for electric circuits, in terms of a possible sequence of intermediate mental models of current, resistance and p.d. leading towards the scientific view. This learning model can help both students and teachers. Students can use it to gauge their level of understanding of circuits and to reflect on what still needs to be understood. Teachers may use the learning model as a tool helping in understanding the difficulties students experience and guiding in what next to teach to improve students' understanding of electric circuits.

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I dedicate this work to my family including my mother and the memory of my father.

Author's Declaration

This thesis is an original unpublished study carried out by the undersigned, which is being presented to the University of York for a Ph.D. degree.

Joan Borg Marks
B.Sc. (Hons.) M.A. (Loughborough) Dip.Ed.Adm.Mgmt.

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Chapter 1 Introduction

1.1 Learning about electric circuits

"Why does a light globe light up? An easy question, or is it? Sitting in (the) workshop I realised that this was not something I had really thought about. I had just taken it for granted that when you turn on the light switch, the light globe will shine. If I had thought about it in any way, my answer was simple and clear, based on my understanding of year 7 electric circuits. My answer would have been as follows: when you turn on a light switch you complete an electric circuit, thus allowing electricity to flow along the wires and give the light globe the energy to shine. Simple isn't it? But wait, a problem, what is electricity and what 'energy' is it giving to the light globe?..."

(Written reflections of an experienced teacher - a biology specialist, teaching physics to 11-16 year olds as part of a general science course - during a teacher workshop.)

(Hart, 2008, p.538)

This research study is about the learning of the topic covering electric circuits. The above extract highlights some problems learners of any age may encounter as they are being instructed in this area of physics. Difficulties may either result directly because of the learner's inability to handle abstract concepts or possibly be a result of the teaching. Teachers may not feel well prepared to teach the topic in a way which is 'easy' for students to understand, or perhaps teachers themselves had problems with the understanding of this topic when **they** were students - problems which may have been left unresolved.

1.2 The origin of my interest to undertake this research

Physics has always been one of my favourite subjects, even as a secondary school student. After graduating as B.Sc. (Hons.) in Physics and Chemistry, I started a career in teaching. I had really never thought that I would end up teaching, but I was offered the job and I took it because I needed the money. Never did I imagine what a stimulating experience teaching would be for me. I like meeting students, conversing with them and helping them with ideas which impede their understanding. At the same time, I feel that I have learned so much from my students as well.

My interest in science education came much later when I started attending a course in educational administration and management. This opened for me, many more interesting aspects of teaching and the psychology of education. I became interested in **how** students learn and I was intrigued with what could be done to help students in their journey towards scientific views.

Reading and researching for my M.A. in education studies gave me the possibility to back up the views, gained from my teaching experience, about how **all** students need to be motivated to learn. The importance of the teacher's role as a catalyst for students' progress towards achieving meaningful learning became one of my strongest beliefs. As much as possible, I tried to involve my students in hands-on and minds-on activities that would improve their meta-cognitive awareness of what they knew and what they were failing at. Moreover, my M.A. thesis about gifted education strengthened my feeling that by observing **all** students, one could gauge the understanding of students' specific learning problems on the one hand, while recognising the levels students may attain when properly guided and motivated to learn, on the other.

The years have rolled by, and I now find that I have been teaching Physics at various levels, except at primary level, for the last 38 years. I have taught advanced level Physics for these last 29 years. At the college where I teach, the syllabus is divided into sections and teachers are asked to teach a particular section by the co-ordinator, as the need arises. Teachers may also opt to ask for a particular topic to teach, but it is always the co-ordinator who makes the final decision of who teaches what. It was some time before I started my Ph.D. work that I realised that I was being given the electricity section of the syllabus to teach, year in, year out, when in previous years topics had been assigned to members of the department on a rotation basis. It was the same story for another three members of staff. It seemed that none of the other teachers were interested in teaching this topic. I started to get the feeling that some teachers, like some of the students I teach, may not particularly like electricity enough to want to teach it to others. At the same time the co-ordinator thought that the job was being done effectively by the teachers, including myself, already teaching electric circuits. My opinion was slightly different. Each year new students exposed the same unscientific ideas through class discussions, showing they experienced the same difficulties in learning the topic. Even if I put all my effort to try and teach circuits effectively, these difficulties seemed to trouble the students more than difficulties they encountered as they learned other sections of the physics syllabus. Some students declared this explicitly, complaining until the end of the scholastic year about problems with grasping the meaning of key concepts related to circuits.

Until this time, I had never read books or journal articles related to students' alternative ideas about electric circuits. Even if I had gathered a store of insights into students' 'misconceptions', I was not yet aware that those about electricity were so widespread. These lifetime experiences made me realise that I should do something to learn more about why so many people perceive electricity as a difficult topic even after instruction, even if I myself could not recall that I had ever experienced the same problems with learning this topic. I thus embarked on this research study with the aim of understanding how students think about electric circuits, by probing the ideas students use when asked to explain or predict the behaviour of a circuit. This would help to identify specific points that many students find difficult, and hence to think about how I might modify my teaching to help more students get over these difficulties. I thought that by trying out some simple teaching activities which are not what I usually do with students, I would perhaps see how effective these would be in helping more students make learning more meaningful.

1.3 General issues which may hinder learning of electric circuits

A lot of research has been conducted in this area, over the last 30 years, showing researchers' interests to improve the teaching and learning of electric circuits. This research corroborates my professional knowledge that this is a difficult topic for many students. The research has identified some specific learning challenges for students, and has suggested some teaching approaches that might help to overcome them. Yet, in spite of this, many people still readily admit that their understanding of circuits is not deep, even after instruction. If students are just trained to use equations to solve numerical examples, and to recall information to get them through an examination, then providing qualitative explanations to questions dealing with circuits becomes difficult (see Mazur, 1997). Often, retention of the learnt material is poor (Fleer, 1994), even if students manage to pass examinations. Such occurrences should make all educators think about whether we are actually teaching students to counterfeit understanding. While this may be said with reference to all topics, it seems even more relevant when abstract concepts are involved, and when learners do not easily relate with scientific mental representations.

Another point which cannot be ignored but which is, unfortunately, often sidelined by teachers, perhaps due to time constraints in covering the syllabus, is that young students come to class with pre-instruction ideas which are heavily influenced by previous personal experience. At the same time, older students may come with partly remembered ideas from earlier years. We know that to be meaningful, new material must be related to existing knowledge. Ausubel (1968) claims: “The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly” (p. vi). Halloun and Hestenes (1985a, 1985b), in referring to the learning of mechanics, also claim that students’ initial knowledge has a large influence on students’ performance in physics. There is a clear indication, therefore, that students’ initial knowledge has to be taken into account during instruction. This, however, can only be done effectively when teachers are aware of the ideas students hold, and know what to do to improve learning. Halloun and Hestenes (1985a) and Aguirre (1988) point towards the need for teachers’ awareness of students’ alternative conceptions, to be able to design effective instructional strategies. Yet, how far are teachers aware of students’ alternative ideas related to circuits? Do teachers discover and tackle students’ recurring difficulties in this area of physics, systematically? How far is research used to inform practice?

Reflecting on these questions, while knowing of the persistent problems with students’ understanding, indicated the need for more systematic research aimed both at helping students with their understanding in this area and at offering teachers a unified approach which may make their teaching more effective.

1.4 The development of understanding in terms of mental model evolution

A number of authors have claimed that models and modelling are central to understanding key concepts in science (see for example Clement, 1989; Duit & Glynn (1996); Gilbert & Boulter, 1998). This study looks into the difficulties students have in understanding electric circuits, exploring whether students have ideas about circuits which might suggest that they have mental representations, or models, of aspects of circuits which underpin the predictions students make and the explanations they offer for their predictions. Students' understanding of electric circuits is thus viewed by this study in terms of the students' ability to use their mental representations in predictions and explanations of how and why the circuit functions. As understanding develops, this involves changes in the mental models held by the learner. The development of understanding is seen as a matter of replacing previous mental models with ones that come closer to the scientific model. Knowing about the mental models students may hold as learning is in progress was used in this study as an aid to understand students' learning pathways during instruction about electric circuits and a way which allows for better planning for more effective instruction.

1.5 Key ideas needed to understand how electric circuits work

One of the most basic ideas required for the understanding of how the simple electric circuit operates concerns **what** constitutes an electric current in a closed loop. Understanding **how** current is generated in the circuit is also important. Resistance and how it controls the current together with the battery must be understood. Furthermore, students are expected to be able to grasp the meaning of p.d./voltage. They must acknowledge that, while there can be no current without having a p.d. across the battery terminals, it is when the current flows that a p.d. is established across resistors in the circuit.

On top of all this, these separate ideas have to be amalgamated, so that the circuit can be viewed as *a system*, where all the parts are working together, with changes made to one part of the circuit affecting the system as a whole.

These key ideas are expected to develop as teaching progresses and as students reflect about what they are taught and what they may observe during demonstrations, practical sessions, and indeed even during everyday life experiences.

1.6 The context of the study

1.6.1 Introduction

This study was carried out with students attending a post-secondary college in Malta. It is therefore appropriate to first look at the teaching content regarding electric circuits used at the various levels of schooling in Malta. Some details will then be presented about the entry requirements to study at the college where this research was conducted, and about learning practices in Malta, with particular reference to science learning.

1.6.2 The teaching content of electric circuits

A look at the Physics syllabi at various levels shows that at present, in Malta, the study of electricity is formally introduced at primary level (Directorate for Quality and Standards in Education (Malta), 2012). Young students are expected to understand, at least, that many things need a source of electrical p.d. in order to work, that a complete circuit is required to make a bulb light, that electricity may not only be converted to light but also to other forms of energy and that a switch can be used to start or stop a current.

At secondary level, students opting to study Physics cover a comprehensive syllabus (see Appendix 1) which introduces them to ideas about both static and current electricity. Students are made aware of positive and negative charges and of current conservation in a circuit. Resistances in series and in parallel are considered and students are taught how the sum of the potential differences across series resistors is equal to the battery voltage, and how the p.d. across parallel resistors is equal to the p.d. across battery terminals. The suggestion is that current and p.d. are introduced through measurements of meter readings. A qualitative description of these terms is also expected, together with an explanation of how p.d., current and resistance are related.

Potential difference (p.d.) seems to be covered rather superficially indicating that curriculum developers are aware that p.d. (or voltage) is a difficult concept to understand, which may be dealt with in more detail with older students at a higher level. Emphasis is put on everyday life experiences, with an experimental approach being suggested by the syllabus. Some websites aimed at promoting the use of multimedia during teaching are also indicated.

At advanced level, current electricity is covered in more depth (see Appendix 2), usually after students have been instructed in static electricity. Current is introduced as the primary concept. Reference is now made to how freely moving charges form the current. Electromotive force (e.m.f.) is defined and p.d. is explained in terms of work done per unit charge. Use is made of Ohm's law and potential division is considered. Factors affecting resistance and how resistance changes may be made in a circuit are also included in the study unit, together with ideas related to energy supply and consumption. At this level, although students are expected to be able to deal with both qualitative and quantitative problems dealing with current, p.d. and resistance, the syllabus does not indicate ways to make ideas more concrete and clearer for the learner. It is left up to individual teachers to devise ways of presenting key concepts to students in ways that help learning to progress.

1.6.3 Entry requirements to study at the post-secondary college

This research study was conducted with students in their second year of study, attending a post-secondary college in Malta. Since I teach Physics at this college, all data were collected with the help of students attending my classes at advanced level during the years of the research. I was thus teacher/researcher for my groups.

To study at the college, students require good passes at Secondary Education Certificate (SEC) level or, when applicable their equivalent, in at least 6 subjects. These must include English, Mathematics, Maltese, Physics or Chemistry or Biology, and any other two subjects. This means that students can study physics at advanced level without being in possession of a certificate at SEC level, but in practice this does not often happen.

It is the policy of the college to allocate students randomly to different groups. Students follow a two year course. They then sit national examinations to obtain the Matriculation Certificate, allowing them to enter University. Students sit six subjects chosen from four areas of study. The choice of subjects must include a language, a humanities or a business subject, mathematics or a science subject, and any other two subjects. The sixth subject is compulsory - Systems of Knowledge. This subject introduces the students to an appreciation of different forms of art, literature and technology. Students must study two subjects at advanced level and four subjects, including Systems of Knowledge, at intermediate level. The intermediate level for any subject is rated roughly a third of an advanced level.

1.6.4 Teaching and learning practices in Malta

It may be helpful at this stage, to also briefly describe teaching and learning practices in Malta.

Malta has always striven to provide a quality education for its students. In recent years the emphasis has been to try and instil creativity in our students and adopt teaching and learning processes which move away from the traditional transmission of knowledge to an inquiry based approach, with the learner in centre stage (see Ministry of Education (Malta), 1999; Ministry of Education, Youth and Employment (Malta), 2005; Ministry of Education, Employment and the Family (Malta), 2011)

This does not, however, mean that Malta can now boast of an ideal education system. A lot still needs to be done. Indeed, in spite of a number of reforms, Vanhear (2010), amongst others, complains that many local students have been conditioned to become passive learners. Professor Roger Murphy from the University of Nottingham, who has been involved in studies and recommendations about how the Maltese system of examinations can be improved, is quoted by Chetcuti (2011) saying that he still believes that much of the teaching in Malta imparts factual knowledge rather than improving reasoning and thinking skills. Furthermore, the performance in Science of Maltese students in Grade 8 (Form 3 in Malta) in the 'Trends in International Mathematics and Science Study' (TIMSS) carried out in 2007 was not very encouraging. Maltese students ranked 30th out of 49 countries (The Times (Malta), 2008; MASE (Maltese Association of Science Educators), 2009). MASE felt the need to comment on students' performance and made a number of recommendations public, amongst them one indicating the need to focus on science syllabi which deal with current issues in science, with the aim of making science more attractive for students. MASE also pointed to the importance of reducing recall of information and memorization of facts, while promoting reasoning and active student participation (MASE (Maltese Association of Science Educators), 2009).

It seems that even if in theory we seem to know what makes a good education system, yet, looking more closely at the details, the indication is that more needs to be done in the classroom to improve the effectiveness of the teaching.

1.7 A brief look at the research strategy adopted

Teaching at the same college where the research was going to be conducted made it possible for me to make cyclic research evaluations and improvements in my teaching methods with different groups of students, in successive school years. Action research or ‘classroom research by teachers’ (Hopkins, 2008, p. 58) was thus seen as the best way to undertake the research, since research plans could be revised and new plans could be put into action upon reflection.

The plan was thus to start my research with a first group of students (Cohort 1), reflect on the results, and re-plan for how to proceed with the teaching and research with a second group (Cohort 2) a year later, with the aim of improving learning outcomes.

Guided by the literature review related to electric circuit studies, the idea was to have students answer diagnostic tests questions about electric circuits, before the course of study, after the course, and also some time later, probing the mental models of the electric circuit which students seem to use as they learn the topic. Interviews with students were also planned, allowing for more in-depth probing of their ideas. In the analysis of the data, emphasis would be put on the reasons students give for their answers to diagnostic questions, as well as what students say during discussions with the researcher and other students in class time. Meaning would thus be given to students’ ideas in terms of mental models implied by their answers and explanations.

1.8 Overview of the thesis

Following on from this chapter, Chapter 2 reviews the research literature on the learning and teaching of electric circuits. Some studies which have shown students’ misunderstandings in this area are discussed and others suggesting methods of teaching to improve understanding are also reviewed.

Chapter 3 outlines the research strategy and explains the details of methods adopted and instruments used in the research with Cohort 1. Justification of what was done is provided. Teaching activities used with Cohort 1, over and above what is normally done during class-time, are indicated. These additional teaching activities were included to help students reflect more on their learning, directing students towards improving their visualization of how the electric circuit functions.

Chapter 4 analyses the performance of Cohort 1 on the physics diagnostic tests which were developed for this study. The results of the tests are compared to see whether students' views moved towards scientific ideas as teaching was in progress, and to check retention of these ideas, one month later. Specific problems which seemed responsible for the lack of understanding of key concepts are pointed out.

Chapter 5 analyses interviews conducted with nine students of different abilities from Cohort 1, with the aim of getting a clearer picture of students' views and the mental models implied by these. Ideas were probed to try to understand the difficulties students had indicated by the pre-test responses.

Chapter 6 then describes the teaching of Cohort 2 and analyses the progress in students' understanding. Reflections on the results obtained with Cohort 1 brought about changes planned in the teaching activities used with Cohort 2. Reasons for these changes are explained. Pre-test results are compared with those from Cohort 1 and changes in students' understanding indicated by the post-test and delayed post-test results are analysed to see by how far the revised teaching activities had led to improvement in students' learning. Interviews conducted with some students from Cohort 2 are used to highlight possible reasons for students' persisting difficulties.

Chapter 7 reflects on how far the research questions have been answered by the study. A discussion is presented comparing and contrasting the results from this work with those from some previous studies, with the aim of highlighting important issues contributing to knowledge. A model of how students' thinking progresses as a sequence of mental models is proposed. The strengths and weaknesses of the study are discussed and suggestions are made for future work.

Chapter 2 Literature Review

2.1 Introduction

Students find the topic of current electricity difficult to learn. This is not just my personal experience, but has been highlighted by many research studies conducted in the area of the study of electric circuits (see, for example, Clement, 2008a; Clement & Steinberg, 2002; Engelhardt & Beichner, 2004; Shipstone, 1985b). It is not surprising that the literature related to this topic is vast (see, for example, Duit, 2009), showing researchers' interest to try to understand students' problems, to find reasons for why these result and to find a solution to improve learning.

Indeed, at the early stages of this work, my main idea was to find out what makes so many students say that current electricity is a difficult topic, and why many actually experience this difficulty, never quite grasping the meaning of the key concepts involved or becoming able to use them in explaining observations and making predictions. Through the teaching of the topic, I was already aware of some problems which hindered students' learning, but it was by reviewing the literature about electric circuits that I realised that these problems with understanding were so common. The review of the literature helped to show what methods other researchers had used to understand students' specific learning problems. It also indicated ways of teaching the subject suggested by other researchers. It exposed students' intuitive ideas and alternative conceptions about key concepts which other researchers had identified by their work. All this information helped in the planning stages of this work, and while carrying out this study. At the same time, reviewing the literature helped to indicate any gaps that might be filled by future research.

This chapter first looks at some general issues concerning the development of ideas for understanding. Since the literature refers to a number of studies related to circuits which explain how students' understanding can be gauged according to the mental models students hold, some researchers' views on the term 'mental models' are first considered. The relation between mental models and analogies is then discussed. Further sections look at specific issues related to the literature about the topic of electric circuits. Some studies which focus on common misunderstandings that students develop are reviewed. This is followed by a discussion about why learning in this area is perceived as difficult, and what methods have been suggested by researchers to improve understanding.

2.2 The development of ideas for understanding

2.2.1 Mental models and modelling

Many authors have claimed that models and modelling are central to understanding key concepts in science (Coll & Lajium, 2011; Clement, 1989; Duit & Glynn, 1996; Gilbert & Boulter, 1998; Harrison & Treagust, 2000; Ramadas, 2009). While the term 'model' is used with a variety of meanings (Duit, 1991), this study refers specifically to mental models. Hestenes (1992) emphasizes the importance of mental models, referring to "a promising new approach to physics instruction in which students are taught from the beginning that in science modelling is the name of the game" (p. 732).

Whether we realise it or not, we all make use of mental representations to help us gauge our understanding. Rouse and Morris (1986) claim that "it is a common assertion that humans have 'mental models' of the systems with which they interact. In fact, it is hard to explain many aspects of human behaviour without resorting to a construct such as mental models" (p.349).

Johnson-Laird (1983) goes further into the details of explaining the nature of mental models, thus:

> Mental models play a central and unifying role in representing objects, state of affairs, sequences of events, the way the world is, and the social and psychological actions of daily life. They enable individuals to make inferences and predictions, to understand phenomena, to decide what action to take and to control its execution, and above all to experience events by proxy; they allow language to be used to create representations comparable to those deriving from direct acquaintance with the world; and they relate words to the world by way of conception and perception (p. 397).

Mental models are psychological representations of real, hypothetical, or imaginary situations (Johnson-Laird et al., 1998). Coll, France and Taylor (2005) define mental models as "human cognitive constructions used to describe and explain phenomena that cannot be experienced directly" (p. 184). Greca and Moreira (2000), like Duit and Glynn (1996), also claim that mental models refer to personal knowledge each of us builds as we perceive the world. Mental models can thus be seen as intermediate steps we create as our understanding develops towards views accepted by the scientific community.

Not all ideas are mental models. Mental models have a function and a purpose, namely to help the individual describe, explain and make predictions of the physical system represented by the mental model (Rouse & Morris, 1986). Mental models help us refine our thoughts and understanding. Lind (1980) claims that "model building has been an attempt to understand the invisible by depicting it" (p. 17). While some mental models help us understand the 'what' of a system, others help us understand and give reasons for 'why' a system works in a particular way. The latter have been referred to as causal models (Grotzer & Sudbury, 2000).

2.2.2 Relating mental models to analogies

Mental models are closely related to analogies. Coll et al. (2005) claim that analogies are "a subset of (mental) models as they involve the comparisons between two things that are similar in some respects. They are often used by scientists to explain abstract science concepts as well as when they are developing the complexity of their mental models" (p. 185).

There seems, however, to be some disagreement in the literature about how analogies are related to models. Coll and Lajium (2011), and Mozzer, Justi and Costa (2011) seem to look at models as analogies. On the other hand, other authors like Clement (2009), see analogy as a tool which can help model development.

Duit and Glynn (1996) claim that "analogies are at the heart of modelling" (p. 166). Figure 2.1 shows how Duit (1991) links analogical reasoning to modelling. An individual may already have a mental model of the analogue. By comparing elements of the analogue to those of the target, a mental model of the target is built, helping the development of ideas and understanding. This is how the relation between mental model and analogy is viewed by the present study.

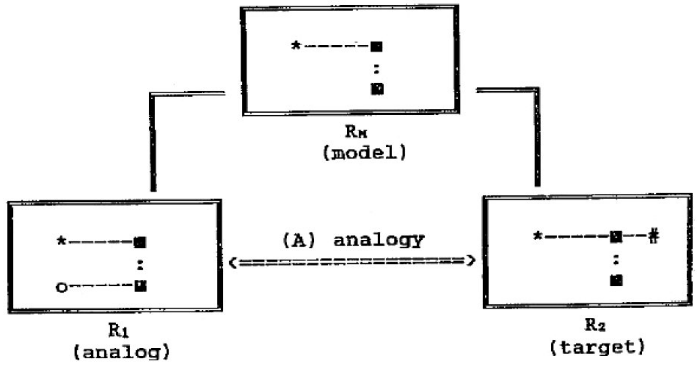


Figure 2.1: The relation between analogy and model (from Duit, 1991)

2.2.3 Analogies and analogical reasoning for understanding

A number of authors refer to the importance of analogy for understanding.

Gentner (1983) proposed a structural mapping theory explaining how analogical reasoning involves a sequence of steps to link elements in the analogue to elements in the target, helping to understand the target. Clement (2009) argues that "an interesting characteristic of analogical reasoning lies in the paradox that by seeming to *move away* from a problem, the subject can actually come closer to a solution" (p. 61). The same author explains how using analogies helps us build new ideas about the target from useful intuitions we may have about the analogue. Clement (2009) further explains the useful nature of analogies by arguing that while authors like Gentner, Gick and Holyoak, Holland et al. and Holyoak and Thagard consider that analogy helps in understanding the target in a more abstract way, yet, perhaps in addition to this, anchoring intuitions and bridging analogies help to enrich students' conceptions of the target.

Some researchers have also looked into spontaneous analogy generation by students (e.g., Clement, 2009; Clement, 1989; Wong, 1993a, 1993b; May, Hammer & Roy, 2006) and how this may be used as a tool to construct and refine ideas during learning. Furthermore, a number of authors have used analogies in their research studies on current electricity (e.g., Bullock, 1979; Clement & Steinberg, 2002; Gentner & Gentner, 1983; Johsua & Dupin, 2010; Osborne, 1983a; Paatz, Ryder, Schwedes, & Scott, 2004) testing by how far analogies can help understanding in this area.

This review of the literature related to analogy and analogical reasoning put a dual emphasis on the importance of the use of analogy, for teaching and research purposes.

Using analogy during the teaching could improve students' development of understanding. Allowing students to generate analogies as they explain their ideas would allow the researcher to probe further into students' ideas and the mental models which these ideas suggest they may hold.

2.3 Students' intuitive ideas

It is a common experience for teachers that students come to the classroom with pre-set ideas about any topic. This undoubtedly includes the topic about circuits. We all tend to formulate ideas about the world around us, depending on our experiences. Such ideas are often referred to as 'intuitive ideas'. The problem is that we may strongly believe in these 'intuitive ideas' and yet they do not necessarily agree with accepted scientific views. While some ideas develop as a result of experience, which may include teaching, others are found to be very resistant to change and can "remain uninfluenced or be influenced in unanticipated ways by formal science teaching" (Osborne, 1983a, p. 73). Problems with learning will result as a consequence.

For more than two decades, students' ideas in science, prior to formal instruction, have become a major concern among researchers in science education. Numerous studies have been published about students' pre-instruction ideas on a large number of topics (see Carmichael et al., 1990; Duit, 2009; Tsai, Chen, Chou, & Lain, 2007; Wandersee, Mintzes, & Novak (as cited in Lee & Law, 2001).

Students' pre-instruction conceptions/ideas have been given different labels by various researchers. Some have simply called them *preconceptions* (e.g., Novak (as cited in Lee & Law, 2001) and others (e.g., Helm, 1980; McDermott & Shaffer, 1992) have referred to them as *misconceptions*, to emphasize the disparity of ideas with the scientific views. However, Driver and Easley (1978) preferred the term *alternative frameworks/ conceptions*, arguing that intuitive ideas make perfect sense to the students and that the students cannot see them as wrong within their own knowledge structures. The neutral term, *children's science,* used by Gilbert, Osborne and Fensham (1982) and Osborne (1983b), also has its significance in explaining that the child's conceptions in question are a result of his/her own thinking.

While all these ‘labels’ have been used with a reason by the various authors indicated, the preference in the present study is for the use of the term ‘alternative conceptions’, since these ideas offer different ways of looking at science, even if views are not yet scientific.

2.4 Some characteristics of studies about electric circuits

2.4.1 The samples in various studies

The fact that current electricity is taught in schools at all levels helps to understand why a lot of the research conducted about circuits involves samples with a wide age range. Moreover, studies regarding circuits have been practically undertaken by researchers from all over the world. The following are some examples.

Fleer (1994) conducted a study in Australia with a group of 5-7 year olds. She explored how a group of 25 students dealt with the abstract concepts related to circuits in early childhood. Not many studies about electric circuits have involved students at this young age. Shepardson and Moje (1994, 1999) examined how elementary school children in two classrooms in the United States dealt with ideas about circuits as they observed and discussed circuit diagrams. Liégeois, Chasseigne, Papin, and Mullet (2003) worked with 100 students in France. Students were 13-17 years old. Borges and Gilbert (1999) conducted their research with 56 participants of different ages and different knowledge of physics. The sample consisted of secondary school students in Brazil (15-16 years old) as well as college and university students, physics teachers, electrical engineers and practitioners (electricians or school laboratory assistants). Fredette and Lockhead (1980) assessed the conceptions of simple circuits of North-American university students studying engineering. They interviewed 24 engineering majors enrolled in introductory physics courses, and later administered a written quiz to 57 freshman engineering students. On the other hand, a much larger sample of 1250 students from all over Europe took part in a comparative study undertaken by Shipstone, von Rhöneck, Dupin, Johsua and Licht (1988). The students were 15-17 years old.

2.4.2 The aims of some studies undertaken

The studies conducted on this topic have had different aims. Some of these are outlined below.

- Some of the earlier works were directed at gaining insight into what individuals understand by current (e.g., Psillos, Koumaras, & Valassiades, 1987; Shipstone, 1985b), trying to put the different ideas into categories indicating the presence of different mental models of current held.

- There were studies which aimed at establishing the meaning students give to potential difference and voltage (e.g., Gunstone, McKittrick, Mulhall, & Case, 2001).

- Some studies were conducted with the aim of finding out more about whether intuitive ideas depended on the age of participants in the study, also trying to establish whether ideas about electricity are primarily dependent on development/cognitive processing or teaching, or both (e.g., Dupin & Johsua, 1987; Monk, 1990; Asami, King & Monk, 2000).

- Deciding how and when students' ideas could be developed and modified through the schooling years was also an important aim (Osborne, 1983a).

- Other studies aimed at establishing students' learning pathways, in terms of mental models inferred when students explained their ideas (e.g., Niedderer, 2006; Niedderer & Goldberg, 1994, 1996).

- Stocklmayer and Treagust (1996) probed images of electricity visualized by learners - whether it is a mechanistic view of moving electrons (a view students usually hold) or a field view (usually used by experts) - with the aim of discovering possible methods of how the teaching of circuits could be approached.

- Some other researchers aimed at developing a more adequate curriculum in this area of study by using the results of their research exposing students' difficulties. Teaching strategies were proposed to facilitate ways of developing students' mental models, leading students to look holistically at the electric circuit (e.g., Carlton, 1999; McDermott & Shaffer, 1992; Shaffer & McDermott, 1992).

2.4.3 Different research designs and data collection methods

The early works published were typically explorative and descriptive, probing students' alternative conceptions (e.g., Shipstone, 1985a, 1985b). Cross-age studies were also conducted (e.g., Borges & Gilbert, 1999; Shipstone, 1984). A good number of case studies also appeared (e.g., Clement & Steinberg, 2002; Paatz et al., 2004). Some of these described an intervention (like the use of an analogy, for example) used during the normal teaching programme, exploring its effect on students' understanding. Other studies like McDermott and Shaffer (1992) and Shaffer and McDermott (1992) were longitudinal in nature and took the form of action research, with cyclic improvement of the teaching based on research evidence.

With regard to data collection methods, paper-and-pencil tests have been a popular way of collecting data. Some researchers preferred open-ended questions referring to simple electric circuit diagrams (e.g., Psillos et al., 1987). Others used questions demanding a 'True/False' answer, or used multiple choice questions (e.g., Shipstone et al., 1988). In this way, many prevailing ideas could be pin-pointed using large samples.

Some researchers (e.g., Fredette & Lochhead, 1980; Osborne, 1983a; Tiberghien & Delacote, 1976) probed students' ideas of how a circuit works through the observation of students as they carried out a given task using batteries and bulbs.

In order to get a deeper understanding of students' answers, some researchers conducted interviews. Clement and Steinberg (2002), Fredette and Lockhead (1980), Niedderer (1994, 1996), Stocklmayer and Treagust (1996) are examples of studies conducted by adopting the interview approach. McDermott and Shaffer (1992) reported a range of methods used in their research, "from individual demonstration interviews to descriptive studies carried out during instruction in the classroom" (p. 995). In a demonstration interview, students were shown a demonstration using real equipment or a computer simulation, and this helped in starting a discussion between the researcher and the interviewee. Different methods of data collection used to investigate students' ideas can, indeed, indicate more specifically, the problems which students encounter in their learning and can thus be used to better guide future teaching and learning processes.

2.5 Literature on common misunderstandings about circuits

2.5.1 Electric Current

To the physicist, "electric current consists of a flow of charged particles", and "the magnitude of the current in a circuit is equal to the rate of flow of charge through the circuit" (Muncaster, 1993, p. 534). The equation,

$$I = \Delta Q / \Delta t,$$

where I stands for the current in a circuit, ΔQ stands for the charge difference/transferred and Δt stands for the time interval during which this charge transfer occurs, offers a mathematical explanation for what is current.

Young students, however, who have not yet had any lessons on the electricity topic, start their schooling experience with the meaning of current which they derive from everyday electricity talk. Duit and von Rhöneck (1998) claim that "it is possible to state that the meanings of words for current in European languages are generally nearer to the meanings of energy than to the current as used in Physics" (p. 50). This might be the result of the visual experience of having a light bulb, for example, giving out light energy, when a circuit is switched on. Such experiences make it possible to confuse current with energy. The use of the general term 'electricity' may also provide the possibility of having students thinking and talking of current without building the necessary model required for understanding. Indeed, Shipstone (1988) warns that it is unwise to assume that when children speak of 'electricity', then they have grasped the concept of current.

Shipstone's work (1984, 1985b) was particularly instrumental in exposing different ways in which students look at current in a simple circuit. Students may model current using the ideas indicated by the diagrams in Figure 2.2.

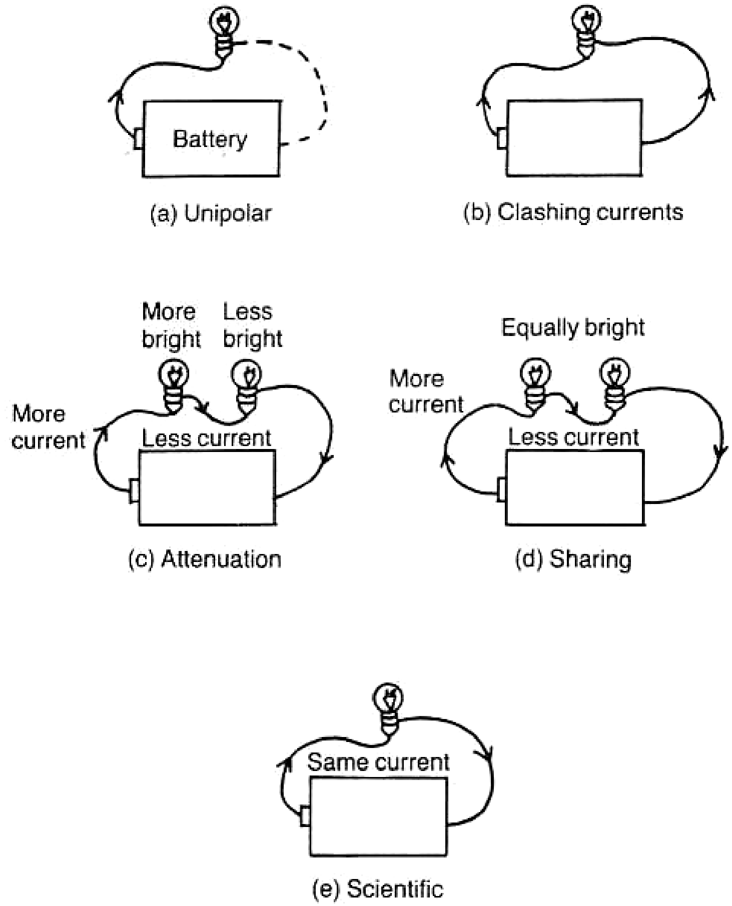


Figure 2.2: Children's models for current in simple circuits (from Shipstone, 1985b, p. 36)

These models of current are briefly explained below.

- The unipolar model (Figure a)

In this model, the return path may not be visualised, and if it is, then no current is seen in it. Some students see this return path as a passive link. This model represents a source-consumer model.

- The clashing currents model (Figure b)

In this model, current flows to the bulb from both terminals of the battery. This is an extension of the previous model. "It represents a clear attempt to assimilate the necessity for the second wire to a source-consumer model" (Shipstone, 1985b, p. 37).

- The attenuation model (Figure c)

There have been a good number of reports indicating the existence of this model. McDermott and Shaffer (1992) report that it is common for students to think that the current is 'absorbed' or 'used up' by the component through which it is passing and that the direction of the current and order of the elements matter. Licht (1991), McDermott and van Zee (1985) and Shipstone (1985b) also refer to students' alternative conception of less current downstream than upstream. Very much linked to this idea is the fact that students tend to reason 'locally' or 'sequentially' about the effects of changes in an electric circuit (Closset, 1983; Shipstone, 1984). If a variable resistor is altered, a change at one point in a circuit is not necessarily seen as causing changes elsewhere in the circuit. Moreover, many authors (e.g., Arnold & Millar, 1987; Engelhardt & Beichner, 2004; Fredette & Lockhead, 1980; McDermott & van Zee, 1985; Millar & King, 1993; Osborne, 1983a, 1983b; Shipstone, 1984) have referred to how students tend to predict changes in meter readings 'after' the resistor but not before. Students may find it difficult to move away from the sequential view. Shipstone (1985b) claims that:

> the importance of the sequential model is underlined because of its high incidence and persistence amongst able students who have specialised in physics: it was found, for example, in 7 out of a group of 18 graduate physicists and engineers who were training to be physics teachers (p. 42).

The sequential model has been referred to by Shipstone (1985b, 2002) as 'a time dependent model' since students fail to see the current simultaneously everywhere in the circuit when this is switched on, but think of the current as taking time to flow from one component to the other.

- The sharing model (Figure d)

In a series connection made up of a number of equal components, the current is seen as being shared equally. Two identical lamps will light up to the same brightness, for example, but current is not regarded as conserved.

* The scientific model (Figure e)

Students look at the circuit like experts do and see the current in one direction being conserved.

Shipstone (1984) reports that the popularity of the various models changes with the pupils' ages and experience. Figure 2.3 shows the results from his study conducted in three 11-18 British comprehensive schools and one sixth form college.

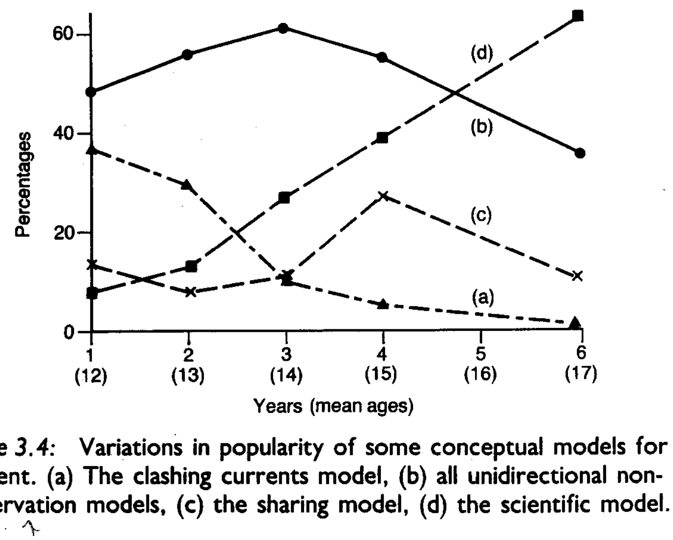


Figure 2.3: Variations of popularity of some conceptual models for current (Shipstone, 1985b, p. 39)

The results shown in the above graph are supported by Osborne (1983a) and Dupin and Johsua (1987) who have shown that some students' general understanding improves with age and instruction. Eylon and Ganiel (1990) claim that mental models of current "become more advanced: primitive models are abandoned in favour of more scientific ones" (p. 79).

Millar and Beh (1993) say that to build a model of current, students need to base their idea on two things:

* "the need for a closed loop; and
* the observation that current is the same at all points around the loop" (p.352).

Shepardson and Moje (1994) claim that to conceptually understand current in simple electric circuits is a prerequisite to understanding conceptually more complex electric circuits. This emphasizes the importance of having students grasp the meaning of current as early as possible in their schooling, otherwise how can they be expected to learn material related to this topic, based on a lack of conceptual understanding of fundamental principles?

2.5.2 The function of the battery

A number of authors (e.g., Licht, 1991; McDermott & Shaffer, 1992; McDermott & van Zee, 1985; Shipstone 1985b, 1988) have reported that many students seem to believe that the amount of current supplied by a battery is always the same, irrespective of the number of components there are in the circuit or the way these components are connected. Steinberg and Wainwright (1993) refer to this as "battery autonomy" (p. 354).

Moreover, Thacker, Ganiel and Boys (1999) also say that a common idea for students is that "charges originate in the battery only" (p. S28). This is referred to as 'battery origin' (Cohen, Eylon & Ganiel, 1983; Steinberg & Wainwright, 1993). The findings from Eylon and Ganiel (1990) and Gott (1985b) indicate that in such a case, the wires are seen as playing no active role in current formation.

Eylon and Ganiel (1990) also claim that the battery may sometimes be seen "to act like a 'pump', causing electrons already present in the wires, to circulate around the circuit" (p. 91).

2.5.3 Resistance and resistance combinations

Psillos and Koumaras (as cited in Liégeois & Mullet, 2002) claim that "from the physicist point of view, resistance is due to the friction of the moving electrons with the conductor/resistor ions" (p. 553). The larger the friction, the smaller the electron flow and therefore the smaller the current. The resistance of a resistor is constant at a constant temperature.

Some students, however, find it hard to give a qualitative explanation of resistance. Johnstone and Mughol (1978) say that since electrical resistance is not an everyday topic which is usually discussed, students do not easily grasp the meaning of the term. Understanding resistance can thus depend largely on teaching, which may not emphasize enough that it is the resistance and the battery together which control the size of the current in the circuit. In a longitudinal study conducted with 800 pupils of mixed ability, taking students from middle secondary schools to sixth formers, Johnstone and Mughol (1978) tested how teaching affected the understanding of resistance. The researchers interviewed students in groups of 6, using circuit boards and other simple apparatus through the interviews. In an effort to use a larger sample, they also set diagnostic test questions based upon the circuit diagrams of the apparatus which was used in the interviews. Some main conclusions from this work were that:

- the majority of students could relate large length of a wire to large resistance;
- most of the older students could relate cross-sectional area of a wire to its resistance;
- students up to age 16 seemed to say that a short, thin wire had the least resistance.

Thus, while ideas regarding length and cross-sectional area, taken separately were shown to be well internalized by students, yet when it came to dealing with two variables simultaneously, namely length and thickness, younger students' intuitions were too strongly influenced by the 'more of A, more of B' style of reasoning (see Andersson, 1986; Stavy & Tirosh, 1996). Students can easily become distracted when dealing with more than one variable, falling back on their unhelpful intuitions.

Another problem some students encounter is related to the total resistance in a circuit. The tendency is for students to focus on the number of components and not on the circuit configuration. This was shown by McDermott and Shaffer (1992) who claim that even 'good' students found it hard to correctly, predict the relevant brightness of the bulbs in Figure 2.4, and explain their reasoning. One student - a prospective teacher - explained that bulbs B, C, D, and E would be equally bright, but half as bright as A. With reference to bulbs B, C, D, and E, the student referred to the battery of the same strength being used on 2 identical bulbs. Thus reasoning was based on the number of bulbs per branch, rather than on how they were connected, ignoring the relative resistance within each branch.

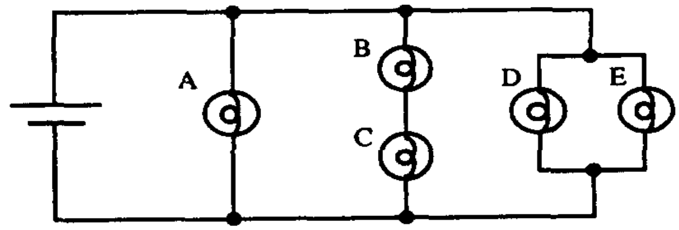


Figure 2.4: Predicting the relative brightness of the bulbs (from McDermott and Shaffer, 1992)

(Note: Students were asked to rank by brightness the five identical bulbs in the circuits shown and to explain their reasoning. They were told to assume that the batteries are ideal. The correct response is A=D=E>B=C)

McDermott and Shaffer (1992) also reported that students had difficulty in identifying series and parallel connections, especially when more than two components were used. Students failed to identify the connections made in complicated circuits.

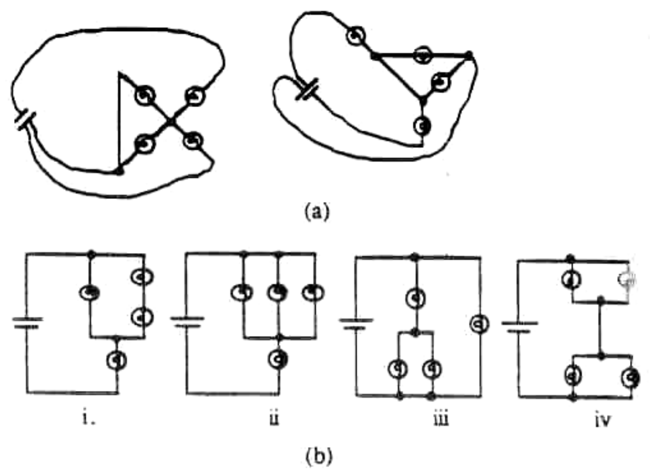


Figure 2.5: Resistance in complex circuits (from McDermott & Shaffer, 1992)

When students were asked to identify which circuit diagrams in Figure 2.5 were equivalent, the same authors claim that:

> students tended to focus on the physical lines connecting the elements rather than on the electrical connections represented by the lines. Lacking an adequate procedure for determining the types of connections between the bulbs, the students would often fail to recognise that the second circuit in Figure 2.5(b) is the correct diagram for both circuits in Fig. (2.5a) (p. 999).

The authors report that "some students would obtain a different answer each time they attempted to solve the problem" (p. 999). This indicates confused ideas, resulting in unstable reasoning related to how components are connected.

2.5.4 Potential difference/voltage and potential

Many researchers, amongst them Gunstone et al. (2001), Jung (1985a, 1985b) and Liégeois et al. (2003) claim that the concept of potential difference is difficult to master. Haertel (2008b) claims that the idea of potential remains rather vague and potential difference is an extension of a vague concept. Liégeois et al. (2003) and Millar and King (1993) claim that p.d. is not commonly dealt with in everyday life experiences and this may be one of the reasons for the difficulty in understanding. Thus, the literature points to a similar problem with p.d., as has already been mentioned in the case of resistance.

Asking a student at secondary school level to explain p.d., he/she may resort to stating the following definition: "The potential difference (p.d.) between two points in an electric field is numerically equal to the work done in moving unit positive charge from the point at the lower potential to that at the higher potential" (Muncaster, 1993, p. 575). But, whether students can define p.d. or not, what meaning do they give to the term 'potential difference'?Duit and von Rhöneck (1998) indicate that some students relate p.d. to 'strength of a battery' or 'intensity of force of the current', before instruction. These authors also say that, even after instruction, students use the p.d. concept in a way which shows that they believe that it has the same properties as the current concept. Liégeois and Mullet (2002) also claim that students and most non-professionals in the field tend "to view electrical current as the origin of potential difference, and potential difference as a mere measure of electric flow, more or less synonymous with intensity of current" (p. 553). Shipstone (2002) reported that 31% of the 232 students in his sample, consisting of students from three 11-18 comprehensive schools and from a sixth form college in the U.K., explained voltage in terms of 'something which flows'.

Students are usually first instructed about current and this may be what makes it easier for them to think primarily of current, rather than p.d., as they explain how circuits work. Cohen et al. (1983) conclude that current is the primary concept used by students, while p.d. is regarded as a consequence of current and not as its cause. McDermott and Shaffer (1992) and Shaffer and McDermott (1992) claim that students are current minded rather than voltage minded and tend to use the rules for current in series and parallel circuits, when dealing with potential differences. Because of this emphasis on current, students confuse cause and effect even in simple circuits (Cohen et al., 1983; Eylon & Ganiel, 1990).

Maichle (1981) also refers to this misunderstanding related to current and voltage, saying that “voltage is very often conceived as part, as quality or property of the current or even as identical with the current” (p. 176). She describes how some students think of the current as existing inside the battery and therefore the battery becomes the ‘giver’ of something - namely the current. In a study undertaken by the same author, 84% of the secondary school children in a German Realschule, 85% of the secondary students from the Gymnasium and 40% of the university students preparing to become physics teachers, looked at current in this way. Students in the first two groups were 13 to 15 years old. In what is termed as the GIVE-schema, the battery is seen as giving current to a bulb, with the voltage becoming a property of the current. The current is thought of giving rise to the voltage, and a ‘has’-relation is thus created, “which denotes the relation between a concept and one of its parts or its properties” (Maichle, 1981, p.176). Figure 2.6 is a rather crude representation of these ideas put together.

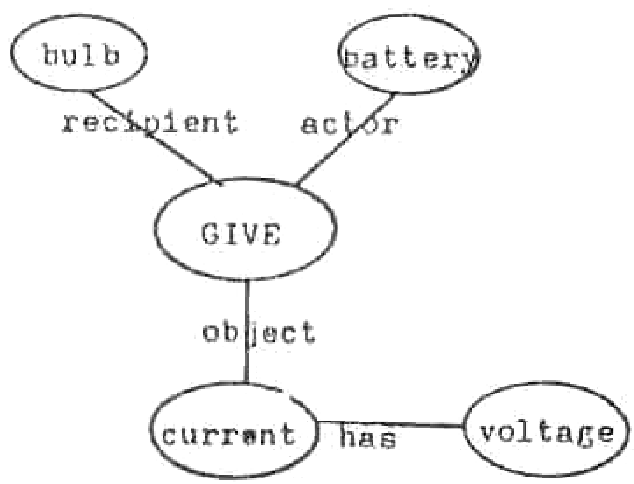


Figure 2.6: Students’ representation of a simple electric circuit by utilizing the GIVE-schema (shown here as presented in Maichle, 1981)

Maichle’s (1981) study also shows that 59%, 71% and 40% of the respective sample groups mentioned earlier, focused on the resistance of the bulb. They saw this as taking off part of the current’s intensity, giving rise to the TAKE-schema.

These ideas from Maichle's (1981) study highlight a very important point, namely, that if electric current is viewed as already existing, stored in the battery (an idea also indicated in Gott (1985b) and Eylon and Ganiel (1990)), then "voltage has lost its function of causing the electric current" (p. 179). The importance of conceptualizing voltage is thus not given prominence by students who have no reason to look for what causes the current. This can make it more difficult for students to form mental representations of voltage, which in turn creates difficulty in the understanding of more complex circuit situations, at least before they come to terms with the meaning of voltage.

Millar and King (1993) and Tiberghien (1983) claim that students find it difficult to discriminate between current and voltage. These researchers cite the work of von Rhöneck who reports that many students (12 to 16 years old) incorrectly predict no voltage across an *open* switch in a simple circuit carrying a battery and a bulb, and that the *closed* switch has the battery voltage across it. Tiberghien (1983) makes it clear that students think of the presence of voltage only when current is circulating.

Moreover, another difficulty for students is when they come to distinguishing between p.d. and potential. McDermott and Shaffer (1992) report that being asked to predict the relative brightness of the bulbs in Figure 2.7, students in their study gave incorrect answers supported either by ideas related to sequential reasoning and current being used up or by faulty reasoning.

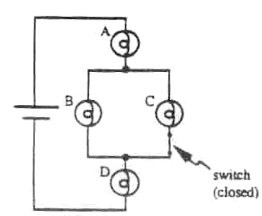


Figure 2.7: Predicting the brightness of identical bulbs when the switch is closed (from McDermott and Shaffer, 1992, p. 998)

These researchers report one student's answer as follows: "Bulb A is the brightest because the potential is highest. Bulb B and Bulb C are next because they're on the same potential. Bulb D is the dullest due to the lowest potential" (p. 998). The authors rightly argue that in providing such an explanation the student "mistakenly associated the brightness of a bulb with the value of the potential at one of its terminals, rather than with the potential difference between the terminals" (p. 998).

2.5.5 The lack of a system view

The difficulties students encounter with the understanding of key concepts can promote an unhelpful view of the electric circuit based on different components working separately. Students do not manage to deal with changes made to a circuit in a holistic manner.

Cohen et al. (1983) who conducted research with a sample of 145 students (15-17 years old) and 21 Physics teachers, asking questions about circuits which mainly required a qualitative answer, refer to this difficulty. The researchers report that many students saw changes made to a circuit affecting the circuit locally, not globally. They say that students find difficulty in dealing with functions with more than one variable, with the difficulty increasing when variables change simultaneously. This is very similar to what was pointed out with reference to how students deal with factors affecting resistance in section 2.5.3.

2.5.6 Persistence and consistency of students' intuitive ideas

It is intended that instruction helps the evolution of students' alternative ideas towards scientific ones. At the same time, the literature related to circuits indicates that some students' can hold on strongly to some alternative ideas, using these even after instruction. Moreover, some studies have shown that students' tend to use some alternative ideas consistently in different contexts.

McDermott and Shaffer (1992) report that the performance of students on several of the tasks given to the students to answer "indicated that most had not yet synthesised the basic electrical concepts into a coherent framework" (p. 1001). Lacking a conceptual model that students could use as a basis for predictions, "the students resorted to formulae, relied on intuition, or attempted to do both" (p. 1001). At the same time, the researchers claimed that some students' intuitions were so strong that when the result of a calculation contradicted expectations, students would sometimes modify the mathematics to accommodate their intuitive ideas.

On the other hand, Licht and Thijs (as cited by Licht, 1991) have reported that secondary school students tend to use alternative conceptions less frequently but more coherently than younger students. It seems that the older students get, the more ingrained their alternative conceptions become and the more students fall back on them, if required. Licht (1991) emphasizes this, at the same time as indicating a way to identify these conceptions. He claims that:

> the construction of clusters of questions which deal with the same concepts in several contexts has a benefit in that it contributes to the identification and fairly precise categorization of errors and conceptual difficulties. It appears that pupils do not make incidental mistakes, but show patterns of conceptual difficulties and ways of reasoning (p. 272).

2.5.7 Retention of the learnt material

There seem to be conflicting reports on students' learning about simple circuits and the retention of ideas acquired through teaching.

Some researchers say that most students learn the scientific view, but given time, they regress to their original non-scientific ideas. Osborne (1983b), for example, refers to a study conducted in New Zealand, with a small group of fifteen, 11 year olds. After a year, more than half the students did not retain the scientific view of current. Interviews conducted with the students gave evidence that while the students were aware of the scientific view, they still could not understand it. They thus held non-scientific views which made more sense to them.

Gauld (1988, 1989) worked with 14 year old secondary school students from New Zealand, using experiments that critically challenged students' existing mental models of circuits. He found that testing the students immediately after the course of study showed that most students had scientific views. When the researcher tested the students 3-4 months later, the results indicated that some students, who had held the scientific view in the short term, had reverted to their intuitive ideas in the delayed interviews. Students had distorted the results of the experiments they had seen, to match the alternative ideas they had previously held before instruction.

Fleer (1994), on the other hand, claims that having used an interactive teaching approach with her students, asking questions about batteries and bulbs which they could investigate, 19 out of the 25 students in her sample showed retention of ideas, 3 months after the course. These students were 5-7 years old.

2.6 Why learning about the electric circuit may be difficult

2.6.1 Introduction

The previous section looked at problems students find as they deal with circuits. This section looks at opinions from different authors who have tried to find reasons for the problems students find. The discussion presented below relates to, what the word ‘abstract’ means in relation to circuits, how students’ intuitions can hinder learning, whether students’ cognitive ability has an effect on learning, and whether teaching can itself create difficulties for the learner. A look is also taken at some studies which highlight the missing link between the teaching of static and current electricity.

2.6.2 The abstract nature of the topic

A number of authors (e.g., Chabay & Sherwood, 1999; Sherwood & Chabay, 2010; Fleer, 1994; Haertel, 2010; Stocklmayer & Treagust, 1996; Taber, de Trafford & Quail, 2006) attribute at least some of the difficulties students find in understanding current electricity to the abstract nature of the topic. Students see the apparatus but cannot see what goes on inside it. A number resulting on an ammeter, or a light bulb which lights up, is only the interpretation of an indication that current is present in the circuit. While there is evidence of the effects of the current, the moving charges in the wires have to be imagined, along with causes for why they move. Furthermore, developing mental visualizations of how a resistance controls the current together with the battery voltage, and giving meaning to p.d. may prove to be difficult tasks to accomplish.

2.6.3 The experiential gestalt of causation

In trying to understand students’ reasoning more deeply, Andersson (1986) suggests that students’ preconceptions in science have a common core. The author calls this core the *experiential gestalt of causation* (EGC). According to Andersson (1986), students' intuitive reasoning pattern can be seen to consist of three elements: agent – instrument – object (see Figure 2.8).

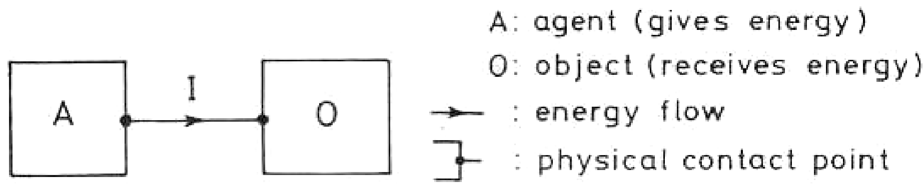


Figure 2.8: Students' intuitive reasoning pattern: agent - instrument - object (from Andersson, 1986, p.157)

Children learn from a very early age to expect this pattern. The child discovers that the greater the effort he makes, the bigger the effect on the object. Different objects resist to different degrees. Several agents have a greater effect than just one. The nearer the agent is to the object, the greater the effect. The child then uses this type of reasoning in many circumstances, applying it in more complex situations, even when EGC leads to incorrect predictions. To give just one example, pupils reason that a larger number of batteries should increase the light intensity from a bulb. This is correct if the batteries are connected in series but not if they are connected in parallel.

It seems that intuitively we are prone to reason in this specific way, even in different contexts. Andersson's report refers to studies conducted with a number of students (ages 12 to 15) attending a Swedish comprehensive school, as well as with Swedish elementary school student teachers and American college students. The results from these studies demonstrate that students use the EGC in their explanations and predictions in different areas of Physics, such as heat, light, mechanics and electricity.

Astolfi (as cited in de Posada, 1997) agrees with Andersson (1986) and claims that students' alternative ideas "are not isolated, they belong to a framework in which different elements support and reinforce one another" (p. 463). De Posada (1997) claims that some researchers take different stands on why students' preconceived ideas are deep-rooted. Preece and Sebastiá (as cited in de Posada, 1997) suggest "that there are some cognitive a priori structures that *canalise (added italics)* the interpretation of the reality in a determinate way" (much like Andersson's (1986) EGC interpretation), "conducting students to create 'natural' interpretations, while students obstruct other 'non-natural' explanations" (p. 462). On the other hand, Castro and Fernández (as cited in de Posada,

1997) refer to Piaget's stages of development (see Inhelder & Piaget, 1966). They point out that "students' ideas are inadequate adaptations to the reality, presumably because students have neither formal nor post-formal operational development" (p. 463).

2.6.4 The level of students' cognitive processing

De Posada (1997) is not alone in suggesting that students' ideas related to models they hold of electric circuits may depend on the level of students' cognitive processing. Monk (1990) carried out a meta-analysis from a Piagetian epistemological perspective of earlier research undertaken on electrical circuits. He attributed stages to students' answers related to mental models of current presented in Shipstone (1985b) (see section 2.5.1), according to the reasoning required to provide a specific answer. He looked at the results of tests in simple electricity from Shipstone (1985b) and, compared them to results indicating the cognitive level of students from a survey reported by Shayer and Adey (1981). Monk found that the percentages of students in Shayer and Adey's sample, at the various cognitive levels, were comparable to those obtained by Shipstone for the different models of current. This provided an indication that the mental models used by students to understand direct current electrical circuits depend on students' Piagetian stage of cognitive development. Both Monk (1990) and Asami, King, and Monk (2000) claim that students cannot understand abstract ideas which are beyond their level of cognitive development.

2.6.5 Teaching as a cause of learning difficulties

In section 2.3, it was mentioned that science teaching might influence ideas in 'unanticipated ways' (Osborne, 1983a; see also Niedderer, 1994, 1996). It seems that while this may result from poor lesson interpretation by the learner, other reasons may include teaching methods which demotivate the learners and imprecise teacher talk. Thus teaching itself can sometimes be a source of learning difficulties.

Ward and Wandersee (2002) explain that situations in the classroom, following the long-established tradition of transmission of knowledge, may not motivate students to learn. They claim that when the teacher just presents knowledge to the learner, without leading students "to grasp the meaning of a learning task, the learners' confidence wanes" (p. 575). Rote learning is encouraged and this does not allow for proper knowledge integration. Often, students “fill the gaps with alternative conceptions to support their conceptual house of cards” (Novak, as cited in Ward & Wandersee, 2002, p. 575).

Shipstone (1984, 2002), and Grotzer and Sudbury (2000) claim that in current electricity, unless teaching is conducted using carefully chosen classroom talk, it is easy to describe current in a sequential way, starting at the battery. Furthermore, the term ‘p.d.’ and the word ‘voltage’ are used interchangeably, both often indicated as ‘V’. This may create confusion. While von Rhöneck (1985) states specifically that “voltage in physics is not a force, it is a potential difference” (p. 283), thus equating the two terms, other authors criticize the interchangeable use of the words ‘voltage’ and ‘p.d.’ Gunstone et al. (2001) claim that it is a complex matter to make inferences about student understanding, when explanations are given in terms of ‘V’. In asking: “Does V refer to ‘voltage’, ‘voltage drop’ or potential difference?” (p. 14), these authors imply that they see some distinction between these terms. They rightly argue that teaching ‘V’ in different ways (e.g., ‘energy provided per unit charge…’ or ‘energy lost per unit charge….’) makes the concept difficult to understand, claiming that “this complexity is to a considerable extent a consequence of physicists not having an accepted response as to the question, ‘What is ‘V’?” (Gunstone et al., 2001, p. 14).

Shaffer and McDermott (1992) aim at reducing misunderstanding by suggesting the use of the word ‘voltage’ at the start of a course of studies, associating it with the voltmeter reading in a circuit. They describe how, in the same way that a bulb would show an increase in brightness when the number of batteries connected in series is increased, a voltmeter replacing the bulb can be used to show that the voltmeter reading indicates the ability of the battery to ‘drive’ the current through the circuit. This would give a meaning to the voltmeter reading to students. Later, “the term *potential difference* is used after the concept of potential has been developed” (p. 1006).

Another issue which may add to students’ confusion may be the different ways of presenting concepts in text books. Considering resistance, when Iona (1979) examined how this was explained in various physics textbooks used from secondary school level to university level, he found that as a general rule it was presented in a rather abstract mathematical way by starting with some defining equation. He also described other approaches which were used, namely the use of ‘the fluid-flow analogy’ or a model of charges moving in an electric field, or detailed experimental investigations and related discussions about length and cross-sectional area of wires to bulb brightness. It was claimed that "in comparing the approach that different authors use in teaching the concept of electrical resistance, one is impressed by the variety of possibilities and the fact that there does not seem to be an obvious relation between the approach and the level for which the various texts are intended" (p. 299). An examination of how the resistance concept in some physics text books being currently used in Malta, from secondary to advanced level (see Duncan, 1994; Farrell, 2004; Xuereb, 1999) shows that after a brief description of resistance as the opposition to the flow of charge by the conductor atoms, the authors quickly introduce equations to define R. Duncan (1994) uses $R=V/I$. Xuereb (1999) uses the same equation and refers to Ohm's law. Farrell (2004) uses the equation $R=\rho L/A$, where ρ refers to the resistivity of the conductor, L to its length and A to the cross sectional area of the conductor. These approaches also indicate a variation in the way the concept is presented, at the same time as possibly reflecting the brisk way in which the resistance concept is sometimes taught, without resorting to tools like analogies and experiments to aid learning.

2.6.6 Macro-micro relationships: the missing link

Research has pointed to difficulties in learning current electricity resulting from treating the concepts learnt in static electricity as separate and perhaps different from concepts used in current electricity. Eylon and Ganiel (1990), Licht (1991), Viennot and Rainson (1992) have referred to this as a missing link between macro-micro relationships. (The term 'micro', short for 'microscopic', in fact refers to sub-microscopic properties of the circuit. These terms are used with this meaning in further sections of this thesis.)

In Israel, Eylon and Ganiel (1990) studied how a sample of 92 students (17-18 year olds) reason about mechanisms in electric circuits, during discussions involving transients in simple circuits. They confirmed that only a minority of students, who had already been instructed in electrostatics and electrodynamics before sitting for the advanced level examinations, were able to tie concepts from electrostatics to their description of phenomena occurring in electric circuits. The authors noted that the situation did not "necessarily represent misconceptions, but rather the lack of any clear concepts" (p. 92). The study revealed that "the concept of voltage remains vague and its formal definitions (quoted correctly) are not utilized operationally" (p. 92). While students performed satisfactorily in the quantitative aspect of the study, they showed superficial generalization of rules, leading to the interpretation of rules erroneously: for example, since V=IR this leads to the conclusion that V=0 when I=0 (also reported by Cohen et al., 1983). The missing macro-micro link was described as the reason behind students' lack of a systemic view of the electric circuit. The authors' plea was for students to be guided to a better understanding by making this macro–micro link between concepts, so as to be in a better position to visualize a functional model of the mechanism in electric circuits.

Licht (1991) supports the analysis of Eylon and Ganiel (1990) and also relates the lack of the macro-micro link to difficulties students show in the understanding of the topic of electric circuits. Licht (1991) suggested a sequence of instruction with an emphasis on covering both qualitative macro and micro phenomena, before proceeding to teaching the quantitative.

Viennot and Rainson (1992) focus on the instability of students' reasoning related to the electric field and argue for the need "to look for ways of unifying the patchwork of ideas" (p. 486) with which electrostatics is linked with electrodynamics. The authors suggest that at least at college level (with students 16-18 years old), instruction should link the idea of field in electrostatics, with the important presence of the field in electrodynamics - a link often not easily acknowledged by learners.

2.7 Finding ways which may help learners' understanding

2.7.1 Towards modifying unhelpful ideas

In the same way as research studies have focussed on common misunderstandings with electric circuits and reasons for learning difficulties, much research has also focussed on ways which may help learners in developing their mental models, moving towards a scientific view.

It must be stated at the onset that, nowhere in the literature regarding studies related to electric circuits is it documented that modifying students' unhelpful ideas is an easy task. Studies have more often shown that students hang on to their intuitive ideas, and even if these are modified as a result of teaching, many students revert to the original ideas, given time (Osborne, 1983b; Shipstone & Gunstone, 1985). On the other hand all educators expect learning as a natural outcome of teaching. It is thus only natural that we start helping students to develop scientific ideas as early as possible. Osborne (1983a) shows concern and "fear that if the children's ideas are not modified at a relatively early age then these children may ossify in their thinking" (p. 81).

While the modification of students' ideas rests primarily on the way students make use of their pre-existing knowledge and their motivation to extend and develop their ideas, educators cannot shift all the responsibility of learning on the students. Schools, as the professional bodies, need to look at what research has been conducted and into problems with students' understanding being consistently reported, such that teaching methods and curriculum development based on the research findings may then be considered and possibly implemented.

2.7.2 Exploring learning pathways

In the late '80s and into the 90's, researchers extended the traditions on students' alternative conceptions to investigations of learning processes. Several focussed their attention on probing 'learning pathways' as teaching and learning are in progress. Scott (1987) described pathways in learning related to the particulate nature of matter. Niedderer (2006) claims that this work was the first learning pathway study conducted. Niedderer and Goldberg (1994) and Clement and Steinberg (2002) probed learning pathways followed by individual students, specifically during instruction in current electricity. Developing learning pathways is seen as a way to help develop teaching approaches to support learning (Scott, 1992).

Niedderer and Goldberg (1994) investigated the learning processes of a group of three prospective elementary school teachers (age 21). While this study, based on a small sample, cannot be considered as offering evidence of a general nature, yet it is valuable because it highlights some basic ideas about how some students learn. Niedderer and Goldberg (1996) described learning pathways by considering a learning route of cognitive states, starting with the prior conception (PC) (which is referred to as Everyday Life Current (ELC)) and going through intermediate conceptions (IC) developed during teaching (see Figure 2.9).

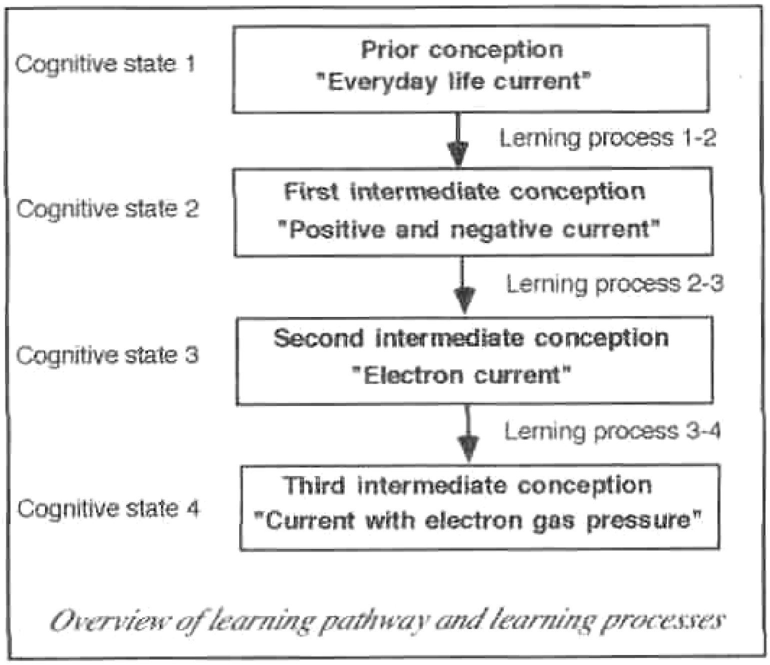


Figure 2.9: Cognitive states learning route (from Niedderer & Goldberg, 1996, p. 3)

The authors claim that ICs become further elaborated upon, by “facets” or “smaller pieces of knowledge that students seem to be applying in problem situations” (p. 1). As the term used implies, ICs are ‘in between’ and ‘somewhat fragile’ and ‘may get either higher or lower’ during the ongoing learning process. The more stable they become, the more these conceptions affect learning. It is claimed that a learning pathway is discovered from intermediate conceptions, which are viewed as stepping stones (Niedderer & Goldberg, 1996). The authors report that “always in new and complex situations, Lynn (the student whose ideas were being followed) starts with the prior conception ‘everyday life current’ (ELC)…..” (Niedderer, 1994, p. 26). So, once again, reference is made to the robust nature of intuitive ideas.

Through the instruction phase, Niedderer and Goldberg made use of the electron gas pressure model to guide the ‘thinking mode’ of the learners (Niedderer & Goldberg, 1994). The same model is used by Steinberg and Wainwright (1993) in the CASTLE Project. They defend this model, saying that “the idea of ‘electric pressure’ in a conducting body is a highly intuitive version of electric potential in *conducting matter*. Mental images of charge being compressed and the ‘pressure’ building up as a consequence are powerful causal concepts that students can use for thinking about what is happening in electric circuits without appealing to mathematical formulas” (p. 355). On the other hand, Mosca and De Jong (1993) strongly criticize the use of the electron gas pressure model for two reasons. In the first place, they do not agree with "raising a loose analogy for the idea of circuit … to the status of a model" (p. 358). The second problem they note is that while electric currents in wires are driven by electric fields which result from surface charge distributions, according to the compressible fluid model it is the pressure gradient resulting from a volume density and not a surface density, which drives the current.

Clement and Steinberg (2002) followed a pathway of student learning using the pressure in a compressible fluid analogy. This makes this research similar to that of Niedderer and Goldberg (1994). Clement and Steinberg (2002) looked into the model evolution of Susan, (the student participating in the case study), as she reassessed and revised her ideas, during instruction. Once again a significant feature of this work is that it is based on the ideas of one student, but at the same time the researchers analyse deeply what the student says during the learning/interview sessions conducted. In this study, comprehension was aided through the use of multiple 'small' discrepant events and analogies built into the lessons (see Figure 2.10).

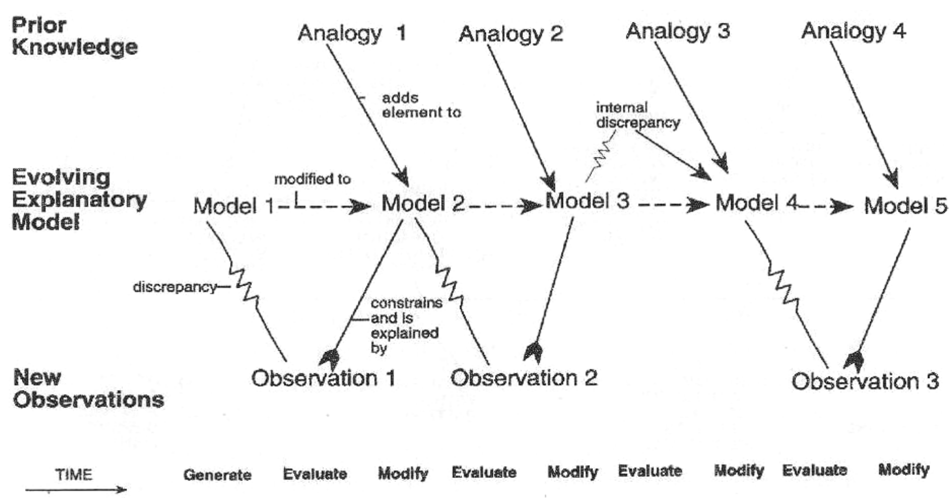


Figure 2.10: Using discrepant events and analogies to help in the evolution of a new model (from Clement and Steinberg, 2002, p. 425)

Discovering possible learning pathways used by different learners can be a first step towards better and deeper understanding of both the key concepts involved in learning a topic and the problems that block understanding of that topic.

2.7.3 Focussing on the mental models of electric circuits

As has already been referred to in section 2.2.1, a number of science educators have found the idea of 'mental models' useful in thinking about how students learn in many scientific domains. Research conducted by Osborne (1983a, 1983b) and Shipstone (1984, 1985b) had indicated the mental models of current held by the participants in their studies. The issue of learning via model construction started to be addressed (Clement, 1989).

When in the late 90's, Borges and Gilbert (1999) reported on a study which they conducted with 56 participants of different ages and experience with physics learning (see section 2.4.1), their research results suggested four models of the electric circuit. These models indicated a progression starting from an early view held by young students and proceeding to a sophisticated view held by scientists, thus:

- electricity as flow;
- electricity as opposing currents;
- electricity as moving charges;
- electricity as a field phenomenon.

Essentially, the first three models focus on current and its presence in a circuit. The last model, making reference to the presence of the field, goes further, including ideas related to p.d.

The research conducted by Grotzer and Sudbury (2000) examines the models of current documented by Shipstone (1984, 1985) and categorises them in terms of whether they are linear or cyclical models, describing them as follows:

- the mono-polar model is the basic idea visualised by the younger learners when they hold a 'linear' or 'sink' model. There is a cause directly linked to an effect;
- the 'clashing-currents model' still indicates a model with an essentially linear structure, even if it is two causes leading to the effect;
- the attenuation model is a definite step forward, away from the linear models. Students now see a complete circuit with current moving in one direction and their ideas evolve

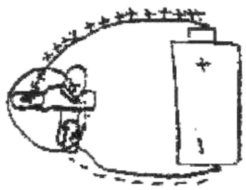
towards a cyclic pattern of events, but the time between cause and effect is still a property of this model. This is a 'cyclic sequential model';

- the sharing model is the first model that clearly moves away from the time lag between cause and effect. Two bulbs are seen as receiving the current simultaneously and sharing it;
- the scientific model is a cyclic model where the effect is experienced simultaneously in every part of the circuit.

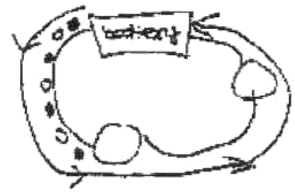
Grotzer and Sudbury (2000) also propose their models of circuits based on conceptual development, accompanied by *causal* reasoning. The models proposed are similar to Shipstone's models, but the authors claim that their proposed models "are grouped by the causal assumptions that one needs to make in order to understand them and the conceptual leaps needed in understanding causality in order to progress from one set to the next" (p.4). This is what distinguishes them from previous models. Moreover, Grotzer and Sudbury (2000) look at the 'why' (i.e. the cause) of current flow, rather than just at the 'how' it happens. Figure 2.11 shows diagrams to represent these causal models. The first three are essentially the same as Shipstone's models. The fourth model is a 'cyclic simultaneous model'. The time lag between cause and effect is no longer a requisite for this model. The circuit can now be visualised as a system working together, much like the often quoted bicycle chain effect. A 'relational interactive' causal model is also presented in a fifth model. Here p.d. is understood as causing a *differential effect,* providing flow because of different charge density accumulation, at different points in the circuit.

Thus the models indicated by Grotzer and Sudbury (2000) progress to provide reasons for why current results in a circuit, directing the learner to move to more powerful and explanatory models, not only of current but also of the abstract ideas behind potential and potential difference.

a: Simple linear models

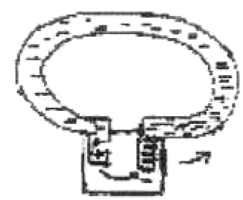


b: Double linear causal models



c: Cyclic sequential causal models

d: Cyclic simultaneous causal models



e: Relational interactive causal models

Figure 2.11: Linear and cyclical causal models of how a simple circuit works (from Grotzer & Sudbury, 2000, p.5)

2.7.4 Proposed teaching sequences

The primary thought behind any lesson planning involves sequencing ideas which can be made use of to design instructional activities aimed at improving understanding. The literature related to circuits has shown a number of researchers advocating the use of some teaching sequence which may have been found to be effective in their work. Different teaching sequences have, however, been presented making it hard to reach an agreement about which teaching sequence best serves the purpose.

Shipstone and Gunstone (1985) (also referred to in Shipstone, 1988), talked about students' initial idea of circuit or "embryonic concept" (p. 93) which relates more to electrical energy than to electric current, when students use the source-consumer model at the start of a learning programme. They thus advocated that referring to 'electrical energy' first, would be more effective. In their instructional sequence used with secondary school students (12-13 years old), current was introduced later, as a cause of the magnetic effect of electricity and as what moving coil ammeters measure, hoping to discriminate between current and energy.

Licht (1991) agreed with the introduction of energy first, but argued, in addition, that the introduction of current as the means of transportation of energy from the cell to the bulb cannot be postponed. In this case, a sequence was proposed in 5 blocks, each being introduced at different levels, to secondary school students. The programme was labelled as follows:

block 1 a phenomenological orientation

block 2 a qualitative macroscopic treatment

block 3 a qualitative microscopic treatment

block 4 a quantitative macroscopic treatment

block 5 a quantitative microscopic treatment, including the theoretical concept of an electric field

(from Licht, 1991, p. 273)

In this sequence, the initial emphasis lay on the qualitative introduction of the topic, based on the observed behaviour of circuits as the number of bulbs or cells is changed. Licht (1991) suggested 'choosing the energy concept as an entrance to the cluster of core concepts in electricity' (p. 274). Like Shipstone and Gunstone (1985), Licht (1991) believes that energy is more closely related to students' intuitive ideas. Later, a treatment of microscopic representations is included, such that students could be brought to visualize what goes on in the circuit before being instructed to deal with the topic quantitatively.

Contrary to the above, Osborne (1983a) stated categorically that:

> electric current is the important and basic idea and a less abstract concept than electric energy. If children are to use simple circuits to examine conductors, if children are going to appreciate why an ammeter may be placed at any position in series circuit, if children are going to really understand why a circuit will not operate unless it is complete, if children are going to understand about series and

parallel circuits, then it is essential they first understand about electric current (p. 80).

Shaffer and McDermott (1992) supported the view that while starting a sequence of instruction by dealing with potential difference or energy offers other possibilities, yet "these alternatives have disadvantages that outweigh the benefits" (p. 1007). These authors explain how dealing with potential difference implies that students have to see both *the flow* and *the push* which they refer to as 'pressure', while starting with current implies dealing with the concept of flow alone, a concept which "is more intuitive to students" (p. 1007). Furthermore, while these authors admit that "students try to base their explanations on energy considerations", yet, "when they attempt to reason on the basis of energy, they have difficulty in reconciling the dissipation of energy with the conservation of current" (p. 1007) and thus introduction of the concept of energy early in the model's development leads to complications. They advocate that "it is easier 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" (p. 1008).

On the other hand, Haertel (1982, 1985a) proposed a different approach. Current, voltage and resistance introduced simultaneously in a qualitative way, would make it more possible to view the circuit as 'a system'. The author explains that contrary to sequential reasoning which is very dominant, the idea of systems with elements having strong relations between each other is not so common. He suggests introducing the circuit system by using analogies which do not reinforce sequential reasoning, referring to the use of the idea of a stiff ring, the bicycle chain and the water analogies as a support for understanding.

2.7.5 Emphasis on the macro-micro relationship

With respect to the macro-micro relationship, it has already been previously pointed out in section 2.6.6, that various researchers have emphasised the importance of having students understand and link concepts in static and current electricity. The literature targeting this problem and how to solve it points in two directions. On the one hand, some researchers work at producing teaching strategies emphasising this link. On the other hand, other researchers take the stand that the link between electrostatics and electrodynamics is missing because instruction is not exposing the students to all content which needs to be learnt in order for the link to be made.

The work of Borghi, De Ambrosis and Mascheretti (2007) is an example of how researchers work at producing teaching sequences with the aim of helping students merge ideas developed in electrostatics with those in electrodynamics. These authors report their on-going research testing a sequence of teaching, based on the examination of problems which were being experienced with ideas in electrostatics by 30 Italian student teachers. The sequence still needs to be tested with high school students. The authors believe that poor understanding of electrostatics phenomena influences the understanding of electric circuits. They claim that if students lack the microscopic models which scientifically explain concepts in electrostatics, then the idea of the circuit as a system and of voltage as the property of the circuit which drives the current cannot be understood. The teaching sequence they have proposed emphasises electrons as the moving charges and guides students towards an understanding of the presence of the force field which surrounds any charge. The experiments they propose focus on the "particular role of electrons as elementary charges both in electrostatic phenomena and in currents" (p. 154), using transients. The innovative aspect of this work is the fact that the researchers managed to include experiments in their teaching sequence which can take the learners 'backwards' in their line of thought, in the sense of being able to experiment and obtain results associated with static electricity, by using a battery.

Microscopic models for bridging electrostatics and currents

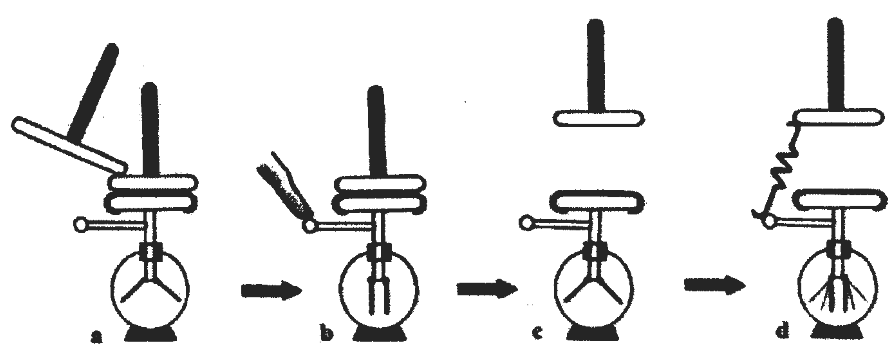


Figure 12. In (a) and (b) two metallic discs are charged. The system is a capacitor with variable capacitance. In (d) a current discharges the capacitor.

Figure 2.12: From electrostatics to electrodynamics (from Borghi et al., 2007, p. 153)

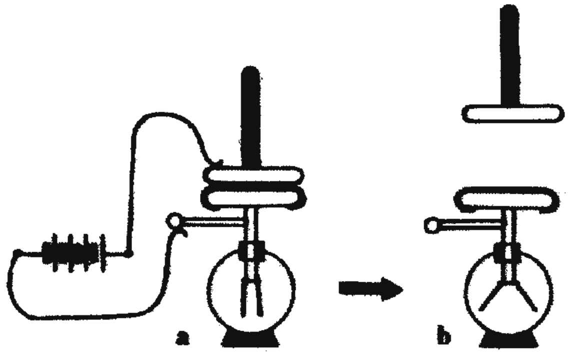


Figure 13. A capacitor is charged by means of a battery.

Figure 2.13: From electrodynamics to electrostatics (from Borghi et al., 2007, p. 153)

The diagrams in Figures 2.12 and 2.13 show apparatus which can be used to help the students to go back and forth with their ideas, merging ideas usually called upon only in static electricity with microscopic ideas required for the understanding of electric circuits.

Other authors and researchers choose to see the problem of the lack of macro-micro link from a different perspective. These argue that students miss the relationship between static and current electricity because they lack instruction on, and exposure to, study material related to *surface charges* which accumulate on wires and resistors and which thus creates the electric fields which guide the movement of charge in the circuit.

Haertel (2008b) has presented work related to the presence of surface charges on wires and conductors making the electric circuit, yet the idea is certainly not a new one. Rosser (1963, 1970) referred to charge distributions being “built up on the surface of the connecting wires in an electric circuit, which serve to ‘guide’ the electric current along the length of the connecting wire” (p. 884). He was already pointing to the fact that the topic of electric circuits was not being covered adequately during teaching, because the idea of the presence of surface charges was not being given the importance it deserved. Other authors like Jefimenko (1962) and Walz (1985) also voiced the same opinion.

Heald (1984) stated further that surface charge distributions are usually “very difficult to calculate and measure” (p. 522). This was offered as one possible reason why the presence of surface charges on current carrying conductors has not been given the importance it deserved in text books and in various courses of study.

While the electric fields are weak and the associated surface charge is very small, Jefimenko (1962) argued that the occurrence of these electric fields in current carrying conductors, "in the laboratory, in nature, and in industry, is at least as frequent as that of the electrostatic fields" (p. 19). He also described how to make the electric fields visible with the aid of printed circuit-type models (see Figure 2.14). The models consist essentially of a printed circuit of the system on glass plates, using transparent conducting ink. The lines of force inside and outside the elements of these models are demonstrated with the aid of grass seeds which are strewn upon them. These seeds are neutral in their natural state, but become polarized in the field, aligning themselves along the electrostatic field lines (Assis, Hernandes & Lamesa, 2001). Thus, the concept of electric field need not be just left to the imagination of the learner.

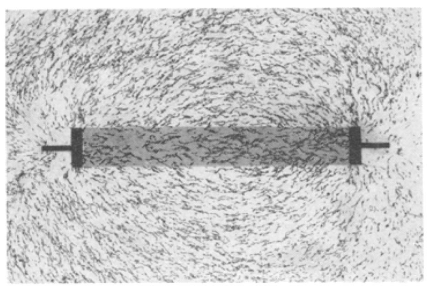


FIG. 1. Electric field of a straight conductor.

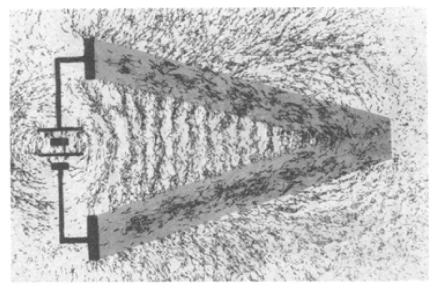
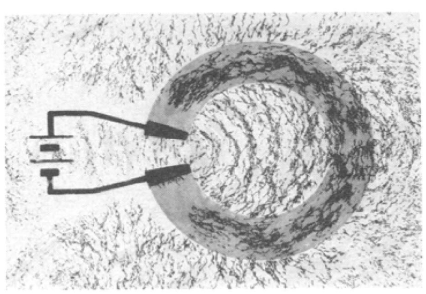


FIG. 2. Electric field of two intersecting straight conductors.



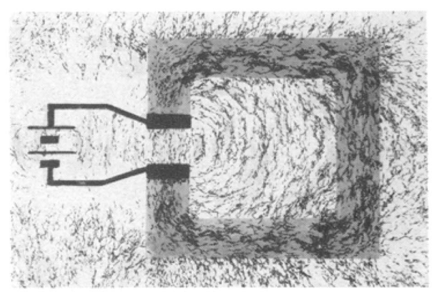


Figure 2.14: Fields inside and surrounding current carrying conductors (from Jefimenko, 1962, p. 20)

Jackson (1996) explained how surface charges on circuit wires and resistors play three roles:

- they maintain the potential around the circuit;
- they establish the electric field in the space around the circuit;
- they assure the confined flow of current

Haertel (1985b), who emphasised the pedagogical importance of surface charges in circuits, provided a diagrammatic explanation of "the process which builds up the extra charges on the surface of a wire and on the resistor after the battery is connected to the circuit" (p. 360; see Figure 2.15).

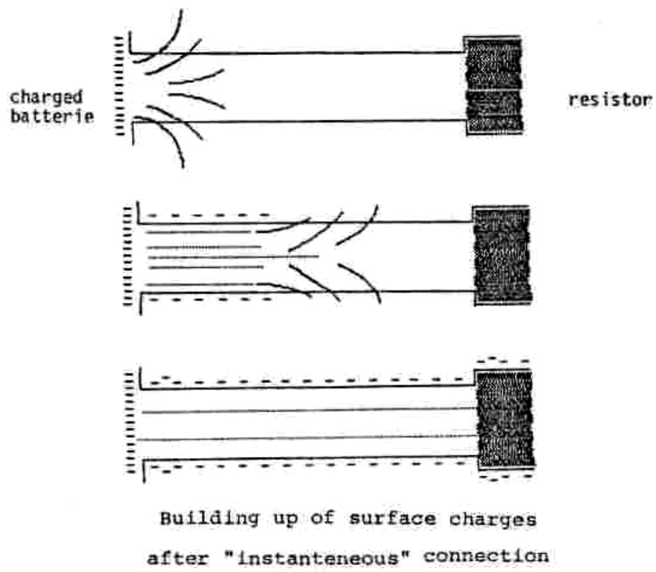


Figure 2.15: Building up of surface charges after connecting a complete circuit (from Duit, 1991)

In a paper entitled 'The so-called simple electric circuit', Haertel (2008a) explains that for a current to be maintained through a conductor, an internal driving force is needed to overcome the opposing effect of the resistivity of the conductor. "Such an internal force, which has to be oriented in parallel to the axis of the conductor, can only be produced by a certain distribution of charges on the surface of such conductors" (Haertel, 2008a, p. 5). This distribution of charge is shown in Figure 2.16.

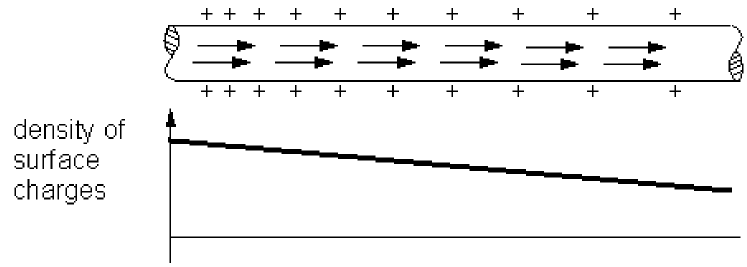


Figure 2.16: Linear density distribution of surface charges on a rectilinear conductor (from Haertel, 2008a, p. 5)

> "For the simplest case of a rectilinear homogeneous conductor, carrying a constant current, it can be calculated that it needs a linear change in the distribution of surface charges to produce an internal constant force oriented parallel to the conductor. This is also called a linear gradient of the surface charge distribution" (Haertel, 2008a, p. 5). In his work Haertel (2008a) also explains how an internal force acts in a similar way in curved conductors. Considering electrons as charge carriers, there is a higher surface charge density on the outbound surface of the conductor compared to the inner side and vice versa for positive surface charges (see Figure 2.17).

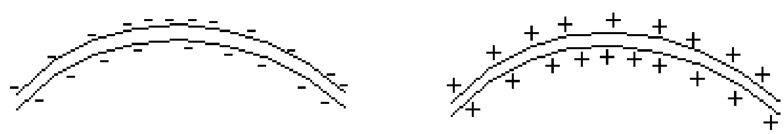


Figure 2.17: Distribution of surface charges for curvilinear conductors (from Haertel, 2008a, p. 5)

Preyer (2000) explains that the electric field inside a conductor adjusts itself such that it is everywhere parallel to the wires.

> In wires of constant conductivity and width, the internal electric field is uniform in magnitude. In other situations the surface charge increases the electric field in high-resistance regions, and decreases the field in low-resistance until, by a feedback process, the current has the same value in all segments. (p. 1006).

Thus the idea of how current is the same everywhere in the circuit may be explained.

The idea of surface charge can also help to explain voltage. Haertel (2008a) explains that:

> A voltage or potential difference between two points within an electric circuit is present whenever charges are separated, either in the form of surfaces with a certain density of charges with opposite polarity or with a difference in surface charge density. Such charge separation calls some Coulomb forces into existence which try to re-install neutrality. These forces create a voltage or potential difference. This is valid for electrostatic situations as well as for current carrying electric circuits (p. 6).

The literature related to surface charge formation in closed electric circuits indicates the belief of the various authors that only when the students become aware of how the charge densities and surface charge affects the circuit, can students qualitatively understand how an electric circuit works as a system. The belief is that when students can deal with ideas expressed by diagrams like the ones shown in Figure 2.18 and other diagrams similar to the ones indicated in this section, then students can make the mental move towards visualizing what a voltmeter reading truly indicates, why the current is the same everywhere in a circuit, and how and why current can move along the circuit, even along the bends in connecting wires.

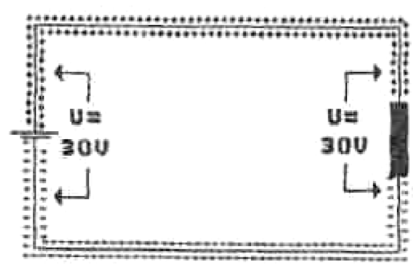


Figure 2.18: Surface charges on a circuit with one resistor (from Haertel, 1985b)

The idea of surface charge can thus link static to current electricity providing clear knowledge of how scientists understand the concepts involved. Perhaps this work may be too advanced for young students, but a brief introduction late at secondary level or sixth form/college level may help students' understanding of how the circuit functions. Chabay and Sherwood (1994, 1999) and Sherwood and Chabay (2010) emphasise that the idea of surface charge together with qualitative reasoning is a way to improve understanding of circuits.

2.8 Summary and conclusion

An extensive literature exists related to learner's understanding of key ideas in simple electric circuits. Much of the research was undertaken to probe students' alternative ideas in this area of physics.

Many studies have been conducted looking at students' representations of current and how these change with age and instruction.

Studies related to resistance are not as numerous as those probing ideas about current, however, popular models of resistance have been identified. Students of different ages who focussed on the load (the resistance or bulb) in a circuit were found to often explain resistance in terms of a Take-schema – meaning that components 'take' the current they need to operate correctly. Other students, who focussed more on the battery and saw this giving 'something' to the resistance/bulb, reasoned in terms of a Give-schema.

Other studies on p.d. have shown that this concept is not one that students understand easily. Some studies suggested giving a meaning to the voltmeter reading, relating it to the ability of the battery to drive a current, rather than presenting voltage/p.d. in some abstract way. A number of studies also showed that many students do not discriminate between p.d./voltage and current. The literature speaks of many students expecting zero p.d. when the current is zero, indicating students' erroneous belief that p.d. does not exist without current.

A number of studies pointed to how students' alternative conceptions may be very deep-rooted, persisting even after instruction. The consistent use of some alternative conceptions was also indicated.

Across the numerous studies conducted, various methods have been used to collect data. Paper-and-pencil tests are quite common, with a majority of these being accompanied with interviews, probing students' understanding more deeply. Sometimes, individual demonstration interviews were used to help students in their discussion and interaction with the researcher.

The literature indicates imprecise teacher talk, as well as the abstract nature of the topic, amongst factors which create difficulty for understanding circuits. It is also important to note that a few researchers linked the ideas which students seem to hold about circuits to students' level of cognitive development. This pointed to an explanation for why some key concepts may be more demanding to understand than others. The missing macro-micro link between the concepts used in electrostatics and in current electricity was also indicated by researchers as a cause for the lack of understanding of circuits. Some authors also pointed to the lack of explanations of electrical phenomena in terms of the surface charge which results on conductors when a current is flowing. Ideas about surface charge in relation to circuits may not be included in syllabi at secondary and post-secondary level. However, by referring to surface charge one can explain the presence of the electric field lines exactly following the line of the wires in the circuit. This helps to explain why free electrons move through the wires when a p.d. is present.

The importance of mental models and analogical reasoning in their central role for understanding is also highlighted by this literature review. Some researchers aimed at establishing mental model pathways tracking students' intermediate mental models during learning. Various teaching sequences have been suggested by different researchers but it is difficult to conclude which sequences might be more effective for improving students' learning. Research conducted more recently has emphasised the importance of causal reasoning and its use in refining mental models, leading towards scientific ideas. The importance of asking the question 'Why?' during the teaching and learning process becomes more pronounced.

Even though so much research has been conducted about circuits, very little has yet tried to link students' intermediate mental models of the key concepts, as learning is in progress. The present study focuses primarily on this issue, with the aim of producing more detailed evidence of how students use and link the key concepts involved, whilst probing why some ideas are more difficult to understand than others. Whilst no blueprint can ever exist whereby all students are guaranteed success in the learning of this abstract topic, the indicators provided by the body of research conducted in this field nonetheless offer insights into how to increase the likelihood of successful learning. These insights helped in planning the research strategy which is presented in the next chapter.

Chapter 3 Methodology

3.1 Introduction

The literature review shows clearly that a lot of research interest has been shown by many researchers who have looked into the various problems students encounter in the understanding of electric circuits. This chapter elaborates on decisions made to organize a research strategy that would help in making this study one which contributes further to the knowledge on this topic.

In the following sections the research questions are first stated. The type of research which was used is described and reasons are provided to indicate why this was deemed to be the best way to answer the research questions. A brief outline of the research strategy chosen for this work is then presented. Further sections describe more specifically, the details of the methods adopted and instruments used in the research. Reasons for choices made, as well as for revisions of plans and actions are given, as the details of the research strategy adopted over the years of study is described.

3.2 The research questions

The primary aim of this study was to try to improve the effectiveness of my teaching of the topic through the course of study. Following the claim by a number of authors that models and modelling are central to understanding key concepts in science (see Coll & Lajium, 2011; Clement, 1989; Duit & Glynn (1996); Gilbert & Boulter, 1998; Harrison & Treagust, 2000; Hestenes, 1992; Ramadas, 2009) it was decided that looking into the difficulties students have in understanding electric circuits, trying to find out what mental models, if any, students develop and seem to use, and how these models change as students learn the topic, was a way of achieving this aim.

The study was guided by the following research questions:

- Which models of electric circuit do Maltese students at pre-university (post-secondary) level appear to use as they study the topic of electric circuits?

- What possible learning pathways can be shown to exist, in terms of mental models which individual students own, and which can serve as a guide towards indicating a general hierarchical structure of models of circuit?
- Is there evidence that particular approaches used during the teaching process have a significant influence at guiding students' thinking towards the use of scientific mental models of the electric circuit?

3.3 The type of research conducted

Since I lecture pre-university students on current electricity, I easily fitted into the role of teacher-researcher, probing students' understanding before the initiation of the course, through the course, and after teaching the topic. I had the possibility of performing cyclic research evaluations and improvements in the teaching methods with different groups of students, during different scholastic years. Each cycle would help refine the previous and inform the next. Action research, or what Hopkins (2008) prefers to call 'classroom research by teachers' (p. 58), was thus the best way to try and answer the research questions. Moreover, action research would allow for the possibility of the research plan to be flexibly revised, after reflecting on the results obtained through the cycles of the study, leading to further action-on-reflection (Cohen, Manion, & Morrison, 2001; Feldman, 1994; Hopkins, 2008).

Hopkins (2008) states that the method of action research makes 'a twin emphasis on committed action and reflection' (p. 49). He explains that "action research combines a substantive act with a research procedure; it is action disciplined by enquiry, a personal attempt at understanding while engaged in a process of improvement and reform" (p. 47).

While Hopkins (2008) quotes a number of definitions of action research from various works by other authors, I particularly related well with the one quoted from Mills (2003: 1), namely:

Action research is a systematic inquiry conducted by teacher researchers to gather information about the ways that their particular school operates, how they teach, and how their students learn. The information is gathered with the goals of gaining insight, developing reflective practice, effecting positive changes in the school environment and on educational practices in general, and improving student outcomes. (p. 48)

This definition formed the basis of my study and took into account what I wished to achieve together with my students. Plans had to be made such that methods would be used that would involve students as Fielding (cited in Hopkins, 2008) described it, that is "not only as 'data sources' or 'active respondents' but also as 'co-researchers' with teachers" (p. 54). Punch (2009) also refers to students acting as 'co-researchers' (p.137). This meant that, while as the teacher-researcher I had to try and understand students' difficulties through the mental models students seem to use, I also needed to guide students in thinking about their own thinking. Even the students needed to become aware of their problems in understanding, so that they would try and find ways of correcting these problems, if possible.

3.4 An outline of the research strategy

In an effort to make it easier to follow the 'circles and spirals' which characterise action research (see Cohen et al., 2001; Costello, 2011; Feldman, 1994; Hopkins, 2008), a brief outline of the research strategy is shown schematically in Figure 3.1.

At the initial stage, the literature review and my teaching experience guided the process of problem identification, in this case, namely, students' poor understanding of electric circuits. This led to the clarification of the research aims, before deciding what research strategy would best be adopted to answer the research questions. Conducting action research meant that the study included various cycles of planning, action and reflection-on-action. In the 1st cycle plans had to be made regarding what teaching activities would be included to help the understanding of Cohort 1 and what methods and instruments would be used for data collection. Some pilot studies had to be conducted early, after the planning stage, to ensure reliability of some of the instruments chosen. In the 2nd cycle plans had to be revised regarding teaching activities and data collection methods, aimed at improving the effectiveness of the teaching with this second group. Data collection and reflection on the results with Cohort 2 then followed. Due to time constraints, a 3rd cycle of the action research was not possible, but reflections on the results from the 2nd cycle helped to indicate the way forward with the next sample group, when that will be conducted.

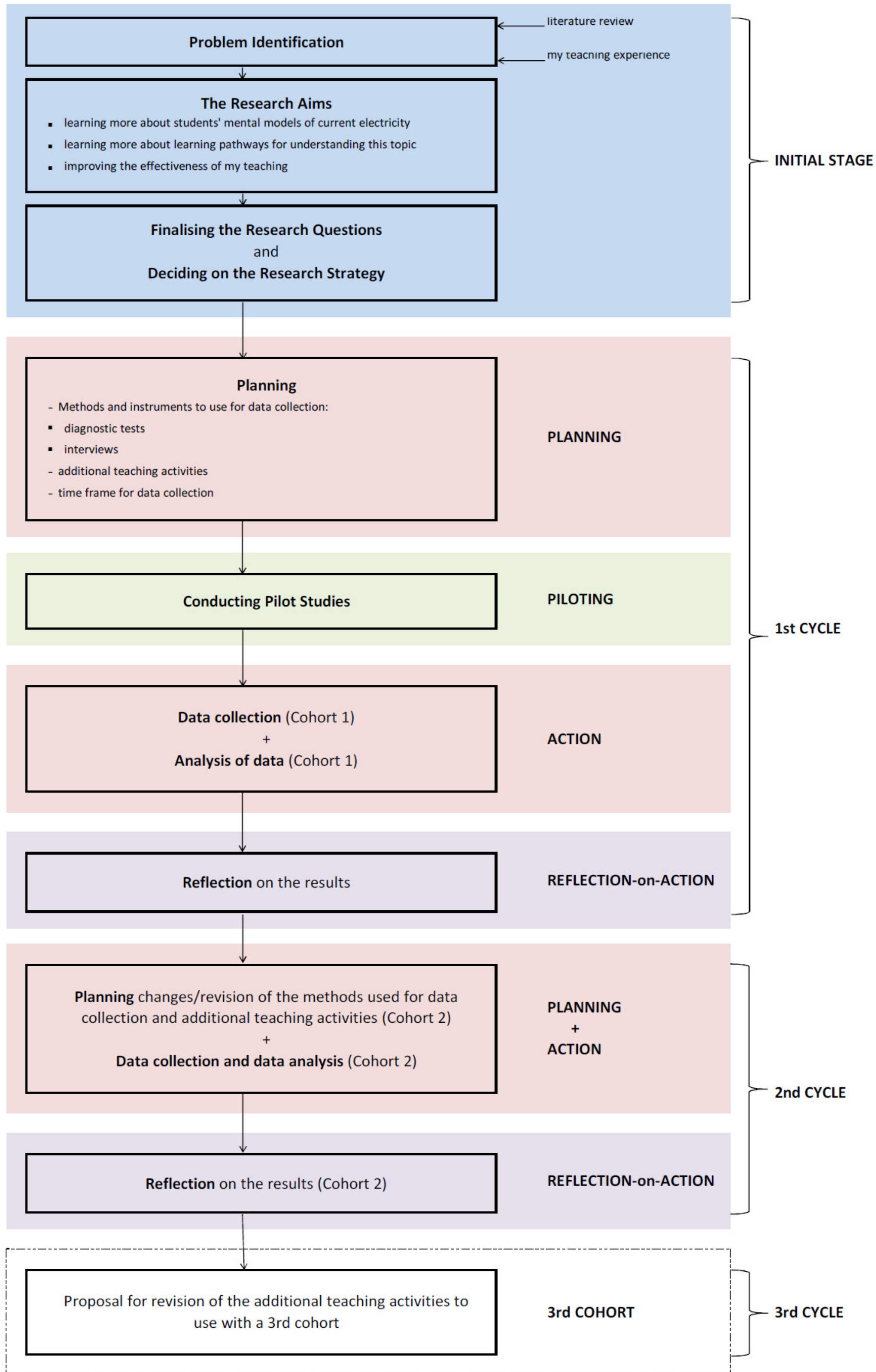


Figure 3.1: An outline of the research strategy used in this study

3.5 The sample

My students at a pre-university college in Malta, being taught current electricity through the years when the study was being conducted, were asked to participate in the study. Every year I lecture to about 30 to 70 students on this topic. The students were 17-18 years of age and were in their second and final year at the college, before they sat for their advanced level examination in Physics. Students at the college are randomly grouped and each year's group was representative of students in Malta studying Physics at pre-university level.

At the beginning of each year, I told the students that I was conducting research related to probing students' understanding of electric circuits. It was explained to the students that participation in the study meant answering some test questions, and that some students would be asked to be interviewed as well. Students were told that some sections of the study I was conducting were part-and-parcel of the teaching programme for my classes. Of course, no-one could opt out of participating in the planned activities during teaching. However, participation in other parts of the study involving piloting and data collection through written tests and interviews was on a voluntary basis. Even so, using Anderson's (1998) recommendations, students were advised regarding the benefits of participation. Students were encouraged to take part since the planned tests and interviews would offer ways of helping students to take charge of their learning. Munn and Drever (1990) claim that it has often been observed that it helps to make the study more reliable if respondents see some gain from being co-operative with the researcher.

All students accepted to participate in the study. Even so, it was made clear to students that in case any student decided to opt out of any data collection exercise, that student would be allowed to stay in class and work on his/her own through that session.

3.6 Plans for data collection

3.6.1 Probing students' understanding before and after teaching

3.6.1.1 Physics diagnostic test

Once the reason for conducting this research was clear, it was important to plan the strategy that would be adopted. This included decisions to be taken on which methods and instruments would best fit the purpose of the research, as well as decisions on a time frame for data collection.

Students' understanding of key concepts in electricity, before the beginning of the course had to be gauged. It was thus decided that a Physics Diagnostic Pre-Test would be prepared, based on ideas about circuits which students had already covered. This test would be administered with my student groups at the start of the scholastic year. The idea was that questions would be asked about very basic concepts. Moreover, as much as possible, questions would be clearly stated, probing one idea only. This would help make the interpretation of students' answers easier to handle (Cohen et al., 2001).

The preparation of a post-test to be administered immediately after instruction was also envisaged, to see by how far and in what ways students had changed their ideas, if at all, also indicating how effective the teaching programme was in promoting learning. Questions from the pre-test which students would find difficult would be asked again, in addition to other questions on work which would be covered through the course which it did not make sense to probe in a pre-test.

A delayed post-test was also planned to see by how far students retain the knowledge gained. This would be administered about one month after the post-test and would consist of the same questions asked in the post-test.

3.6.1.2 Deciding on the question choice for the diagnostic testing

The following question was used to guide the planning of the questions which were deemed important to be asked in the tests:

'What ideas should students have understood after having covered a basic course in electricity at secondary and post-secondary level?'

Reflecting on this question, while also being guided by the syllabi that the students cover at each level, and ideas students have been shown to hold through previous studies mentioned in the literature review, helped in making sound decisions. The following are items which were decided important to probe:

- the models of current which students use;
- knowing whether electric charges constituting the current are only present in the battery or whether they are everywhere and start moving because of the presence of the battery, in a complete circuit (This is a microscopic view which students may find difficulty

with but it is a very crucial point which students need to understand, if they are to understand circuits at all);

- conservation of current at a junction;
- the division of current at a junction depending on the resistances within the respective branches;
- knowing that it is not the battery alone which controls the current;
- knowing that the current through a larger resistance will be smaller, if the battery is unchanged;
- the effect on the current of adding resistors in series;
- the effect on the current in the main circuit, of adding resistors in parallel;
- whether it is the potential difference (p.d.) which gives rise to the current or vice versa;
- the models held by students about p.d. in series circuits. (Is p.d. across series resistors additive? Does p.d. exist across the resistors and/or connecting wires? Does each resistor in a series circuit have the total p.d. of the battery across it?);
- the effect on the current of increasing the p.d. across the battery (battery p.d. shown numerically);
- the role of batteries connected in series (This item would look at the same idea as the previous one without stating the p.d. numerically);
- the models held of p.d. in parallel circuits. (Is the p.d. across resistors in parallel additive and in total equal to the p.d. across the battery? Is the p.d. across equal resistors in parallel equal to the p.d. across the battery divided by the number of resistors? What happens to the current within a parallel branch, when resistance is changed within other branches?);
- the role of batteries connected in parallel;
- the differentiation of current and p.d. (Is there a current in an open circuit, even if a voltmeter reads the p.d. across the battery? Is there a p.d. across an open switch, when

no current is flowing? Do the rules which apply to currents in circuits, also apply to p.d. across various points within circuits?).

Diagnostic questions from the Evidence-based Practice in Science Education (EPSE) project (see Millar, Leach, Osborne, & Ratcliffe, 2006) based on current electricity were deemed appropriate for the diagnostic testing envisaged. Having access to the entire bank of questions developed in this topic made it possible to choose a set of questions to adequately probe students' understanding. Most of these questions are of the two-tier multiple choice type, requesting an answer and a reason for it. The reason is either prompted in a multiple choice set of answers or required as an open-ended response. Tsai et al. (2007) claim that "many science educators have used two-tier instruments to diagnose students' alternative conceptions and reported reliable results" (p. 485). Moreover, it was important for this study to be supported by qualitative reasons students base their answers upon because scientifically valid causal reasoning which supports and explains an answer is an indication of deep understanding (Lee & Law, 2001). Grotzer and Perkins (2000) refer to and acknowledge "a paucity of causal models in students' understanding" (p. 1) and "shallow explanations" (p. 3) which students usually offer when understanding in science is probed. Thus, only by dealing with students' reasons for their answers could the probing of ideas lead to some indication of students' ideas and their understanding.

A vast number of questions were available to choose from. Careful examination of the questions available and fine tuning to differentiate between key ideas which the questions were probing was required. This was not an easy exercise. Moreover, for each idea being tested, two questions probing that same idea in a slightly different way were chosen. This would increase reliability of the data collected from the Physics Diagnostic Tests (PDTs).

Once the selection was ready, the questions were put in a question bank (see Appendix 3) to be later used during the planned tests.

3.6.2 Probing students' mental models as they evolve during teaching

3.6.2.1 The importance of conducting interviews

While the diagnostic tests were planned to probe students' mental models at the start of the course and after the course was finished, I also wanted to probe students' ideas as the teaching was progressing. This would create the opportunity for getting some insight into students' ideas as they develop, perhaps providing evidence of mental models students use, and maybe help to get a sense of how these models or reasoning that uses them is changing. For this reason, interviews were planned, to be conducted with a sub-group of the students taking part in the study. Welzel and Roth (1998) refer to the work of Champagne et al. and Wandersee et al. when they argue that "for research purposes, interviews are often considered among the most reliable ways for determining what a person knows" (p. 25).

The interviews would provide the opportunity of interaction between interviewer and interviewee. This would help collect more in-depth information about students' thinking, providing more insight into ideas which students use as they "articulate their reasoning…", giving students the opportunity to "develop both reasoning ability and conceptual clarity" (Shaffer & McDermott, 1992, p. 1008). The plan was to try to evaluate students' progress in understanding electric circuits by conducting these interviews weekly with some of the student sample, as the course on electric circuits was being followed. The interviews would focus on concepts which students would indicate as being difficult to grasp, after having been administered the pre-test.

3.6.2.2 The type of interview to choose

Interviews can be conducted in many different ways, depending on the data one expects to collect. Cohen et al. (2001) claim that:

> Kvale (1996: 126-127) sets the several types of interview along a series of continua, arguing that the interviews differ in their type of purpose, their degree of structure, the extent to which they are exploratory or hypothesis testing, whether they seek description or interpretation, whether they are largely cognitive-focused or emotion-focused. (p. 270)

In this study, the choice fell on the use of *semi-structured interviews.* A semi-structured interview moves away from the formalised set of questions that symbolise the structured interview. An interview schedule for a semi-structured interview would include the topics and the open-ended questions to be discussed but "the exact sequence and wording does not have to be followed with each respondent" (Cohen et al., 2001, p. 278). Denzin and Silverman (as cited in Cohen et al., 2001) claim that a semi-structured interview "permits flexibility rather than fixity of sequence of discussions, and it enables participants to raise and pursue issues and matters that might not have been included in a pre-devised schedule" (p. 147).

This type of interview fitted the purpose for this study because it would allow for more probing of ideas, when the situation required it, with the aim of having students make an answer more elaborate and clear, better understood by the interviewer, hence allowing for better reliability of interpretation. On the other hand, "by standardizing the interviews to some degree", as is allowed for by using semi-structured interviews, "the researcher preserves a degree of comparability across interviews" (Shank, 2006, p. 50) – another quality which was expected to be of help in the analyses of the data.

3.6.2.3 The use of the Predict-Observe-Explain technique through interview sessions

The Predict-Observe-Explain (POE) technique offers an effective way for probing understanding (White & Gunstone, 1992). The importance of POEs in research has been indicated by various research studies (Shipstone, 1985b; Shipstone, 1988; Clement & Steinberg, 2002; Shaffer & McDermott, 1992). During a POE task, reasons for predictions made are asked for, as well as reasons for any explanations given if the prediction is incorrect and another idea is offered instead. This can bring the student to a situation which Lawson (as cited in Westbrook and Rogers, 1994) refers to as "reasoning to a contradiction" (p. 73). There is thus the implication of conflict which arises within the individual and which, solved or unsolved, still leads the way to meta-cognition of the learning process. Thus students themselves can decide what they know or don't know, being given the possibility to take some control of their learning.

Interviews were being planned to probe understanding and the mental models students use. Holt (1982) suggests that we can try to get behind students' ideas and understanding by giving them something to do with which they can test their own understanding, without the teacher having to tell them what is right. Moreover, Driver (1991) argues that in making meanings and probing students' thinking in some detail, "it is the reasons pupils give for their answers, and not the answers themselves, that are important" (p. 26). Studies reported by Coll et al. (2005) suggest that "in order to successfully develop conceptual understandings in science, learners need to be able to reflect on, and discuss their understandings of scientific concepts as they are developing them" (p. 194). Prain and Hand (1999) and Constantinou and Papadouris (2004) also refer to how discussions help to improve understanding, making learning meaningful. Thus, using predict-observe-explain tasks through the interviews was seen as covering these important aspects, probing understanding while also helping it to develop.

Plans were made to supply students with simple apparatus which they would use through the sessions. This would give them a hands-on experience, which many a student is usually enthusiastic about. It was envisaged that by making students' thinking explicit and encouraging self-reflection, POEs would help in pointing out existing mental models of circuits to both student and researcher.

3.6.2.4 Deciding on who to interview

In an earlier study which I had conducted (Borg Marks, 1998) I had the opportunity of experiencing the intensive drive exhibited by academically gifted students in the way they approach learning. Winner (1997) calls this "the rage to master" (p. 4). The importance of interviewing students of different ability, including the high ability ones, could thus not be ignored.

While it was hypothesized that the lower and average ability students would help by exposing their existing unhelpful ideas, the views of the higher ability students would show where meaningful learning could take **all** students. Moreover, there was the possibility that even the higher ability students would indicate problems in understanding some of the key concepts. If that were the case, then this would indicate complex concepts requiring a higher level of reasoning ability to be understood. Thus, the possibility of gauging the level at which different mental models can exist within a hierarchy of models would be increased.

3.6.2.5 Instruments to help choose the student sub-group for interview sessions

While the performance on the pre-test would be an indication of students' ability to handle questions related to content, the possibility of some students doing well in a test through rote learning could not be ruled out. Since my aim was to probe students' mental models, and since these models are likely to evolve through reflection and thought, it was decided that it would be useful to have an indication of students' level of logical reasoning as well. A number of tests that would help in this were identified, and a decision on the best test to fit the purpose, in this situation, was taken after conducting pilot studies (see section 3.7 for further discussion).

3.6.3 Qualitative and quantitative data

The use of diagnostic tests and interviews would generate quantitative and qualitative data. Qualitative and quantitative approaches are two distinct ways of carrying out research, both having their advantages and disadvantages (see Jacobs, Kawanaka, & Stigler, 1999). These authors claim that:

> Academics have begun to argue that qualitative and quantitative approaches can serve complementary functions: qualitative research can be used to generate new questions and theories, which can then be tested through quantitative means, and later revised or expanded through further qualitative study, and so on. The call is now frequently made for researchers to incorporate these two traditions, and when possible, to draw on the strengths of both in a single-study design. (p. 718)

Thus, planning for the collection of both types of data was thought of as making the study more thorough, approaching it using different perspectives complementing each other. Moreover, according to Feldman (2003), qualitative and quantitative data can support and challenge one another, helping to increase the trustworthiness of a study.

3.6.4 Introducing additional teaching activities during the course

3.6.4.1 The aims of introducing additional teaching activities

The introduction of additional teaching activities during the course was aimed at helping students:

- reflect more deeply on key concepts related to the topic, trying to reduce the macro-micro gap between current and static electricity;
- come to terms with the abstract nature of the topic by trying to improve their visualization of *how* the electric circuit works, and in so doing, possibly understanding *why* it works that way.

3.6.4.2 The teaching activities planned to be included in the course

- Revision of the static electricity course

  At the college, students cover the topic of static electricity, with another lecturer, during their first year of study. This may help in making students learn static and current electricity in a fragmented way. Moreover, Eylon and Ganiel (1990), Licht (1991), Viennot and Rainson (1992) have referred to the macro-micro gap — the missing link between static and current electricity. These authors see the macro-micro gap as a problem which limits the understanding of key concepts related to circuits. It was thus planned to cover static electricity again with the students, at the beginning of the second year (see section 3.8.5 referring to the implementation of this activity), helping students to reflect deeper on the concepts they had already been exposed to, with the hope that the link between concepts learned in static and current electricity would be made, thus improving understanding.

- Preparing a DVD

I edited a DVD (Great Pacific Media Physics Essentials, 1996) related to static and current electricity and which was available as a teaching resource at my physics department, so that I would show it to the students through class time. A section on the DVD focused on presenting the entire electric circuit filled with mobile charges represented as tiny spheres. These spheres would be shown moving together as the current flows. The aim was to help students in their mental visualization of current, making it look less abstract and more concrete, perhaps helping in the evolution of mental models of the electric current towards the scientific view.

- Preparing a PowerPoint presentation

A number of studies and physics books (Mee, Arnold, Crundell, & Brown, 2000; Hewitt, 2002; Paatz et al., 2004 amongst others) dealing with current electricity refer to analogies between electricity and other ideas in physics, like for example, water circuits and gravitational potential energy. It was thus decided to prepare a PowerPoint presentation, to make students aware of these analogies, hopefully setting the spark for students' deeper reflections and helpful visualizations aiding understanding.

3.7 The pilot studies

3.7.1 Choosing the reasoning test to use

One of the methods which aims at judging levels of development is based on the Piagetian tradition (Kieting, 1976). In a previous research study (Borg Marks, 1998), the cognitive level of students with whom I was working was gauged using tests of logical thinking adapted from Piaget's original experiments described in Inhelder and Piaget (1966). These tests which had been conducted on a one-to-one basis had proved laborious and very time consuming to conduct and analyze. In the present study, the possibility of administering a group test was intriguing. This would allow for quicker processing of the data, with a larger sample.

3.7.1.1 The group tests identified

Three group tests were identified:

- '<u>Reasoning Tasks</u>' prepared by Shayer, Adey, Kuchemann & Wylam (1973/78).

These tasks are based on the experiments by Inhelder and Piaget. After careful examination of a set of tasks, two were chosen. These were the 'The Pendulum' (see Appendix 4) and 'Equilibrium in the Balance' (see Appendix 5) which test control of variables and proportional reasoning, respectively. These tasks were chosen from the set available because it was thought that the apparatus required would be readily available in the department where I teach, the tasks were simple to administer, and they tested ideas which students had come across in their previous physics studies.

- The <u>TOLT</u> (Test of Logical Thinking) created by Tobin and Capie (1981) (see Appendix 5).

This paper-and-pencil test probes five aspects of formal reasoning, namely:

- Proportional Reasoning;
- Controlling Variables;
- Probabilistic Reasoning;
- Correlational Reasoning;
- Combinatorial Reasoning.

Tobin and Capie (1981) state that TOLT "provides a means of assessing formal reasoning ability as a diagnostic aid for teachers or as data for researchers investigating the nature of learning" (p. 422). Moreover, they state that "whether subjects use formal reasoning, or not, may be ascertained from their reasons for developing or choosing a response" (p. 414). In fact, each question in TOLT requires both an answer and a justification for it.

- Lawson's Classroom Test of Scientific Reasoning (Arizona State University, revised August 2000)

This test looks into seven different aspects of reasoning as well as some of these aspects combined together, namely:

- Conservation of weight;
- Conservation of displaced volume;
- Proportional thinking;
- Advanced proportional thinking;
- Identification and control of variables;
- Identification and control of variables and probabilistic thinking;
- Probabilistic thinking;
- Advanced probabilistic thinking;
- Correlational thinking (includes proportions and probability);
- Hypothetico-deductive thinking.

Comparing the Lawson test with the TOLT, I concluded that while the Lawson Test looks into more aspects of formal reasoning, yet it is a much longer test, allowing students less time to think before answering. The length of the test was considered to be a disadvantage. Students were expected to finish the test during class time and TOLT, being more concise, would allow them more time to think. Having made these considerations, it was decided that the tests which would be pilot tested with students would be the TOLT and the two reasoning tasks. Piloting of these tests was done to discover how students interacted with the test questions and to check the time students needed to finish the tests.

'The Pendulum' task was administered first, during a one hour class, to students I was teaching in 2005. These were taking Physics at advanced level, similar to the students who would later form the sample for the 'Action' part of the study. All students accepted to take part in the piloting of the tests. Had any of the students decided not to participate they would have been allowed to work on their own in class.

The 'Equilibrium in the Balance' task was administered to the same students one week later. Two weeks after this, TOLT was administered to the same group. A time interval between administrations of the tests was allowed, so that students would not complain that they were not covering their syllabus because of the research being conducted.

It is important to mention that the students taking the tests were ones who had passed an English national exam, before being admitted to the college. It was therefore not deemed important to translate the tests into Maltese. The only question some students had was about the meaning of the word 'broad', which was used in Qn 9 of the TOLT. This was explained to the students.

3.7.1.2 The results of the tests

For 'the pendulum' and 'the equilibrium in the balance' tasks, the test results were graded according to the instructions of the authors. Grading of the TOLT was done according to the method used by Valanides (1997). Results from my pilot studies had shown similar results which had been indicated by Valanides (1997), namely that some students had a TOLT result of 4, when they had not been able to answer correctly three different sections of formal thinking. For this reason, the TOLT results were graded according to the following scheme shown in Table 3.1.

Score on TOLT	Grade	Scheme	Cognitive level
0 - 1	2B	1	Concrete
2 - 3	2B/3A	2	Transitional
4 - 7	3A	3	Formal
8 - 10	3B	4	Rigorous Formal

Table 3.1: Rearrangement of TOLT scores in relation to cognitive levels

The results from the three tests are shown in Appendix 6. Analysis of the results indicated that correlations between 'the pendulum' task and TOLT, and between 'the equilibrium in the balance' task and TOLT, were statistically significant. The results from the two reasoning tasks did not, however, correlate significantly with each other (see Table 3.2). This was taken to mean that while there was, as expected, some underlying common factor between each reasoning task and the TOLT, yet the reasoning tasks required different reasoning abilities.

N= 37		
Pair	Pearson correlation	Sig (2-tailed)
TOLT / Balance	0.461**	0.004
TOLT / Pendulum	0.496**	0.002
Pendulum / Balance	0.202 (not significant)	0.232

Table 3.2: Comparing the results on the three tests

Through this piloting exercise it was noted that TOLT was easier to mark, and that it was a test which was of the type which the students were used to doing - a paper-and-pencil test which students could answer in a quiet classroom environment. Moreover, TOLT discriminated between students in a similar way as the other tests. The choice thus fell on using TOLT as the instrument which would be used together with the Physics Diagnostic pre-test, to select students to be interviewed.

3.7.2 Piloting of the PDT

Important things that were taken into account whilst finalizing the question set before piloting were:

- the syllabus in current electricity which students were expected to have covered at secondary level (see Appendix 1).

  The questions chosen were based on ideas which students had already been exposed to, with some questions trying to extend students' reasoning further than others.

- the duration of the test.

  I used my judgement in deciding how many questions to include in the test, keeping in mind that students had to finish the test in a one hour lecture period.

- the wording used in the chosen questions.

  Consistent wording was used in the test questions chosen. This was meant to improve the possibility of making questions more clearly understood.

- the circuit diagram presentation.

Consistency in circuit diagram presentation was also adhered to, trying to make the test set-up more uniform. A lot of thought was put into deciding where best to put the battery symbol in the circuit. For this reason, various text books used locally were consulted (Farrell, 2004; Johnson, 1996; Mee et al., 2000; Xuereb, 1999, 2007). It was found that the majority of the diagrams used in these books had the battery drawn in the centre of the top or bottom line of the circuit diagram. When reference was made to potential difference, however, some text books quite often used the analogy of electrical with gravitational potential. When this was done, the battery was drawn on one side line, with the positive terminal on top to indicate a higher potential. While I believe that this analogy is a strong and useful one, only a minority of circuit diagrams were presented this way in the text books. The decision taken was thus to draw the battery symbol on the top line of the circuit diagrams. This was the representation which was showing up as most commonly used in the text books, and thus the one which students would be more familiar with. The aim was to try to reduce students' problems referred to by Gott (1985a), McDermott and Shaffer (1992) and Shaffer and McDermott (1992) related to diagram interpretation .

Seventeen questions from the question bank were chosen and administered as class tests with my students in 2005/2006, and 2006/2007. This was done to check whether students encountered difficulties with understanding the chosen questions, in which case changes would be made. Moreover, it was also important to check whether students were being given enough time to answer the test questions during the normal one hour of class time.

No problems were in fact encountered. These questions formed the pre-test (see section 4.2).

3.7.3 Piloting of the Predict-Observe-Explain (POE) tasks used in interviews

As explained in section 3.6.2.3, POE tasks were planned to be used during interview sessions. POEs may be conducted either on a one-to-one level (White & Gunstone, 1992) or with groups of students (Thornton, 2008; Thornton, 2009; Sokoloff & Thornton, 1997). Some questions from the question bank that students found difficult to answer were chosen and used during POE tasks (Borg Marks, 2007, 2009a, 2009b). The POEs were used with individual students and also with groups of students, having a maximum of three students within each group. This was done to help in deciding whether this study would benefit from POEs used on a one-to-one basis or with a group of students.

At the same time, the piloting served as practice in conducting an interview, asking questions which do not lead students' views, while at the same time encouraging students to voice their thoughts. It was observed that when students participated in groups, conflicting ideas invariably surfaced and students were discussing and learning from each other, but there was the disadvantage that those students who did not find it easy to speak their mind were put somewhat out of the limelight by students who wanted to speak all the time. Thus it was sometimes difficult to follow the ideas of all the students in the group. POEs on a one-to-one basis, on the other hand, made it more possible to hear what individuals had to say, without there being any interfering influence of ideas from listening to the views of others. At the same time, conflicting ideas were still given the possibility to surface because of the nature of the POE technique itself. These still contributed to self-reflection and revision of intuitive ideas when required, in the drive to come up with valid reasons for why electric circuits function in the way they do. Thus, the learning pathway followed by the student, in terms of mental models implied, could be made evident.

The piloting of the POEs helped in deciding that for the purpose of this study, mental models could be better probed during interviews with individual students since in such cases the student could *not* rely on peers for explanations proposed.

3.8 Putting the plans into action

3.8.1 The sample for the 1st cycle

Plans were put into action at the beginning of the scholastic year 2007/2008. Sixty-one students who attended my lectures in Physics at advanced level during that scholastic year, and who were in their second year at the college, formed the sample of the 1st cycle of the study.

3.8.2 Administering the pre-test

The pre-test (see section 4.2) was given to students at the very start of the course, so that the ideas and reasoning that students seemed to be using before the teaching could be gauged.

3.8.3 Administering the TOLT

The TOLT was administered to the same student sample one week later.

3.8.4 Conducting the interviews

3.8.4.1 Choosing the students to be interviewed

Students' performance in the physics diagnostic pre-test and the TOLT was used to select candidates for the sub-group to be interviewed. Once the tests were scored, the results of the PDT and the TOLT were compared.

N = 61												
PDT/29	TOLT/10											Total
	Concrete		Transitional		Formal				Rigorous Formal			
	0	1	2	3	4	5	6	7	8	9	10	
5							1					1
6											1	1
7		**2**				1	1					4
8				2						1		3
10					1		**2**	1				4
11				1		1				1	1	4
12								1	1			2
13			**1**									1
14						1		1	**4**	**1**		7
15				1	1					1	1	4
16					2					2	**1**	5
17							1	2	1	1	2	7
18							1		1			2
19								1	1	1		3
20									1	2		3
22					1				1	1		3
23						1					2	3
24											**2**	2
26								1		1		2
Total	0	2	1	4	5	4	6	7	10	12	10	61

Table 3.3: Cross-tabulation of PDT and TOLT results (Cohort 1)
(Note: Numbers in bold print indicate the performance of students chosen to form the interview sample)

Table 3.3 shows a cross tabulation of the student scores. Some students did poorly in both tests, others scored high in both tests, and some students scored high in the TOLT but low in the PDT. Very few students did poorly in the TOLT whilst showing good performance in the PDT.

Analysis also showed that there was a strong and statistically significant correlation between the results of the two tests (see Table 3.4). There were, however, quite a number of students with a good TOLT result but whose PDT result was not as high as expected. These students who were categorized as formal and rigorous formal thinkers were not showing such a good understanding of the work they had covered on circuits at secondary school level.

N = 61		
Correlation	Pearson Correlation Coefficient	Sig. (2-tailed)
TOLT (Cohort 1) - PDT	0.425	0.001

Table 3.4: Correlation between PDT and TOLT scores

It was thus decided to choose students to be interviewed, from the three following categories, namely:

- students judged to be at the concrete level of cognitive development and who performed poorly in the PDT. These were graded as showing '*Low Performance* ' (L);
- students judged to be at the rigorous formal level of cognitive development but who showed an average to poor performance in the PDT. These were graded as showing '*Average Performance*' (A);
- students judged to be at the rigorous formal level of cognitive development and who also showed good performance in the PDT. These were graded as showing '*High Performance*' (H).

Interviewing students of *low performance* might help to clarify the problems that they were encountering in the understanding of circuits. It was also deemed important to find out what was causing the students with apparently good reasoning ability to perform poorly in the PDT. Interviews with students scoring high on the TOLT and PDT were intended to elicit the type of reasoning offered by such students and at the same time, to demonstrate what one could expect from the other students at the same level of schooling.

A number of students in each of the three categories above were identified. Observation of how students reacted in class interactions helped in finalizing a group of students who would be asked to take part in the interviews. It was important to choose students who would not find difficulty in talking about their ideas with the researcher.

Students selected in this way were then asked if they were willing to take part in interviews (see Cohen et al., 2001; AAAS (American Association for the Advancement of Science), 2008) in which they would be asked to elaborate on their views on key issues in the topic of current electricity. The fact that the interviews were part of a research project was explained. Students were advised that through their participation they themselves could benefit in the better understanding of simple key ideas related to the topic, but they were still told that it was up to them to decide whether they wanted to accept to participate in the interview exercise or not. All the students who were contacted expressed their willingness to participate in the proposed exercise. However, in some cases, it was impossible to find a common free slot in the time-table for both interviewer and interviewee. This factor had a strong influence on the final choice of the interview sample.

Appointments were fixed with nine students who could make themselves available during school hours.

The criteria for the choice of students who participated in the interview sessions may therefore be summarized as follows:

- student performance in the TOLT and PDT (Low, Average and High Performance students were chosen);
- voluntary acceptance to participate in the interviews;
- the availability of students during the time when the lecturer/researcher would also be available, during school hours;
- a fair knowledge of the students' starting ideas regarding the topic in question and their personal characteristics (for example the student finds it easy to express his/her views) through class time interactions.

It is important to point out that the students were to be interviewed a number of times. The process would be time consuming for both students and researcher, over and above a normal school day. While the temptation, on the side of the researcher, was to interview as many students as possible, it was important to be realistic and accept the constraints of the situation. Other studies dealing with the analysis of thinking processes and students' reasoning have also interviewed small groups of students. Indeed, in the research studies conducted by Clement and Steinberg (2002) and Niedderer (1994), only one student's line of thought and understanding was followed. In terms of the interview sample size, this study therefore collected a stronger data base for analysis than some previous published studies.

3.8.4.2 Classification of the students in the sub-group

Table 3.5 lists the nine students who participated in the interview sessions, indicating their scores for the PDT and the TOLT. For ethical reasons, the names shown in Table 3.7 are pseudonyms.

Name	PDT/29	TOLT/10	Performance
Andi	7	1	Low (L) (Concrete and poor performance in PDT)
John	7	1	Low (L) (Concrete and poor performance in PDT)
James	13	2	Low (L) (Transitional and poor performance in PDT)
Mari	10	6	Low (L) (Formal but poor performance in PDT)
Kyle	14	8	Average (A) (Rigorous formal but average performance in PDT)
Theri	14	9	Average (A) (Rigorous formal but average performance in PDT)
Chris	16	10	Average (A) (Rigorous formal but average performance in PDT)
Mitch	24	10	High (H) (Rigorous formal and good performance in PDT)
Robi	24	10	High (H) (Rigorous formal and good performance in PDT)

Table 3.5: Student classification – the interview sample

3.8.4.3 Choosing the interview questions

Clement and Steinberg (2002) claim that:

> physicists and engineers are generally agreed that effective reasoning about electric circuits requires a robust conception of electric potential. However, research in the 1980s found that electric potential typically remains unlearned after instruction (Closset, 1983; Cohen, Eylon, & Ganiel, 1983; Duit, Jung, & von Rhoneck, 1985). Students reason exclusively with current and resistance when possible, and when asked explicit questions about potential difference many confuse the concept with current (p. 393).

Rosenthal and Henderson (2006) also argue that "introductory physics students often fail to develop a coherent conceptual model of electric circuits. In part, this failure occurs because the students did not develop a good understanding of the concept of electric potential" (p. 324).

The above extracts place a clear emphasis on the importance of the understanding of electric potential for effective reasoning about electric circuits. This was a point which was kept in mind during the preparation of the tasks for the interviews. On the other hand, the same ideas which guided the questions in the PDT had to be considered also, because it was these same ideas which were to be consolidated and refined through the interviews. Mental models of current, resistance and potential difference all needed to be probed, with particular attention being given to students' understanding of the concept of potential difference.

Priority was thus given to probing ideas related to the following key points:

- how current flow is mentally visualized – the mental models of current;
- the idea of whether charges come out of the battery into an empty wire or whether charges everywhere are made to circulate together;
- the role of the resistance and how it is pictured;
- whether it is just the number of resistances in the circuit which counts, or the way in which they are connected in series and parallel circuits;
- the role of the battery and resistance in determining the current;
- what sense is given to a voltmeter reading, leading to 'voltage' or potential difference and the way in which students imagine this physical quantity;
- how the p.d across the battery is related to the p.d. across resistors connected in series;
- how the p.d across the battery is related to the p.d. across resistors connected in parallel with the battery;
- the differentiation of current and p.d.

Interview questions and schedules were planned carefully around these themes, so that students' ideas could be studied systematically. The aim was to get some insights into mental models inferred by students. It was envisaged that through the interviews one could catch that phrase or sentence which could guide the researcher towards the students' mode of thinking, as this progressed and evolved, hopefully towards the scientific view. In cases where progress was blocked, then the causes for this were of interest.

3.8.4.4 Conducting the interview sessions

The planned questions and interview schedules were used during POE tasks. "Being interviewed is an uncommon, sometimes anxiety provoking experience for many respondents" (Rizk, 2003), but using POEs was found to help students in realizing that they could take charge of their learning by "automatically sieving out what does not fit with what they have seen" (Cosgrove, 1995, p. 307). Students soon got used to what Cosgrove (1995) calls "science-in-the-making" (p. 295), as opposed to having to ask for what was right or wrong. During the POE, in predicting the result of an experiment giving reasons for the prediction, and immediately getting feedback about their ideas by doing the experiment, students were encouraged to reflect on their original prediction, possibly correcting it, giving reasons. This helped in creating the space for mental model evolution.

Moreover, while the main objective was to use the interviews as a tool to probe students' mental models, the interviews were also serving as tutorial sessions, with the students refining their own knowledge. Cohen et al. (2001) emphasize that "it is crucial to keep uppermost in one's mind the fact that the interview is a social, interpersonal encounter, not merely a data collection exercise" (p. 279). This idea is also referred to by Rizk (2003) and Welzel and Roth (1998), with the latter authors also emphasizing that "interviews do not simply assess, but actually scaffold (or interfere with) the cognitive activities of the interviewees" (p. 40). Welzel and Roth (1998) also point out the need for interviewers to act expertly and be sensitive to the average level of complexity at which interviewees' engage, avoiding possible communication breakdown. Using interviews as tools in this way, while adopting the recommendations from these studies, made the interviewing exercise more effective for both interviewer and interviewees. Indeed, the latter became intrinsically motivated, showing their will to wholeheartedly participate in forthcoming interviews, knowing that they were getting something back in return for voicing their thoughts.

Having said all this in favour of interviews, it is however worth mentioning that the researcher was also aware of the possible errors that may result from data collected during interviews. Interview data cannot be considered unproblematic as a source of data on what students think. Inevitably, there is an interaction between the interviewer and the interviewee which may result in the interviewee being influenced by what the interviewer may say and do. Care was thus taken during interviews to build a good rapport with the interviewees, trying to remain detached and professional, but at the same time relaxed and friendly (Oppenheim, 1992).

The interviews were conducted in the physics laboratory so that the necessary apparatus was available. Rizk (2003) refer to "the need for contextual naturalness of response and setting" (p. 978) during interviews. Care was taken to allow time for "participants to generate responses with little or no influence from the questions" asked (Rizk, 2003, p. 978). Allowing students to handle the apparatus themselves helped in making the interview more exciting and something students admitted they looked forward to.

All interviews were audio-taped and transcribed before analysis was undertaken.

3.8.5 Conducting the additional teaching activities (1st cycle)

- The revision of the work on static electricity was done through the first tutorial sessions conducted through the scholastic year. This revision emphasized the qualitative reasoning involved in understanding the topic, especially with work related to potential and potential difference.

- At the end of the course, the students were shown the DVD and the PowerPoint presentation. The DVD was mainly shown to try and link the theory which had been covered with the use of electricity in our everyday life, and to improve students' visualization of how an electric circuit works as a system, indicating charge flow through the circuit in all parts of the system at the same time, when current flows. The PowerPoint aimed at using common analogies, relating other topics with electricity, to help understand the electric circuit at work. Students were given time to discuss what they had seen, and a number of them expressed the view that this had now helped them to clear some of the doubts they had held through the course. The DVD and PowerPoint presentation helped to summarize and conclude the study unit.

3.8.6 Administering the post-test with Cohort 1

At the end of the course, students sat for an assessment test based on the material covered through the course. This was normal practice and students had prepared for the test. A week later, students were given the diagnostic post-test (see section 4.2). This consisted of 17 questions picked out of the question bank. Some questions were the same as those on the pre-test. These were questions which a good number of students had found difficult to answer. New questions were also added, mainly based on ideas dealing with p.d. and current in parallel branches when changes are made to the circuit.

3.8.7 Administering the delayed post-test with Cohort 1

One month later, the students were given the delayed post-test. This consisted of the same questions as the post-test.

3.8.8 Summary of the time frame for covering sub-sections of the topic and data collection (1st cycle)

It is normal practice for advanced level students doing physics to be allotted two lecture periods and a tutorial, each of a one hour's duration, together with a two-hour practical session, weekly. During a tutorial, students are usually working numerical problems and discussing any difficulties they may have with qualitative answers to questions. Through a practical session, students handle the apparatus assigned to them, using it to devise an experiment to answer questions asked. In their write-up for the experiment, students explain ideas which lead them to their conclusions.

The schematic drawing in Figure 3.2 shows a time frame which gives a general indication of what students were being instructed in, during the lectures which were conducted alongside the data collection exercise, as the project was gaining rhythm.

It is important to note that, inevitably, not all students could be interviewed on the same day and that one can never know exactly what material students had covered on their own. The good use students could make of their knowledge, through more elaborate thinking, was the main objective of the interviews.

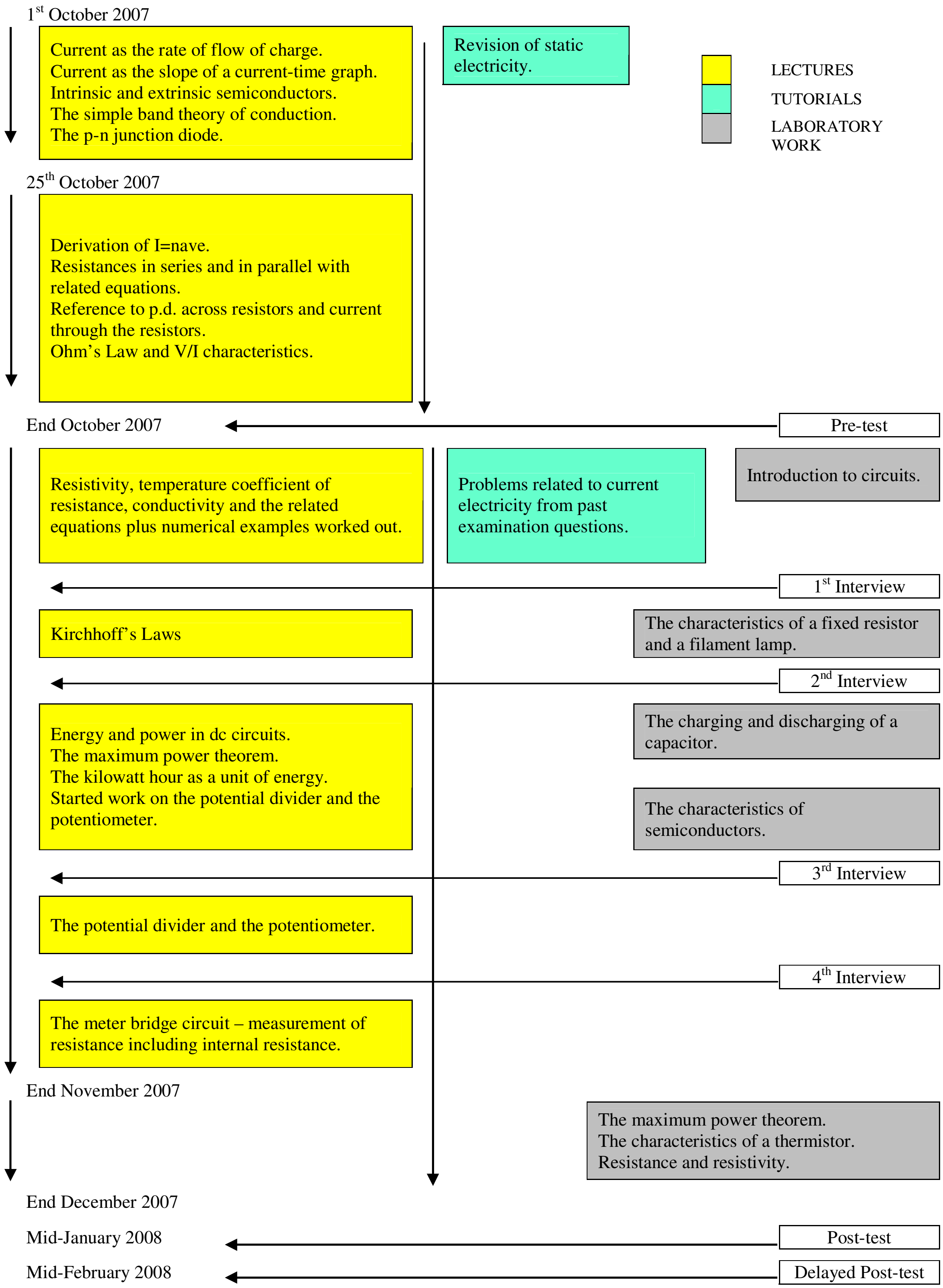


Figure 3.2: The time frame for instruction and data collection (1st cycle)

3.9 Analysing and reflecting on the data collected with Cohort 1

An analysis of the data that was collected in the 1st cycle is discussed in Chapters 4 and 5.

The 2nd cycle of the action research had to reflect the outcomes of the study so far. An examination of the results obtained with the Cohort 1 suggested that some changes could be made concerning the additional teaching activities that would be used with the Cohort 2. These changes will be described in detail in Chapter 6, once the analysis of the data and the results obtained with the Cohort 1 have been exposed. The next section briefly outlines the methods of data collection used with Cohort 2. Similarities and differences between what was done during the two cycles of the action research will be indicated.

3.10 The 2nd cycle of the research project

The 2nd cycle of the action research was conducted with my students taking advanced level physics during the scholastic year 2008-2009. The sample now consisted of 49 students. The same pre-test and the TOLT, used in the previous year with Cohort 1, were administered to the Cohort 2 at the start of the course.

The same post-test was used a week after an assessment test had been conducted with the students at the end of the course, similarly to what had been done during the previous year.

Interviews with Cohort 2 were also conducted with some students of different ability. In this case, however, the interviews were scheduled for after the post-test, with the aim of exposing reasons for why certain problems in understanding were still persisting, in spite of having used teaching activities which were meant to enhance meaningful learning. Each interviewee was met on one occasion only.

The same delayed post-test, as used with Cohort 1, was also administered with Cohort 2, one month after doing the post-test.

3.11 Analysis and reflection on the results of the 2nd cycle - suggestions for further work

The data collected during the 2nd cycle of this work was analysed in a similar way as data from the 1st cycle of the research. The findings are reported and discussed in Chapter 6.

This study does not describe a 3rd cycle of the research. This has not yet been conducted because of time constraints in writing this thesis and also because the research questions could still be answered using the results from the two cycles conducted. Suggestions for further research are made in Chapter 7.

3.12 Addressing validity in action research

Validity refers to by how far an instrument or method measures what the researcher has set out to measure. Different authors often refer to threats to validity (Watkins, 1991), and how easy it is to slip into invalidity at any stage of a piece of research (Cohen et al., 2001; Robson, 2002). The claim is that it is impossible for research to be 100% valid and that "at best we strive to minimize invalidity and maximize validity" (Cohen et al., 2001, p.105). In this study, the question was how to maximize validity in action research.

The literature regarding action research acknowledges the different characteristics of action research which distinguish it from other forms of research. Reason and Bradbury (2006) claim that the difference is not only in the method. They specify that in action research "the distinction between researchers and subjects may become quite blurred in the course of what is usually a lengthy, collaborative relationship. Additionally, there is a different relative emphasis on the importance of action and its relationship to conceptual insight" (p. xxiv). Another key characteristic of action research is pointed out by Newman (1999) who refers to the work of Schon which describes the situations reported in action research as being "unique from moment to moment".

A problem arises due to the specific nature of action research. Robson (2002) claims that this problem is due to the fact that the terms 'reliable' and 'valid' have "been operationalized so rigidly in fixed design quantitative research" (p. 170). Kvale (as cited in Reason and Bradbury, 2006) "questioned the validity of the very question of validity, that is to say, raised a question as to whether we are foolishly trying to fit the qualities of action research into a traditional discourse about validity whose concerns have little to do with those of action research" (p. 343). Authors and researchers thus started to look for terms or criteria better suited for action research.

Pioneers like Lincoln and Guba (1985), whose work is also cited in Bassey (1999), Feldman (2003) and Robson (2002), suggested terms other than 'reliability' and 'validity' (which apply to surveys and experiments) that can be more useful to use when discussing the outcome of a flexible research study. Lincoln and Guba (1985) used the terms: credibility, transferability, dependability, and confirmability, when talking about the 'trustworthiness' of a finding or claim.

Reason and Bradbury (2006) argued in terms of "broadening the 'bandwidth' of concerns associated with the question of what constitutes good knowledge research/practice" (p. 343). These authors claim that in action research we need to shift our concern towards "engagement, dialogue, pragmatic outcomes and an emergent, reflexive sense of what is important" (p. 343). Feldman (2003) also shares this idea.

On the other hand, Newman (1999) points out that what is important is to see that the research questions are answered and that the method by which this is done is described with enough detail so as to make it possible for other readers to 'resonate' with the work produced, trying to improve their practice (Newman 1999). This view which is shared by other authors, including Reason and Bradbury (2006), emphasizes the clarity and quality expected of the work produced, while at the same time, putting the reader in charge of deciding whether a finding might be applied to other situations and thus whether it can be considered generalizable.

All the issues outlined above were considered through all stages of this study, with the aim of trying to make the work more trustworthy. Moreover, the point made by Springer (as cited in Punch, 2009), that in action research "collaborative participation becomes central" (p. 137), could not be ignored. In this study, such participation was not only encouraged between the student and the researcher. As much as possible, it also involved members of the thesis advisory group, including my supervisor, with whom interpretations of the data collected could be shared, and with whom further plans and actions could be decided upon. This helped in guarding against researcher bias, reducing threats to validity (Robson, 2002). Furthermore, opportunity was taken to present sections of the project at local and international conferences (Borg Marks, 2007, 2008, 2009a, 2009b) thus getting important feedback from the professional audience.

3.13 Conclusion

The research strategy described above focused on using different data collection instruments to probe students' understanding, with the aim of answering the research questions.

Diagnostic test questions (mostly two-tier) and semi-structured interviews using POE sessions were used in both cycles of the research, aimed at probing students' ideas and causal reasoning. Data was collected at different stages through the course of study.

Both qualitative and quantitative data were collected and measures to improve the reliability and validity of the study were adopted.

Different teaching activities were organised through each cycle of the data collection, aimed at trying to improve students' qualitative understanding of the topic, through guided reflection and discussion.

Moreover, in designing the research strategy the need to work with students of different ability was acknowledged. Feedback was required about mental models which different ability groups tend to use. The aim was to try and link all these mental models, framing them into one picture, as learning pathways could be drafted. Students' guided reflection on the topic was directed at helping the academically weak so that these could 'see' the scientific models, while at the same time the academically able were helped in clarifying their doubts. Thus, the research strategy described above, aimed not only at collecting the data and analyzing it whilst answering the research questions, but also at bringing about improved learning outcomes for the students.

Chapter 4 The Physics Diagnostic Tests (Cohort 1)

4.1 Introduction

This chapter analyses students' performance and mental models used in the three Physics Diagnostic Tests (PDTs) conducted with Cohort 1 (see section 3.8.8 for an indication of when these tests were performed with students). An overall look at students' performance on the pre-test is first presented, before a detailed description of the analysis of students' answers in this test in terms of mental models students seemed to have been using is exposed. A comparison is then made between student performance on the pre-test and the post-test, focusing mainly at how students' understanding may have changed after the teaching. Further changes in students' responses to the delayed post-test are then briefly described. The analysis points to important findings corroborating previous literature, as well as findings which are specific to this particular sample and study.

4.2 The questions asked in the tests

Appendix 3 shows a question bank including all questions used in the pre-, post- and delayed post-tests. Table 4.1 shows which questions from the question bank were used in these tests. A description of the type of question used is also included.

Question number in the question bank	Question number in the pre-test	Question title	Question type	Question number in the post-/ delayed post-test
1	PR 1	Current at points (a) and (b)	Two-tier (3 x 3 options)	PO 1
4	PR 2	Microscopic views of circuit	True/False (6 parts)	PO 2
9	PR 3a; 3b	Current conservation at junctions and within a parallel branch; Parallel resistors' control of current	True/False; Yes/No with open ended explanation	
9'			Two-tier (3 options x open response); Yes/No with open ended explanation	PO 7(a); 7(b)
5	PR 4	Use of a larger resistance	Two-tier (4 x 4 options)	
6	PR 5	Adding an equal resistance in series	Two-tier (4 x 5 options)	PO 3
8	PR 6	Adding an equal resistance in parallel	Two-tier (3 x 3 options)	PO 4
3	PR 7	Picture of battery and bulb	Two-tier (3 x 4 options)	PO 5
7	PR 8	Increasing the variable resistance	Two-tier (4 x 4 options)	PO 6
10	PR 9	Increase of supply voltage indicated numerically	Two-tier (3 x 3 options)	
2	PR 10	Current using two ammeters	Two-tier (4 x 3 options)	
12	PR 11	p.d. across resistances and ideal connecting wires	Multiple choice (6 parts, 4 options each)	
12'			Multiple choice (3 parts, 4 options each)	PO 8
13	PR 12	p.d. across equal resistances in series	Multiple choice part (a) (5 options); open ended reason for part (b)	PO 9
14	PR 13	p. d. across unequal resistances in series	Multiple choice part (a) (4 options); open ended reason for part (b)	PO 10
11	PR 14	Connecting another battery in series	Two-tier (4 x 4 options)	
15	PR 15	p.d. across equal parallel resistors	Short answer with open ended explanation	PO 11
16	PR 16	p.d. across unequal parallel resistors	Short answer with open ended explanation	PO 12
17	PR 17	p.d. across an open and closed switch	3 short answers	
17'		p.d. across an open and closed switch	2 short answers with open explanations	PO 13
19		Addition of a battery in parallel with the first: Voltmeter reading	Two-tier (4 x 4 options)	PO 14
20		Addition of a battery in parallel with the first: Ammeter reading	Two-tier (3 x 4 options)	PO 15
21		Addition of a parallel resistor: effect on the current within a branch; effect on the current within the main circuit	Two-tier (3 x 4 options) each	PO 16 (a) and (b); PO 16 (c) and (d)
18		p.d. across a resistor, adding another resistor in parallel	Two-tier (3 x 3 options)	PO 17

Table 4.1: Test questions related to question number in the question bank
(Note: ' represents a question which was adapted from the question with the same number in the pre-test.)

For ease of reference, from here onwards, all question numbers refer to the number of that question in the Question Bank.

4.3 A look at students' overall performance in the pre-test

4.3.1 Scoring the test answers

4.3.1.1 Why scoring was important

Seventeen questions were asked on the pre-test. Test scores were important to provide an overall measure of each student's performance on the understanding each test was assessing. Pre-test scores were also used, together with students' performance on the TOLT, to identify possible interview candidates.

4.3.1.2 The method adopted for scoring the answers

As indicated in Table 4.1, questions asked were of a different type. It was decided to allocate scores as follows:

- when the question was of the two-tier multiple choice type, one mark was scored for a correct part (a) answer in conjunction with a correct reason in part (b);
- in Qn 4 about microscopic views of circuits, which consisted of six parts, a mark was scored when the student answered correctly and consistently to two parts of the question, which were deemed complimentary to each other. Thus, in all, 3 marks were allotted for Qn 4. The same approach was used in all questions of this type;
- when answers requested a prediction and an open response from the student, as in Qn 15, one mark was allotted for correct prediction with correct explanation;
- when no justification was asked for in parts of the question, as in Qn 17, one mark was scored for each correct response.

4.3.2 Students' scores on the pre-test

Figure 4.1 shows students' scores out of a total of 29, on the pre-test. These indicate a normal distribution and confirm that students in the sample were of different ability.

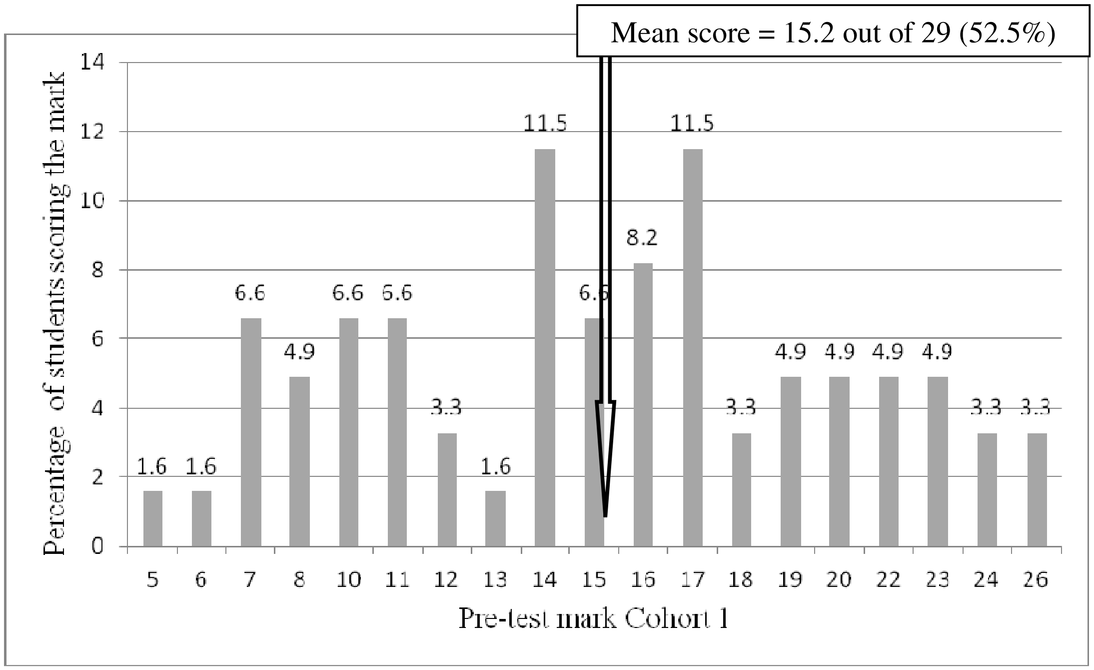


Figure 4.1: Students' pre-test marks

4.3.3 Facility values

A simple measure of student performance on each question is the facility value (the fraction of the sample giving correct answers). This value was calculated for all part questions, and for groups of questions which included reasons for students' answers, or indicated consistency in students' views. Facility values for the pre-test questions are shown in Table 4.2. Results are shown sorted in rank order according to the facility values. Coloured data bars help to indicate the levels of difficulty experienced.

Facility values were used to judge whether a question would be asked again in the post-test. Easy questions were omitted in the post-test, while new questions based on course work, which could not have been asked in the pre-test as the points they probe had not yet been taught, had to be introduced.

Moreover, facility values helped in decisions as to which questions would be explored in interviews with students.

4.3.4 Item-total correlation

The item-total correlation coefficient (Pearson) was also calculated for each item. These values, considered along with the facility value of the question, help to identify questions which may provide unreliable data. The results are also included in Table 4.2. Coloured data bars have been used to compare correlation values. Questions like 4(a+d), 4(b+e), 9a(i), 5, 6 and 17b(ii), asked in the pre-test, showed a very poor correlation with the total mark scored, pointing to a poor discrimination between students who knew the material and those who did not.

Question number in the Question Bank	Item - Total correlation coefficient	Facility Values	Code to item being tested: Current (I), Resistance (R), Voltage (V)	Item being tested
9a(i)	0.111	0.951	I	Conservation of current at a junction
12a	0.328 **	0.885	V	The use of a voltmeter to read the p.d. across the battery terminals
17b(i)	0.279 *	0.885	I	An ammeter indicates zero current in an open circuit
5a		0.869		
5b		0.869		
7a		0.852		
5	0.087	0.836	R	The effect on the current of increasing the resistance
3a		0.836		
11b		0.836		
12d		0.803		
10b		0.787		
9a(iv)		0.77		
11a		0.77		
11	0.327 **	0.77	V	Effect on the current of increasing the number of batteries connected in series
9a(v)		0.754		
10a		0.754		
12e		0.754		
9a(iv)+(v)	0.260 *	0.738	I	Conservation of current within the main circuit
12d+12e	0.316 *	0.738	V	P.d. across a resistance in a series circuit
4b		0.721		
1a		0.689		
9a(ii)		0.689		
6a		0.689		
2a		0.689		
2b		0.689		
2	0.628 **	0.689	I	Conservation of current
10	0.541 **	0.672	V	The effect on current of increasing the voltage
1b		0.656		
1	0.530 **	0.656	I	Conservation of current
9a(iii)		0.656		
9a(ii)+(iii)	0.503 **	0.656	I	Conservation of current within a parallel branch
12b	0.425 **	0.656	V	P.d. across resistances connected in series with the battery
3b		0.639		
8b		0.607		

Table 4.2: Pre-test results (Cohort 1) expressed in rank order according to facility values

(Note: * = significant to 5% level; ** = significant to 1% level)

(This table continues on the following page)

Question number in the Question Bank	Item - Total correlation coefficient	Facility Values	Code to item being tested: Current (I), Resistance (R), Voltage (V)	Item being tested
15predict	0.585 **	0.574	V	Predicting the p.d. across equal resistances connected in parallel to the battery
9b	0.490 **	0.525	R	Division of current at a junction, using unequal resistances within branches
3	0.391 **	0.525	I	Models of current flow in a simple circuit
13a		0.525		
13	0.478 **	0.525	V	Potential division using equal resistances in series
4e		0.508		
4d		0.475		
4f		0.475		
7b		0.459		
7	0.510 **	0.459	R	The effect on current of increasing the resistance using a variable resistance
15	0.516 **	0.459	V	Modelling p.d. across equal resistances connected in parallel to the battery
4c		0.443		
4b+4e	0.204	0.41	I	Charge is everywhere and the battery provides the push
16predict	0.583 **	0.393	V	Predicting the p.d. across unequal resistances connected in parallel to the battery
16 model	0.583 **	0.393	V	Modelling p.d. across unequal resistances connected in parallel to the battery
14a		0.344		
14 model	0.539 **	0.344	V	Potential division using unequal resistances in series
12f		0.311		
6b		0.279		
6	0.208	0.262	R	The effect on the current of adding a resistor in series
17b(ii)	0.208	0.262	V	The presence of p.d. without a current
4a		0.246		
12c		0.246		
4c+4f	0.373 **	0.213	I	It is not electrons which are absorbed by a bulb but energy
12c+12f	0.434 **	0.213	V	P.d. across ideal connecting wires
17a	0.411 **	0.213	V	P.d. across a closed switch
8a		0.197		
4a+4d	0.309 *	0.164	I	Not only the battery contains charge but charge is everywhere
8	0.502 **	0.164	R	The effect on the current of adding a resistor in parallel

Table 4.2 (continued):Pre-test results (Cohort 1) expressed in rank order according to facility values

(Note: * = significant to 5% level; ** = significant to 1% level)

It can be seen that question Qn 17b(ii), for example, has a low correlation coefficient and facility value. There are also questions with a low item-total correlation coefficient, and a high facility value, such as Qn 5. Such situations are not unexpected because, when a question is very easy, then few students answer it incorrectly, some of these being students with high overall score who make a careless mistake on this question. Similarly, when a question is too difficult, only a few answer it correctly and this probably includes some weak students who happened to guess correctly.

4.4 Students' mental models of the electric circuit at the pre-test stage

4.4.1 Grouping the pre-test questions for analysis

To try to understand students' thinking on the basis of their pre-test answers, the 17 test questions were first grouped by the concepts being tested, as shown in Table 4.3.

Group	Ideas probed	Question number in the question bank	Question title
A	Microscopic views of circuit	4	Microscopic views
B	Mental models of current	1	Current at points (a) and (b)
		2	Current using two ammeters
		3	Picture of the battery and bulb
		9a	Current conservation at junctions and within a parallel branch
C	How resistances control the current	5	Use of a larger resistance
		6	Adding an equal resistance in series
		7	Increasing the variable resistance
		8	Adding an equal resistance in parallel
		9b	Parallel resistors control of current
D	Conceptualisation of potential difference (p.d.)	10	Increase of the supply voltage indicated numerically
		11	Connecting another battery in series
		12	p.d. across resistances and ideal connecting wires
		13	p.d. across equal resistances in series
		14	p.d. across unequal resistance in series
		15	p.d. across equal parallel resistors
		16	p.d. across unequal parallel resistors
		17	p.d. across an open and closed switch

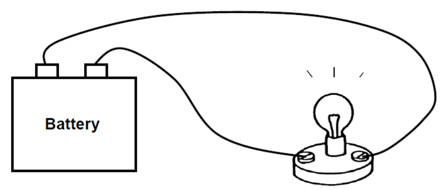
Table 4.3: Pre-test questions grouped by the concepts probed

4.4.2 Students' problems with microscopic views of circuit

Qn 4 was the only question which made direct reference to electric charges present and moving in wires and through the battery. While this question was deemed very important, it was not used as the first question on the test. Instead a simpler question was placed first, to put students at ease as they start answering the test questions. Qn 4 was a long question with six parts (see Figure 4.2). The question consisted of pairs of complementary statements exploring three ideas, in order to be able to check responses for consistency.

Qn 4

In this circuit, the bulb is lit.



Read each of the statements below.

Decide whether each statement is 'True' **or** *'False' and mark your answer on the answer sheet.*

	Statement	True	False
(a)	Before the battery is connected, there are no electric charges in the wire. When the battery is connected, electric charges flow out of it into the wire.		
(b)	When the circuit is connected, the free electrons gain kinetic energy. As they move round, the free electrons give this energy to the components they pass through.		
(c)	The battery, the wire and the bulb filament are all full of charges, all the time. When there is a closed circuit, the battery makes all these charges move round together.		
(d)	Before the circuit is connected up, there are free charges in the battery only. There are no free charges in the wires or the bulb filament.		
(e)	When the circuit is connected, the free electrons which are moving are absorbed by the bulb, to produce light.		
(f)	Before the circuit is connected up, there are free charges in the battery, the wires and the bulb filament.		

Figure 4.2: Qn 4 - 'Microscopic views of circuit'

4.4.2.1 Where do charges reside?

Parts (a), (d), (c) and (f) of Qn 4 probed whether students visualized charges as residing only in the battery, being pushed out of it when the circuit is connected, much like water coming out of a pipe, or whether they saw the charges already present everywhere and moving simultaneously when the circuit is switched on.

A cross-tabulation between parts (a) and (d) (see Table 4.4) shows that only 10 students out of 61 (16%), answered both these part questions correctly. Indeed, almost half (27; 44%) believed that the free charges resided in the battery and that these only move into the wires once the circuit is switched on. Twenty-four students, (19 +5; 39%), gave a wrong answer to one part question, showing inconsistent views.

		Qn4(d)		Total
		Correct	Incorrect	
Qn4(a)	Correct	10*	5	15
	Incorrect	19	27	46
Total		29	32	61

Table 4.4: Results to parts (a) and (d) of Qn 4
(Note: * shows the correct answer)

Similarly, in parts (c) and (f) only 13 students (31.3%) gave correct answers to both questions (see Table 4.5). Many students thus had unscientific views about where free charges reside in an electric circuit, before and after the circuit is connected.

		Qn4(f)		Total
		Correct	Incorrect	
Qn4(c)	Correct	13*	14	27
	Incorrect	16	18	34
Total		29	32	61

Table 4.5: Results to parts (c) and (f) of Qn 4

4.4.2.2 Combining the results of parts (a), (d), (c) and (f) for Qn4

Table 4.6 shows that 53% of the students made a mistake in 2 or more part questions. This is a high percentage, indicating inconsistent ideas which suggest weak understanding and poor ability to visualize how charge moves and behaves in an electric circuit.

Combination of responses to parts (a), (d), (c), (f)	Number of students with this pattern as a response	Percentage (N=61)
All parts correct	8	13%
3 parts correct	7	12%
2 or more parts *incorrect*	32	53%
All parts incorrect	14	23%

Table 4.6: Comparing answers to parts (a), (d), (c) and (f) of Qn 4 - 'Microscopic views'

4.4.2.3 Summary of problems with the microscopic 'image' of a circuit

Many students saw charges as residing within the battery, moving out when the circuit is switched on. A poor understanding of charge behavior was indicated.

4.4.3 Students' models of current

4.4.3.1 Introduction

A number of questions were meant to probe students' models of current (see Table 4.3, Group B). These were aimed at indicating popular ideas amongst students as to whether current is conserved or not, in simple circuits and within parallel branches.

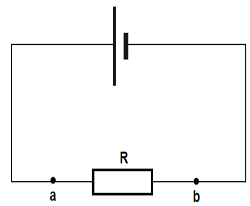
4.4.3.2 Performance on Qn 1 and Qn 2

Of the questions in Group B, Qn 1 (Figure 4.3) and Qn 2 (Figure 4.4) were the most similar in format and presentation. It was thus expected that students would be consistent in their response if they held a specific model of current strongly in their mind. The analysis of these responses was indeed indicative of the main mental models of current used by the sample.

Students' responses to Qn 1 are shown in Table 4.7. The models of current which the students appeared to be using in this question were thus indicated, and are shown in Table 4.8.

Qn 1

In this circuit, a battery is connected to a resistor, R.



(a) What can you say about the electric current at points **a** and **b**?
Choose one answer.

i	The electric current at **a** is bigger than at **b**.
ii	The electric current at **b** is bigger than at **a**.
iii	The electric current is the same size at **a** and **b**.

(b) How would you explain this?
Choose one answer.

i	The current is the same all round the circuit.
ii	**Some** of the current is used up by the resistor.
iii	**All** of the current is used up by the resistor.

Figure 4.3: Qn 1 - 'Current at points (a) and (b)'

		Qn1(b)			Total
		i	ii	iii	
Qn1(a)	i	0	17	1	18
	ii	0	1	0	1
	iii	40*	0	2	42
Total		40	18	3	61

Table 4.7: Number of students giving responses to Qn 1
(Note: * indicates correct responses)

Answer to Qn1(a)	Answer to Qn1(b)	Mental model consistent with answers	Mental model code	Number of students	Percentage (N=61)
(iii)	(i)	Conservation of current	CC	40*	66%
(i)	(ii)	Attenuation of conventional current	ACC	17	28%
(i)	(iii)	Attenuation of conventional current	ACC	1	2%
(ii)	(ii)	Attenuation of electron flow	AEF	1	2%
(iii)	(iii)	Clashing currents	CL	2	3%

Table 4.8: Mental models of current used in Qn 1 – 'Current at points a and b'

While the majority (40 students; 66%) held the scientific view of current conservation (CC), 18 students held an attenuated conventional current view (ACC). The latter view could be a consequence of students not being able to discriminate between current flow and energy transfer (Shipstone, 1988; Shipstone and Gunstone, 1985). Even though the number was small, it was rather surprising to find that two students gave answers consistent with the clashing current (CL) model - a model which is usually exhibited by younger students (Fleer, 1994).

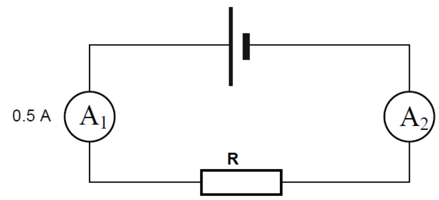
In Qn 2 (Figure 4.4), 42 students (69%) answered parts (a) and (b) correctly (see Table 4.9). The 19 students who answered part (a) incorrectly also chose an incorrect option to part (b). Students either conserved the current or held an attenuation view.

		Qn2(b)		Total
		i	iii	
Qn2(a)	i	2	0	2
	ii	0	42*	42
	iii	17	0	17
Total		19	42	61

Table 4.9: Students' answers to Qn 2 - 'Current using two ammeters'

Qn2

The figure shows a battery connected to a resistor. Two ammeters measure the electric current at different points in the circuit. The reading on ammeter A_1 is 0.5 A.



(a) What will the reading on ammeter A_2 be?
Choose one answer.

i	More than 0.5 A.
ii	Exactly 0.5 A.
iii	Less than 0.5 A, but not zero.
iv	Zero.

(b) How would you explain this?
Choose one answer.

i	**Some** of the current is used up by the resistor.
ii	**All** of the current is used up by the resistor.
iii	The current is the same all round the circuit.

Figure 4.4: Qn 2 - 'Current using two ammeters'

Table 4.10 shows the mental models of current consistent with students' answers to Qn 2.

Answer to Qn2(a)	Answer to Qn2(b)	Mental model consistent with answers	Mental model code	Number of students	Percentage (N=61)
ii	iii	Conservation of current*	CC	42*	69%
iii	i	Attenuation of conventional current	ACC	17	28%
i	i	Attenuation of electron flow	AEF	2	3%

Table 4.10: Mental models of current in Qn 2 - 'Current using two ammeters'

These results show that no student chose the (a)(iv) / (b)(ii) option, indicating that no-one saw 'all' the current being used up by the resistor. It was more common, therefore, for these students to think in terms of 'some' of the current only, as being used up. In this question, no clashing current views were evidenced.

4.4.3.3 Consistency shown in mental models used in Qn 1 and Qn 2

		Model Qn2			Total
		CC	AEF	ACC	
Model Qn1	CC	36*	1	3	40
	ACC	4	1	13	18
	AEF	0	0	1	1
	CL	2	0	0	2
Total		42	2	17	61

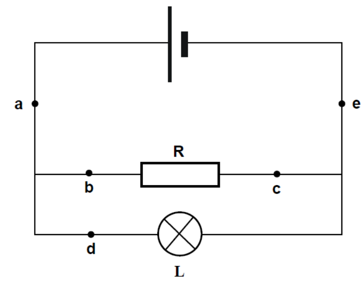
Table 4.11: Mental models of current in Qn 1 and Qn 2

By checking students' answers to Qn 1 and Qn 2, consistency in students' answers could be probed. Table 4.11 indicates that in these two questions, out of the four questions in group B, a substantial number of students were consistent in their ideas. Thirty six students (59%) consistently conserved the current, whereas 13 students (21%) showed ideas consistent with the ACC model. The results also show that some students were still confused at this stage, choosing one answer based on current conservation and another based on attenuation.

4.4.3.4 Conservation of current in a more complicated circuit

Qn 9

In this circuit a battery is connected to a resistor R and a bulb L, as shown.



(a) What can you say about the following statements related to the currents at the various points in the circuit?
*Choose True **or** False for each statement. Mark the answer sheet.*

	Statement	True	False
i	d + b = a		
ii	b is larger than c		
iii	b equals c		
iv	a is larger than e		
v	a = e		

(b) Is b equal to d? Yes / No

How would you explain this?

Figure 4.5: Qn 9 - 'Current conservation at junctions and within a parallel branch'

Qn 9(a) (Figure 4.5) probed whether students used conservation of current at junctions and within parallel branches.

N=61					
Qn9(a)	(i)	(ii)	(iii)	(iv)	(v)
Statement	d+b = a	b larger than c	b = c	a larger than e	a = e
Frequency of correct answers	58	42	40	47	46
Percentage	98%	69%	66%	77%	75%

Table 4.12: Results to Qn 9(a) - 'Current conservation at junctions and within a parallel branch'

The results shown in Table 4.12 indicate that almost all students (98%) saw current as conserved at a junction. The percentage of correct answers in the other four parts never rises as high, even though more than half of the sample answered correctly in each part.

As Table 4.13 shows, 45 students (74% of the sample) who answered question 9a(iv) correctly, also answered 9a(v) correctly. These students show understanding of current conservation (what enters the battery has to leave it), in contrast with the 13 students who firmly held on to attenuation views.

		Qn9a(v)			Total
		True	False	Missing	
Qn9a(iv)	True	1	13	0	14
	False	45*	1	1	47
Total		46	14	1	61

Table 4.13: Answers for Qn 9a(iv) and Qn 9a(v) - 'Current conservation in the main circuit'

Moreover, 40 students had ideas consistent with conservation of current within a parallel branch, answering correctly to part questions 9a(ii) and 9a(iii) (see Table 4.14), and 19 students chose answers consistent with current attenuation.

		Qn9a(iii)		Total
		True	False	
Qn9a(ii)	True	0	19	19
	False	40*	2	42
Total		40	21	61

Table 4.14: Answers to Qns 9a(ii) and 9a(iii) - 'Current conservation within a parallel branch'

4.4.3.5 Overall results for Qn 9(a) and consistency of answers

While 58 students (98%) conserved current at a junction, 36 students (59%) consistently conserved current in all four parts of Qn 9a(ii)-(v) (see Table 4.15). These saw current conservation within a branch and throughout the whole circuit. Eleven students (18%) gave the wrong answers to all four parts of the question, suggesting totally mixed up views. The next largest group is 8 students (13.1%) who appear to think that what comes out of the battery must go in, but are not clear on current conservation within the parallel branch. This result may indicate that students find it easier to think of current conservation to/from the battery rather than before/after a resistor.

Response patterns for the part questions in Qn9(a)	Number of students with indicated response pattern	Percentage (N=61)
(a)(ii), (a)(iii), (a)(iv), (a)(v)		
X, X, X, X	11	18%
X, X, ✓, ✓	8	13%
✓, X, X, ✓	1	2%
✓, ✓, X, X	2	3%
✓, X, ✓, ✓	1	2%
✓, ✓, ✓, X	2	3%
✓, ✓, ✓, ✓	36*	59%

Table 4.15: Different response patterns for questions 9a(ii) to 9a(v)
(Key: Response for part questions to Qn 9: X = wrong answer; ✓ = correct answer)

The cross-tabulation of results in Table 4.16 for Qn 9a(ii) to 9a(v), Qn 1 and Qn 2 shows that 33 students (54%) gave answers consistent with the CC model in all questions. Moreover, of the 11 students who gave no correct response to Qn 9a(ii) to 9a(v), none used current conservation models consistently in both Qn 1 and Qn 2. This implies that 44 students (33+11; 72%) were indicating ideas consistent with either the scientific conservation model or the attenuation model, in the various test questions.

Combination 9a(ii) to 9a(v)	Model Qn1	Model Qn2		
		CC	AEF	ACC
XXXX	CC	0	0	1
	ACC	2	1	6
	CL	1	0	0
XX✓✓	AEF	0		1
	ACC	1		6
✓**XX**✓ ✓XX✓	CC	1		
✓**X**✓✓ ✓X✓✓	ACC			1
✓✓XX	CC	0		1
	ACC	1		0
✓✓✓**X** ✓✓✓X	CC	2		
✓✓✓✓	CC	33	1	1
	CL	1	0	0

Table 4.16: Different response patterns for Qn 9a(ii) to (v) compared to ideas indicated in Qn 1 and Qn 2

4.4.3.6 Summary of students' ideas about current

Almost all students conserved current at a junction. More than half the students consistently used current conservation in a simple circuit. About one quarter attenuated the conventional current. No student had the view that all current would be used up by the resistor. Moreover it seemed that current conservation to/from the battery was more easily understood than conservation before/after a resistor.

4.4.4 How resistance controls the current

4.4.4.1 Introduction

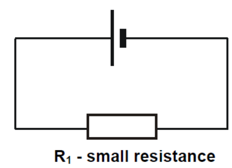
Questions in Group C probed whether students recognized that it is the resistance control on the battery push which decides the current in the circuit. Some questions also probed students ideas related to the effect of resistances within parallel branches. Students were expected to know that increasing the resistance in the circuit results in a smaller current, even if, having students at this stage using ideas consistent with models that focus only on the battery or resistances separately, was also considered a possibility.

4.4.4.2 Resistance as a control of the battery push

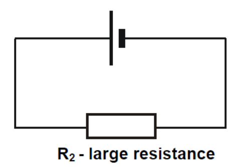
In Qn 5 (Figure 4.6), 51 students (84%) gave a scientifically correct response. These students saw that, all else being constant, the bigger the resistance, the smaller the current (see Table 4.17).

Qn 5

The resistor in this circuit, R_1, has a small resistance.



It is replaced by R_2, which has a large resistance.



(a) What happens to the current in the circuit?
Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller, but not zero.
iv	It drops to zero.

(b) How would you explain this?
Choose one answer.

i	The battery is not strong enough to push any current through a larger resistor.
ii	The resistor controls the size of the current that the battery can push around the circuit. The bigger the resistance, the smaller the current.
iii	A large resistance needs more current than a small resistance. The bigger the resistance, the bigger the current.
iv	It is the same battery, so it always supplies the same current.

Figure 4.6: Qn 5 - 'Use of a larger resistance'

		Qn5(b)				Total
		i	ii	iii	iv	
Qn5(a)	i	0	1	0	0	1
	ii	1	0	1	4	6
	iii	0	51*	2	0	53
	iv	0	1	0	0	1
Total		1	53	3	4	61

Table 4.17: Results to Qn 5 - 'Use of a larger resistance'

No student chose answer a(i) with b(iii), reflecting 'the more of A, the more of B' model (Andersson, 1986; Stavy & Tirosh, 1996). Four students appeared to hold the alternative conception that 'the same battery provides the same current', whatever the resistance (see Chabay & Sherwood, 1999; Cohen et al., 1983; Eylon & Ganiel, 1990; Licht, 1991; McDermott & van Zee, 1985; McDermott & Shaffer, 1992; Shipstone 1985b, 1988; Steinberg & Wainwright, 1993; Thacker, Ganiel & Boys, 1999). Only 2 students looked locally at the increased resistance, thinking this 'needs'/absorbs more current (Maichle, 1981). The results are shown in Table 4.18.

Answer to Qn5(a)	Answer to Qn5(b)	Mental model consistent with answers	Mental model code	Number of students	Percentage (N=61)
iii	ii	Scientific (R as a control to the battery push)	SCI(R)	51	84%
ii	iv	Same battery, same current	BAT	4	7%
iii	iii	I gets smaller because larger R 'needs' bigger I	R-TAKE	2	3%
Others		Unclassified	U	4	7%

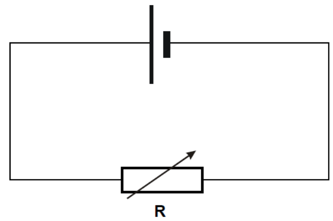
Table 4.18: Mental models of resistance in Qn 5

4.4.4.3 Consistency of students' responses about resistance

Qn 5 and Qn 7, 'Increasing the variable resistance' (Figure 4.7), were very similar, both in question format and in the wording used.

Qn 7

Peter makes this circuit, with a battery and a variable resistor, R.



He then **increases** the resistance of R.

(a) What happens to the current in the circuit?
Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller, but not zero.
iv	It drops to zero.

(b) How would you explain this?
Choose one answer.

i	The battery is not strong enough to push any current through a larger resistor.
ii	The battery cannot push as big a current through a larger resistor.
iii	A larger resistance needs more current than a smaller resistance.
iv	It is the same battery, so it supplies the same current.

Figure 4.7: Qn 7 - 'Increasing the variable resistance'

The results for Qn 7, shown in Table 4.19, indicate that quite a high percentage of students (85%, 52 students) gave a scientific answer to part (a). However, only 29 of these, just less than half, chose a scientific reason for the decrease in current when the resistance increases. 3 students gave an inconsistent answer to their answer in part (a), focusing on ideas consistent with the BAT model (same battery, same current). Another 6 students still focused on the battery but thought that it cannot push as large a current through a larger resistance. A rather large number of 14 students (23%), on the other hand, had ideas consistent with the R-TAKE model.

		Qn 7(b)				Total
		i	ii	iii	iv	
Qn 7(a)	i	0	0	0	1	1
	ii	1	0	0	7	8
	iii	6	29*	14	3	52
Total		7	29	14	11	61

Table 4.19: Answers to Qns 7(a) and 7(b) - 'Increasing the variable resistance'

Students' answers and the mental models of resistance these were consistent with are shown in Table 4.20.

Answer to Qn7(a)	Answer to Qn7(b)	Mental model consistent with answers	Mental model code	Number of students	Percentage (N=61)
iii	ii	Scientific	SCI(R)	29*	48%
ii	iv	Same battery, same current	BAT	7	12%
iii	iii	A larger resistance 'needs' more current	R-TAKE	14	23%
Others		Unclassified	U	11	18%

Table 4.20: Mental models of resistance in Qn 7

Considering all answers, the BAT model appeared common amongst students, with 7 students (12%) answering in line with this model.

When answers to part (a) of Qns 5 and 7 were compared (see Table 4.21), the results indicated that in both questions the same 50 students could recall, or perhaps even understand that the increased resistance helps to decrease the current. Only 29 students, however (see Table 4.20), could consistently select a scientific reason for why this happens. This is thus strong evidence of recall of information which is not backed by proper scientific understanding. At the same time, it was noted that more students seemed to have been confused in choosing the correct reason for the answer to Qn 7, when the variable resistor was shown in the circuit, than for Qn 5, when the first resistance *was changed* for a larger one (Tables 4.19 and 4.17).

		Qn7(a)			Total
		i	ii	iii	
Qn5(a)	i	0	0	1	1
	ii	1	5	0	6
	iii	0	3	50*	53
	iv	0	0	1	1
Total		1	8	52	61

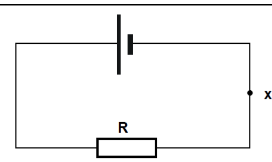
Table 4.21: Comparing answers to Qn 5(a) and Qn 7(a)

4.4.4.4 The effect on current of adding an equal resistance in series

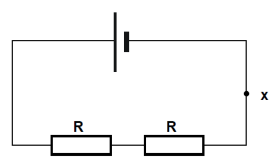
The analysis of Qn 6 (Figure 4.8) again suggested recall of information without appropriate scientific backing.

Qn 6

Sam makes this circuit.



He then adds a second identical resistor.



(a) What happens to the current in the circuit at point x?
Choose one answer. Use the answer sheet.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller, but not zero.
iv	It drops to zero.

(b) How would you explain this?
Choose one answer. Use the answer sheet.

i	The battery is not strong enough to push any current through two resistors.
ii	The battery cannot push as big a current through two resistors.
iii	It is the same battery, so it supplies the same current.
iv	Two resistors need more current than one on its own.
v	The current is shared between the two resistors, so each gets half.

Figure 4.8: Qn 6 - 'Adding an equal resistance in series'

		Qn6b						Total
		i	ii	iii	iv	v	Missing	
Qn6a	i	0	0	0	2	0	0	2
	ii	1	0	4	0	7	0	12
	iii	1	16*	2	9	13	1	42
	iv	1	1	1	0	1	0	4
	Missing	0	0	0	0	0	1	1
Total		3	17	7	11	21	2	61

Table 4.22: Student's answers to Qn 6 - 'Adding an equal resistance in series'

Table 4.22 shows that of the 42 students (69%) who gave the correct answer to Qn 6(a), only 16 (26%) could select the correct explanation for the effect of the increased resistance.

The mental models students appeared to use in Qn 6 are shown in Table 4.23.

Answer to Qn6(a)	Answer to Qn6(b)	Mental model consistent with answers	Mental model code	Number of students	Percentage (N=61)
iii	ii	Scientific (R as a control to the battery push)	SCI(R)	16*	26%
i	iv	More of A, more of B; direct proportion	More A, More B	2	3%
iii	iv	More resistors 'need' more current	R-TAKE	9	15%
iii	v	Sharing model	SHARE	13	21%
ii	iii	Same battery, same current	BAT	4	7%
Others		Unclassified	U	17	28%

Table 4.23: Mental models in Qn 6 - 'Adding an equal resistance in series'

Nine students who chose options a(iii) and b(iv) seemed to think of resistance in terms of the R-TAKE model. While this model puts the resistance at the focus of students' attention, attenuation is also implied. This may be a result of having these students not yet distinguishing between current and energy – a problem referred to by Shipstone (1988) and Shipstone and Gunstone (1985).

It is also interesting to note that, when given the choice in this question to think in terms of ‘sharing of current', 13 students actually opted to use it. Such reasoning may be linked to basic everyday causal reasoning described by Andersson (1986).

The models suggested by answers to Qns 6 and 7 shows consistent answers from only 14 students (23%), who gave a correct scientific reason for their response to both questions (see Table 4.24). Such poor performance is again evidence of recall of information. Many students did not show that they understood that an increased resistance provides a larger control over the battery push. Many indicated that they did not see the battery and the resistances working together.

		Model Qn6							Total
		SCI(R)	R-TAKE	BAT	SHARE	More A, more B	U	Missing	
Model Qn7	SCI(R)	14*	1	1	9	0	2	2	29
	BAT	1	0	3	2	0	1	0	7
	U	1	8	0	2	2	12	0	25
Total		16	9	4	13	2	15	2	61

Table 4.24: Models inferred in Qn 6 and Qn 7

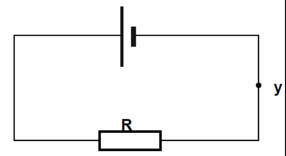
4.4.4.5 Resistances connected in parallel

In asking Qn 8 (see Figure 4.9), it was borne in mind that students had not covered a lot of material related to parallel circuits in their previous years of schooling (see Appendix 1).

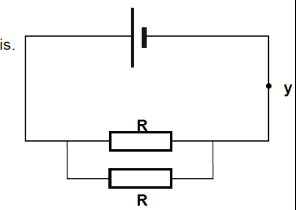
The results in Table 4.25 show that only 12 students predicted correctly that connecting a second resistor in parallel increases the current in the main circuit. Only 10 of these chose a correct explanation. Comparing these results to those in Qn 6 for resistances in series (see Table 4.22), while a larger number of 42 could predict correctly in that question, yet only 16 chose correct explanations. It seems that often, students’ choices are based on guess-work rather than understanding of basic principles.

Qn 8

Sam connects this circuit. A current flows.



He then adds a second identical resistor, like this.



(a) What happens to the current at y?
Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller.

(b) How would you explain this?
Choose one answer.

i	The battery cannot push as big a current round the circuit.
ii	The second resistor provides an extra path for current to flow.
iii	It is the same battery, so it always supplies the same current.

Figure 4.9: Qn 8 - 'Adding an equal resistance in parallel'

		Qn8(b)				Total
		i	ii	iii	missing	
Qn8(a)	i	1	10*	0	1	12
	ii	1	15	12	0	28
	iii	5	12	3	1	21
Total		7	37	15	2	61

Table 4.25: Students' answers to Qn 8

Table 4.26 shows the mental models students appear to have used in Qn 8.

Answer to Qn8(a)	Answer to Qn8(b)	Mental model consistent with answers	Mental model code	Number of students	Percentage (N=61)
i	ii	R in parallel branch provides extra path – I increases	SCI(R)	10*	16%
ii	iii	Same battery, same current	BAT	12	20%
iii	i	Only the number of resistances count, not how they are connected	R↑, I↓	5	8%
Others			U	34	56%

Table 4.26: Mental models used in Qn 8 - 'Adding an equal resistance in parallel'

The large number of unclassified responses indicates that many students were not making informed decisions. However, an important point noticed was that, out of the 34 students with an unclassified response, 27 (encircled in Table 4.25) could 'see' the 'extra path' offered by the second resistor connected in parallel, even if in part (a) the prediction was incorrect. This may be an indication that teaching parallel circuits in terms of added extra paths across the first resistor "may be a simpler conceptual step from mono-circuits than progressing to circuits with several resistors in series" (Millar and Beh, 1993, p. 353).

It was also worth noticing that once again the 'same battery, same current' model (BAT) resurfaced quite strongly. However, general statements must be made carefully since a cross-tabulation with Qn 7 indicated that only 3 of the students who used the BAT model in Qn 8, also used it in Qn 7 (see Table 4.27). On the other hand, there is also the possibility that students' confusion because of limited knowledge about parallel resistors may have affected results.

		Model Qn8				Total
		SCI(R)	BAT	R↑, I↓	U	
Model Qn7	SCI(R)	7*	4	2	6	29
	BAT	0	3	0	4	7
	U	3	5	3	14	25
Total		10	12	5	34	61

Table 4.27: Comparing models in Qn 7 and Qn 8

4.4.4.6 The control of current by resistors in different branches

Analysis of Qn 9(a) in section 4.4.3.4 has already shown how a majority (98%) of the students could conserve current at a junction. Qn 9(b), (see Figure 4.5 for Qn 9) partly of an open-response type, probed further into how students saw the current splitting at a junction and the effect of unequal resistors in parallel branches. Students were expected to say that the currents through the branches were unequal since a larger resistance in a branch would allow the passage of a smaller current.

In order to categorize responses, a method similar to that used by Millar and Gill (1996) to analyze open ended responses, was adopted. The following examples indicate how the analysis was conducted.

Some students gave a *correct and complete* answer, like the following:

> 'No. This is because the resistances are not equal. Hence, the current passing through each will be different.'
> 'No. If the resistor and the bulb have the same resistance they will be equal, but if not the currents are different.'

Other students gave a *correct but incomplete* answer, as in the following example:

> 'No. This is because there is the filament lamp and the resistor; they have different resistances'.

Here, the effect on the current is implied but not specifically mentioned.

On the other hand, there were students who suggested equal splitting regardless of the resistance values - an unscientific view.

'Yes. This is so, since current is divided **equally** between branches of a parallel circuit'.

The results in Table 4.28 show that only 58% of the students answered correctly, providing scientific reasons for their answer.

Answer to Qn9(b): 'Yes/No'?	Explanation	Number of students	Percentage (N=61)
'No'	Correct + complete	23*	38%
	Correct + incomplete	10*	16%
	Unclassified explanation	2	3%
'Yes'	Correct and complete	1*	2%
	Equal division of current at a junction because in parallel	17	28%
	Others	7	12%
Missing 'Yes/No' answer	Correctly explaining that if R=L, then the current would be equal	1*	2%

Table 4.28: Answers to Qn 9(b) - 'Parallel resistors' control of current'

A good number of students (17; 28%) expressed the view that current divides equally between 2 parallel branches, thus not appreciating current control by resistances within each branch.

4.4.4.7 Summary of students' ideas about resistance

While many students could state that as the resistance increases the current decreases, giving the correct reason for this was not always easy. When the resistance was increased, many students did not see the resistances working with the battery as a system, controlling the current. The R-TAKE model, the BAT and the SHARE models seemed to be easily used by some students. About one quarter of the sample split the current equally between parallel branches in a circuit. Moreover, students indicated they could easily 'see' the extra path for charge flow offered by a parallel branch, even if they still did not relate this to an increase in the current before and after the branching points.

4.4.5 Conceptualization of potential difference

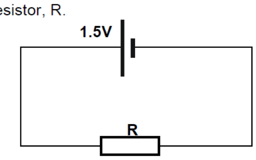
4.4.5.1 Introduction

Questions in Group D probed students' understanding of p.d. While it was expected that students would know that increasing the p.d. would increase the current in the circuit, all else being kept constant, yet, knowing that students had not been exposed to a lot of ideas about p.d. at this stage, the possibility that not many would differentiate p.d. from current was not ruled out.

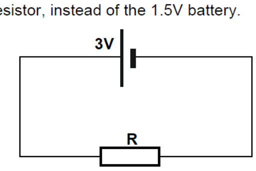
4.4.5.2 Changing the driving force – changing the supply voltage

Qn 10

This circuit consists of a 1.5V battery and a resistor, R.



A 3V battery is now connected to the same resistor, instead of the 1.5V battery.



(a) What happens to the current through the resistor?
Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller, but not zero.

(b) Which of the following is the best explanation for this?
Choose one answer.

i	It is the same resistor so it needs the same current.
ii	The potential difference increases, the resistance then has a larger effect, therefore the current is less.
iii	The 3V battery exerts a bigger 'push' on the electric charges.

Figure 4.10: Qn 10 - 'Increase of the supply voltage indicated numerically'

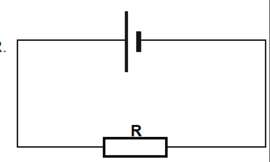
In Qn 10 (Figure 4.10), 41 students (67%) answered scientifically, appreciating that an increase in p.d. of the battery increases the current because the battery can now exert a bigger push (see Table 4.29). A further 6 students appreciated the presence of a bigger push, but did not equate this with an increase in current. Another 5 students had ideas consistent with an R-TAKE model (Koumaras, Kariotoglou & Psillos, 1997; Maichle, 1981), focusing primarily on the same resistance 'needing' the same current.

		Qn10(b)			Total
		i	ii	iii	
Qn10(a)	i	3	2	41*	46
	ii	5	0	6	11
	iii	2	1	1	4
Total		10	3	48	61

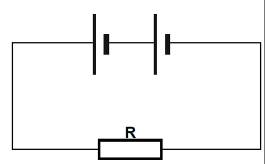
Table 4.29: Results for Qn 10

Qn 11

This circuit consists of a battery and a resistor, R.



A second identical battery is added.



(a) What happens to the current through the resistor?
Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller, but not zero.
iv	It drops to zero.

(b) Which of the following is the best explanation for this?
Choose one answer.

i	Two batteries exert a bigger 'push' on the electric charges.
ii	It is the same resistor so it needs the same current.
iii	The potential difference increases, the resistance then has a larger effect, therefore the current is less.
iv	The two batteries push in opposite directions and cancel each other out.

Figure 4.11: Qn 11 - 'Connecting another battery in series'

Qn 11, ‘Connecting another battery in series’ was similar to Qn 10. Forty seven students (70%) gave a scientific response (see Figure 4.11; Table 4.30), while 5 students chose answers consistent with the R-TAKE model.

		Qn11(b)			Total
		i	ii	iii	
Qn11(a)	i	47*	0	0	47
	ii	4	5	1	10
	iii	0	1	3	4
Total		51	6	4	61

Table 4.30: Results for Qn 11

A cross-tabulation of the models that students appeared to be using in Qns 10 and 11 (see Table 4.31) showed that only 2 students used ideas consistent with the R-TAKE model. On the other hand, only slightly more than half the sample (36 students) used consistent scientific views, recognizing that a higher battery voltage exerts a bigger push on the electric charges. When potential difference (p.d.) was not understood scientifically, students were confused, with a few looking only at the resistance which was remaining constant.

		Model Qn11				Total
		SCI(p.d.)	R-TAKE	V↑,R↑,I↓	U	
Model Qn10	SCI(p.d.)	36*	2	1	2	41
	R-TAKE	2	2	0	1	5
	V↑,R↑,I↓	1	0	0	0	1
	U	8	1	2	3	14
Total		47	5	3	6	61

Table 4.31: Mental models in Qn 10 and Qn 11

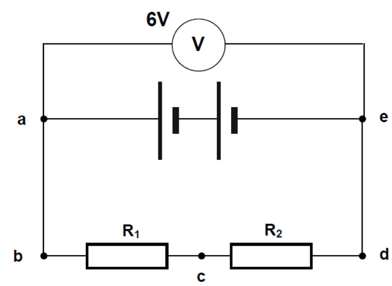
At the same time it must be acknowledged that performance on these two questions asking directly about an increased p.d. was better than for most other questions about resistance, shown in section 4.4.4. Clearly, many students find it easier to predict effects on current by an increased p.d. rather than by changes made to circuit resistances.

4.4.5.3 P.d. across equivalent points in the circuit

Qn 12, ‘p.d. across resistances and ideal connecting wires’ (Figure 4.12), probed ideas about how p.d. is distributed across series components.

Qn 12

The circuit consists of some batteries connected to two resistors R_1 and R_2.
A voltmeter connected across a and e reads 6V.



For each question, choose one answer. Mark your answer on the answer sheet.

		More than 6V	6V	Less than 6V	Zero
(a)	What is the potential difference (pd) between points a and e?				
(b)	What is the potential difference (pd) between points b and d?				
(c)	What is the pd between points a and b?				
(d)	What is the pd between points b and c?				
(e)	What is the pd between points c and d?				
(f)	What is the pd between points d and e?				

Figure 4.12: Qn 12 - ‘p.d. across resistances and ideal connecting wires’

Students’ answers are shown in Table 4.32.

(N=61)				
	Number of students choosing each answer			
Qn12	More than 6V	6V	Less than 6V	Zero
(a)	1	54*	4	2
(b)	2	40*	16	3
(c)	2	35	9	15*
(d)	1	10	49*	1
(e)	0	10	46*	5
(f)	1	30	11	19*

Table 4.32: Answers to Qn 12 - 'p.d. across resistances and ideal connecting wires'

Parts (a), (b), (c) and (f) looked into students' views regarding equivalent points in a circuit. Results to Qn 12(a) show 54 students who could see that a voltmeter reading indicates the value of the p.d. across two points in the circuit. Of these 54 students, only 38 (62%; see Table 4.33) indicated that they could transfer the knowledge from part (a) to stating the p.d. value across *equivalent* points in the circuit, answering correctly to part (b).

		Qn 12(b)				Total
		>6V	6V	<6V	Zero	
Qn 12(a)	> 6V	0	1	0	0	1
	6V	2	38*	12	2	54
	<6V	0	1	3	0	4
	Zero	0	0	1	1	2
Total		2	40	16	3	61

Table 4.33: Students' answers for Qn 12(a) and Qn 12(b)

A substantial number of students (12, encircled; 20%) answered 'less than 6V' in part (b), after answering part (a) correctly. This may imply that these students saw 'something' being wasted in the connecting wires.

Parts (c) and (f) of the question both required the knowledge that it is scientifically accepted that there is no p.d. across an ideal connecting wire. Performance in these two questions was very poor indeed (see Table 4.34). Twenty-six students consistently answered ‘6V’ to both parts of the question, when the answer should be ‘zero’. The 5 students who chose the 6V/zero options may point toward problems with distinguishing p.d. from potential, ‘seeing’ a potential of 6 V at one end of the battery and 0 V at the other end.

		Qn12(f)				Total
		>6V	6V	<6V	Zero	
Qn12(c)	>6V	1	1	0	0	2
	6V	0	26	4	5	35
	<6V	0	2	6	1	9
	Zero	0	1	1	13*	15
Total		1	30	11	19	61

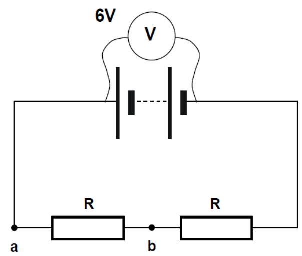
Table 4.34: Answers to Qn 12(c) and Qn 12(f) - ‘p.d. across connecting wires’

4.4.5.4 Predicting and explaining potential difference across series resistors

Qns 13 and 14 probed students’ ideas of potential difference across equal and unequal resistances connected in series. Part (b) of both questions asked for an open response (Figures 4.13 and 4.14).

Qn 13

In this circuit, a 6V battery is connected to two identical resistors in series.



(a) What is the potential difference (pd) between the points a and b?
Choose one answer.

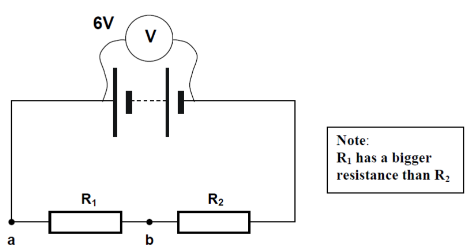
i	6V.
ii	Between 6V and 3V.
iii	3V.
iv	Between 3V and zero.
v	Zero.

(b) How would you explain this?

Figure 4.13: Qn 13 - 'p.d. across equal resistances in series'

Qn 14

In this circuit, a 6V battery is connected to two resistors in series. The resistance of R_1 is **bigger** than the resistance of R_2.



(a) What is the potential difference (pd) between the points a and b?
Choose one answer.

i	6V.
ii	between 6V and 3V.
iii	3V.
iv	between 3V and zero.

(b) How would you explain this?

Figure 4.14: Qn 14 - 'p.d. across unequal resistances in series'

The results of part (a) for **both** questions show that only about half the sample could correctly predict the p.d. across the resistor indicated in the circuit (see Table 4.35). Six students chose the 6V option (i) in both questions. Again, this may be an indication that these students did not distinguish p.d. from potential. On the other hand, students may have had a somewhat strong intuition that, perhaps based on the notion of p.d. as a measure of battery strength, the 6V across the battery go totally across the first resistor.

		Qn14(a)				Total
		6V	Between 6V and 3V	3V	Between 3V and zero	
Qn13(a)	6V	6	7	0	0	13
	Between 6V and 3V	1	6	1	3	11
	3V	0	29*	0	8	37
Total		7	42	1	11	61

Table 4.35: P.d. predictions in Qns 13(a) and 14(a)

In explaining p.d. predictions in Qn 13, only two students from the sample could give a *correct and complete* scientific explanation. This is one example:

> '3V' 'Since the current is the same and the resistances are identical, the p.d. is divided into two'.

About half the students (30; 49%) (see Table 34) gave a *correct but incomplete* answer with no reference made to the equal current through the two resistors thus:

> '3V' 'The voltmeter across both (resistances) reads according to the resistance of the whole circuit, which is 2R. The voltage across 'a' and 'b' would be half the amount of the voltmeter since it is only across half the resistance'.

A few explanations just restated the voltmeter prediction, thus:

> '3V' 'It splits'.

Some answers hinted at ideas which researchers had previously noted concerning common alternative conceptions of this situation. Two students answered as follows:

> '6 V' 'The same voltage **from** the battery to the two same (equal) resistors'.
> '6V' 'The resistor only changes the current, and whatever the current, the voltage will always be the same from the battery'.

These students considered the battery as an agent which 'gives' equal voltage, as much as it can supply, to each resistor – a 'give schema' (Koumaras et al., 1997; Maichle, 1981).

Other students saw the resistance as the primary actor, 'taking' potential from the battery – a 'take schema' (Koumaras et al., 1997; Maichle, 1981). One student wrote:

'Between 6V and 3V' 'Some of the potential has been **used up by the resistor'**.

Analysis of Qn 14 was conducted in much the same way as for Qn 13. Ideas referring to a direct proportionality between the two variables were considered correct. A few students said incorrectly that as resistance increases, the voltage decreases. This was categorized with other alternative ideas. One may assume that students who offer this relationship between resistance and voltage, are thinking more in the line of what happens to current when the resistance is increased (the bigger the resistance, the smaller the current) as they express their visualization of voltage.

	Qn 14						
	Correct and complete	Correct but incomplete	Explanation repeats part (a)	Using alternative ideas	Unclassified	Missing	Total
Qn 13							
Correct and complete	2*	0	0	0	0	0	2
Correct but incomplete	2*	16*	4	2	6	0	30
Explanation repeats part (a)	0	1	2	1	1	0	5
Using alternative ideas	0	0	0	5	1	0	6
Unclassified	0	0	7	3	6	0	16
Missing	0	0	0	0	0	2	2
Total	4	17	13	11	14	2	61

Table 4.36: Results for Qn 13 and Qn 14

The results shown in Table 4.36 indicate that many students gave a correct answer to part (a) which they could either not explain completely or not explain at all. Some used alternative ideas in their explanation or their answers were unclassified.

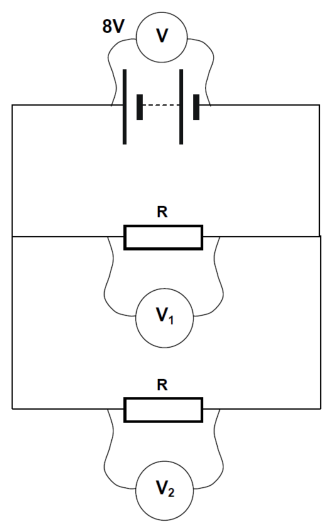
4.4.5.5 Predicting and explaining potential difference across parallel resistors

Qns 15 and 16 both probed ideas about p.d. across parallel resistors.

In predicting the voltmeter readings in Qn 15 across equal parallel resistors (see Figure 4.15), almost all students 'saw' the same reading on both voltmeters. The correct answer - '8V, 8V'- was offered by 57% of the sample. A considerable number split the 8V across the source, and said that both voltmeters would read 4V (see Table 4.37). This again shows the popularity of a 'sharing' answer, as explained in section 4.4.4.4, pointing towards basic causal reasoning.

Qn 15

The two resistors in this circuit are identical. The voltmeter connected across the battery reads 8V.



(a) What is the reading, in volts, on voltmeter V_1?
Use the answer sheet.

How would you explain this?

(b) What is the reading, in volts, on voltmeter V_2?
Use the answer sheet.

How would you explain this?

Figure 4.15: Qn 15 - 'p.d. across equal parallel resistors'

Student Answer to Qn15	Number of students predicting the answer	Percentage of sample (N=61)
(8V, 8V)	35*	57%
(4V, 4V)	23	38%
other	2	3%
Missing	1	2%

Table 4.37: Voltmeter reading predictions Qn 15 - 'equal resistances'

Students' open-ended responses were analyzed, as has been described in previous sections for other open-ended responses. One student wrote:

'(8V, 8V)' 'They are in parallel. The p.d. across R is equal to that of the cell.'

This answer was coded as *correct and complete,* showing that the student was seeing the voltage as a difference of 'something' which the voltmeter was reading across the terminals of the battery.

Another student's answer was as follows:

'(8V, 8V)' 'When in parallel, the current is divided and not the voltage'.

Here, the student is acknowledging the parallel connection, knows that current divides at the junction but is saying that the voltage is not divided but stays the same, hence the 8V across each resistor. The explanation could thus be considered brief but *correct*, even if *incomplete*.

Other answers simply offered an assertion of the correct answer without explanation, providing no clear evidence of the student's model of p.d, thus:

'(8V, 8V)' 'Voltage is the same'.

Results in Table 4.38 show that 7 students out of 35 who predicted the voltmeter readings correctly, suggested incorrect reasoning when it came to explaining why each voltmeter read 8V. One example was:

'8V, 8V' 'The p.d. is the same because the resistance is the same.'

		Qn15 explanation			Total
		Correct	Incorrect	Missing	
Qn15 prediction	Correct	28*	7	0	35
	Incorrect	0	25	0	25
	Missing	0	0	1	1
Total		28	32	1	61

Table 4.38: Predictions and explanations to Qn 15

When students split the 8V into two, it was always because they saw equal resistances:

'(4V, 4V)' 'Since the resistors are identical, the voltage is divided by two.'

Voltage was seen by such students as something which could be shared or controlled by the resistances. These ideas of sharing and the 'voltage split' suggest some students' inability to distinguish between current and voltage. Such students could only imagine what happens to current at a junction and then applied this to voltage.

Interpretation of students' responses helped to establish how students visualized voltage. Table 4.39 shows the models of voltage students appeared to be using.

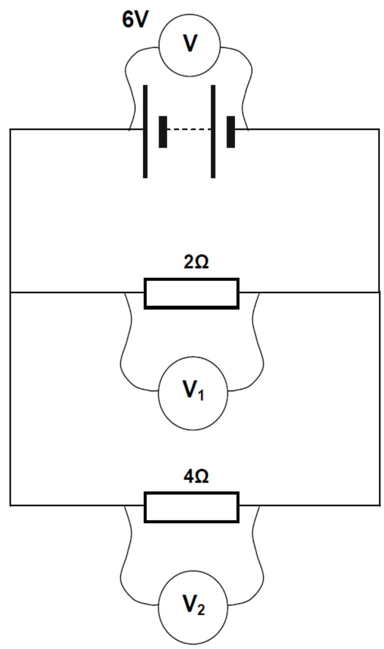
Voltmeter reading	Mental model consistent with answers	Mental model code	Number of students	Percentage (N=61)
8V, 8V	p.d as a difference of 'something' between two points (*causal* reasoning was offered)	SCI(C); *correct and complete*	4*	7%
8V, 8V	p.d. seems a *difference* of 'something' between two points (reason is not explained)	SCI(D); *correct and incomplete*	24	39%
8V, 8V; 4V,4V	p.d. as something which flows, like current, and depends on the resistances	p.d.FLOW(I)	27	44%
8V, 8V	Unacceptable explanation recalling information	U	4	7%
Others; No answer	Confused	U	2	3%

Table 4.39: Models of p.d. in Qn 15 - 'p.d. across *equal* parallel resistors'

In Qn 16 (Figure 4.16), when unequal parallel resistances of 2Ω and 4Ω were used, students' voltmeter predictions were either correct or clearly indicated that the main idea behind the response was that the sum of both voltmeter readings should be 6V.

Qn 16

In this circuit, the voltmeter across the battery reads 6V.



(a) What is the reading, in volts, on voltmeter V_1?
Use the answer sheet.

How would you explain this?

(b) What is the reading, in volts, on voltmeter V_2?
Use the answer sheet.

How would you explain this?

Figure 4.16: Qn 16 - 'p.d. across unequal parallel resistors'

The results are shown in Table 4.40.

Students' answer	Number of students	Percentage (N=61)
(6V, 6V)	24*	39%
(3V, 3V)	5	8%
(4V, 2V)	9	15%
(2V, 4V)	10	16%
Other	9	15%
Missing	4	7%

Table 4.40: Voltmeter predictions to Qn 16 - 'p.d. across unequal parallel resistors'

Students' explanations helped to interpret responses as was done in Qn 15. When the voltage was split, the indication was that students were treating voltage like current splitting up at a junction. The 5 students who suggested a (3V, 3V) split had also predicted an equal split of p.d. in Qn 15. For these students the split just depended on the number of parallel branches and *not* the resistances within these branches.

For other students, the split was in some way dependent on the value of the resistances, thus:

> '(2V, 4V)' 'The voltage splits between the two resistors, but not equally, as these have a different resistance.'

Voltmeter readings	Mental model consistent with answers	Mental model code	Number of students	Percentage (N=61)
6V, 6V	p.d. as a difference of 'something' between two points (*causal* reasoning was offered)	SCI(C); *correct and complete*	1*	2%
6V, 6V	p.d seems a *difference* of 'something' between two points (reason is not explained)	SCI(D): *correct and incomplete*	23	38%
3V, 3V	p.d. as flow: p.d.is split depending on the number of branches	p.d.FLOW(I)	3	5%
2V, 4V; 4V, 2V	p.d. as flow: p.d. is split depending on the value of the resistances	p.d.FLOW(I)	12	20%
3V,3V; 2V, 4V; 4V, 2V; others; no answer	unacceptable explanation	U	22	36%

Table 4.41: Models of p.d. in Qn 16 - 'p.d. across *unequal* parallel resistors'

Students' answers consistent with mental models of voltage are shown in Table 4.41. A cross-tabulation of the models students seemed to use in Qn 15 and Qn 16 yielded the results in Table 4.42.

	Model Qn16			
Model Qn15	Difference model	Flow model	Other	Total
Difference model	21*	4	3	28
Flow model	2	9	16	27
Other	1	2	3	6
Total	24	15	22	61

Table 4.42: Models of voltage in Qn15 and Qn16 - 'resistances in parallel'

Twenty one students saw a 'difference between 2 points' model consistently in both questions. Nine seemed to indicate a 'flow' model consistently. About one quarter of the sample who appeared to use a 'flow' model in Qn 15 were confused by the introduction of unequal resistances in Qn 16.

4.4.5.6 Inability to distinguish p.d. from current

It is well documented that one major problem which hinders understanding of p.d. is that the latter concept is often not distinguished from current (Maichle, 1981; Tiberghien, 1983). Qn 17 (see Figure 4.17) was used to probe students' ideas directly along this line. In early research on this topic, Tiberghien (1983) had also used this question with the same aim.

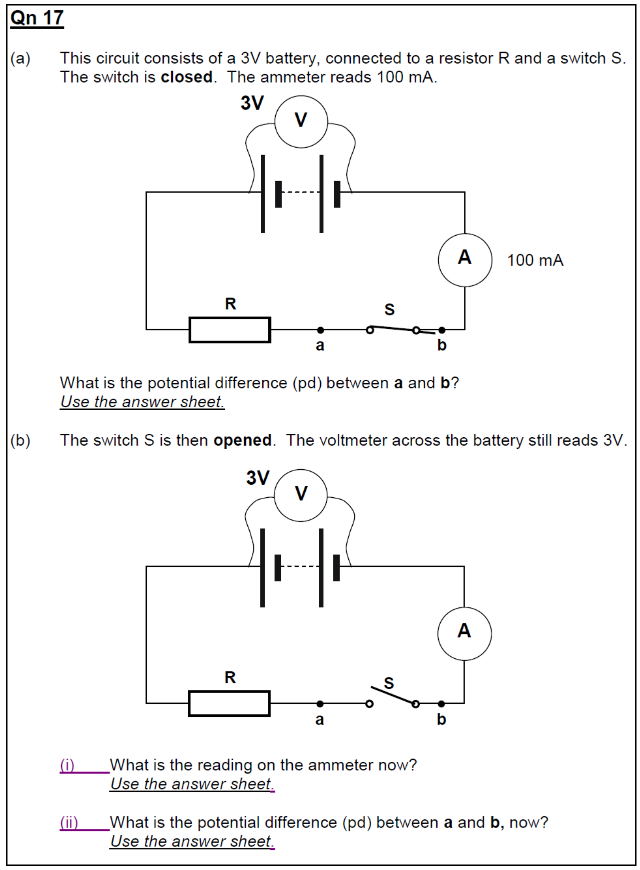


Figure 4.17: Qn 17 - 'p.d. across an open and closed switch'

In Qn 17(b) the overall results show that it was relatively easy for students to realize that there is no current in an open circuit, with 54 students (89%) giving a correct answer to part b(i). Many, however, did not acknowledge that there can be a p.d. between two points when no current is present. Results show (see Table 4.43) that only 14 students (23%) predicted 3V across the open switch, when the current is 'zero'. On the other hand, 39 students (64%) answered 'zero' current and 'zero' p.d. across the open switch, suggesting that they held the view that p.d. cannot exist without a current (Tiberghien, 1983). Students basing their reasoning on the equation V=IR would easily believe that when I=0, V=0 also.

		Qn17b(ii)				Total
		<3/0	0	3	Missing	
Qn17b(i)	<100	0	0	1	0	1
	0	1	39	14*	0	54
	1.5	0	0	1	0	1
	100	0	4	0	0	4
	Missing	0	0	0	1	1
Total		1	43	16	1	61

Table 4.43: Answers for Qn 17(b)

4.4.5.7 Summary of how students conceptualized p.d.

Slightly more than half the sample group consistently held the view that a higher p.d. across the battery exerts a bigger push on the charges. About half the sample could not 'see' zero p.d. across ideal connecting wires, some giving the idea that they mixed p.d. with potential or that they perhaps viewed p.d. as a measure of battery strength being exerted on the first series resistor.

With resistors connected in parallel, students' answers suggested p.d. as 'some difference between points' or as some type of 'flow'. In the latter case, students saw p.d. as current.

4.4.6 Summary and conclusion to the pre-test analysis

At the pre-test stage, students' understanding of current electricity was based on material which had been covered during a short introductory course at secondary level, a year earlier. Looking at the overall analysis of the pre-test questions it can be said that students did not perform as well as had been expected.

Students were expected to have a good grasp of current conservation in simple circuits but only one half of the sample consistently answered correctly to questions probing models of current. Eighteen percent were consistent in their indication of attenuation of the conventional current. The rest had inconsistent views. Indeed, students had problems with the microscopic views of the electric circuit. Almost half the students (44%) saw free charges residing in the battery alone and believed that these charges only move into the wires once the circuit is switched on. Such views would more likely lead to sequential and attenuation views of current.

Students were expected to find it easy to answer direct questions related to the effect of changing the resistance in the circuit. In fact, 82% of the students indicated that they could easily recall that using a larger resistance reduces the current. Many students however, could not choose a valid reason for their answer. The indication was that students' learning was superficial, done by rote. Moreover, students indicated a tendency to use ideas consistent with the BAT and SHARE models. The BAT model was only used consistently by a few students, yet it appeared in the answers to **all** questions related to resistance. Even if students may use this model intermittently, the idea may be a strong one hindering progress in learning. Sherwood and Chabay (1999) refer to the BAT model as a "deep-seated misconception of the role of batteries in circuits" (p.12). They explain how 'students often think that a battery either outputs zero current (if nothing is attached to it) or outputs a standard amount of current, independent of what is attached to the battery (p.12).

Furthermore, understanding of p.d. was a major problem. In answers related to the supply voltage slightly more than half the sample (36 students; 59%) were consistent in recognizing that a higher battery voltage provides a bigger push on the electric charges. Other results also confirmed some students':

- difficulty to distinguish between p.d. and potential (McDermott and Shaffer, 1992);
- inability to distinguish between p.d. and current (Maichle, 1981; Tiberghien, 1983)

Voltage was often seen as something which could be shared between the resistances, or be inversely related to the resistances. References were made to a 'voltage split' between parallel branches. Students imagined that what happens to current at a junction could also be applied to p.d. Only 14 students (23%) 'saw' p.d. across an open switch when no current was flowing in the circuit. For the majority, zero current meant zero p.d.

In open-ended questions on p.d. no student gave a deep explanation in terms of an 'imbalance' across points, in the way a scientist would have perhaps been expected to do (Grotzer & Sudbury, 2000). The answers offered were often closed replies – short replies with limited/incomplete or no explanation. This may well back the claim made by Gilbert, Boulter and Rutherford (1998) that "whether the expectation implied in a teacher's explicit question is either open or closed, it is very likely that the students will give a closed reply, having interpreted it in a narrow context of the topic being considered" (p. 84).

The pre-test data analysis reflected a picture of students who had been exposed to the material being tested but who sometimes found difficulty in choosing/providing reasons for their answers. After answering the pre-test questions, students embarked on their course in current electricity at advanced level. Through this course, students were expected to consolidate ideas which they had been exposed to at secondary level. New material was also introduced relating specifically to resistance in parallel circuits, and p.d. It was hoped that the course would help improve students' understanding in all areas, without specifically referring to test questions. The next section reports on students' answers to a similar set of diagnostic questions used as a post-test immediately after the teaching of the topic.

4.5 Students' answers to the post-test questions

In the final lesson of the course on current electricity students were shown a DVD and PowerPoint presentation (see Appendix 7) about models used in electricity. The aim was to help students gain more insight into what goes on in the closed loop we call 'the electric circuit'. Students were then asked to prepare for a test based on course work, as is normal practice at the end of a study unit. A week after this test, students answered the post-test questions (see Table 4.1) during class time. The post-test was administered with the aim of identifying students' ideas and understandings which had changed, and how they changed during the teaching.

4.5.1 The questions asked in the post-test

Questions with low facility values in the pre-test were used in the post-test. In order to accommodate new questions based on the new material which had been covered through the course, only those questions in the pre-test with facility value in the range 0 - 0.65 were included in the post-test. This kept the testing time to roughly one hour.

4.5.2 Grouping the post-test questions for analysis

For analysis, the questions in the post-test were again divided into groups according to ideas probed. Table 4.44 shows the questions in each group. There is a large number of questions on p.d. This reflects the amount of work covered on this sub-section throughout the course.

Group	Idea probed	Question number in the question bank	Question Title
A	Microscopic views of circuit	4*	Microscopic views
B	Mental models of current	1*	Current at points (a) and (b)
		3*	Picture of the battery and bulb
		9'(a)*	Current conservation within a parallel branch
C	How resistances control the current	6*	Adding an equal resistance in series
		7*	Increasing the variable resistance
		8*	Adding an equal resistance in parallel
		9'(b)*	Parallel resistors' control of current
D	Conceptualisation of potential difference (p.d.)	12'*	p.d. across resistances and ideal connecting wires
		13*, 14*	p.d. across equal and unequal resistances in series
		15*, 16*	p.d. across equal and unequal parallel resistors
		17'*	p.d. across an open and closed switch
		19	Addition of a battery in parallel with the first: *Voltmeter reading*
		20	Addition of a battery in parallel with the first: *Ammeter reading*
		21	Addition of a parallel resistor: effect on the current within a branch; effect on the current within the main circuit
		18	p.d. across a resistor, adding another resistor in parallel

Table 4.44: The questions asked in the post-test arranged in groups
(Note: * indicates questions also asked in the pre-test)

Analysis of the post-test questions was conducted along the same lines as has been explained in detail for the pre-test. Table 4.45 shows the facility values and item-total correlation coefficient for the post-test questions.

Question number in the Question Bank	Item-Total Correlation Coefficient	Facility Values	Code to item being tested: Current (I), Resistance (R), Voltage (V)	Item being tested
4b		0.984		
1a		0.934		
1b		0.934		
1	0.309 *	0.934	I	Conservation of current
3a		0.934		
7a		0.885		
15predict	0.379 **	0.852	V	Predicting the p.d. across equal resistances connected in parallel to the battery
9'a	0.509 **	0.836	I	Conservation of current within a parallel branch
18a		0.836		
12'a	0.284 *	0.820	V	P.d. across resistances connected in series and directly to the battery
13a		0.803		
18b		0.770		
18	0.386 **	0.770	V	The effect on the p.d. across a resistor of adding another resistor connected in parallel
3b		0.738		
3	0.363 **	0.705	I	Conservation of current
14a		0.705		
13 model	0.465 **	0.689	V	Potential division using equal resistances in series
15 model	0.286 *	0.689	V	Modelling p.d. across equal resistances connected in parallel to the battery
4c		0.623		
4d		0.623		
4f		0.623		
6a		0.607		
16predict	0.378 **	0.590	V	Predicting the p.d. across unequal resistances connected in parallel to the battery
19b		0.574		
8b		0.557		
9'b	0.517 **	0.557	R	Current control by resistances in parallel
12'c		0.557		
4e		0.541		
19a		0.541		
4b+4e	0.090	0.525	I	It is not electrons which are absorbed by a bulb but energy
7b		0.508		
7	0.663 **	0.508	R	The effect on current of increasing the resistance using a variable resistance
14 model	0.399 **	0.508	V	Potential division using unequal resistances in series
12'b		0.492		
12'b+12'c	0.466 **	0.492	V	P.d. across points which have no resistance between them (ideal connecting wires)
4c+4f	0.456 **	0.475	I	Charge resides everywhere and the battery provides the push
17'a	0.611 **	0.475	V	Prediction of p.d.across closed switch
19	0.540 **	0.475	V	The p.d., as read by a voltmeter, across batteries connected in parallel
16 model	0.460 **	0.459	V	Modelling p.d. across unequal resistances connected in parallel to the battery
17'a model	0.562 **	0.443	V	No p.d. across a closed switch
6b		0.377		
4a		0.361		
6	0.265 *	0.361	R	The effect on the current of adding an equal resistance in series
4a+4d	0.360 **	0.344	I	Not only the battery contains charge
8a		0.328		
8	0.544 **	0.295	R	The effect on the current in the main circuit, of adding an equal resistance in parallel
20a		0.246		
21c		0.246		
20b		0.230		
21a		0.230		
20	0.273 *	0.213	V	The effect on the current through the circuit, of adding an identical battery in parallel with the first
21d		0.213		
17'b	0.495 **	0.164	V	Prediction of p.d. across open switch
21b		0.164		
21a+21b	0.062	0.148	V	Same voltage and current through a parallel branch, adding another resistance in parallel with that branch and with the supply voltage
17'b model	0.326 *	0.098	V	The presence of p.d. without a current
21c+21d	0.237	0.066	R	The effect on the current through the main circuit of adding a resistor in a parallel branch

Table 4.45: Post-test results expressed in rank order according to facility values
(Note: * = significant to 5% level; ** = significant to 1% level)

Table 4.46 compares the facility values of common questions in pre- and post-test.

PRE-TEST			POST TEST		
Question number in the Question Bank	Facility Values	Code to item being tested: Current (I), Resistance (R), Voltage (V)	Question number in the Question Bank	Facility Values	Code to item being tested: Current (I), Resistance (R), Voltage (V)
	Facility	Code		Facility	Code
1	0.656	I	1	0.934	I
12b	0.656	V	15predict	0.852	V
15predict	0.574	V	12b	0.82	V
9b	0.525	R	3	0.705	I
3	0.525	I	13	0.689	V
13	0.525	V	15	0.689	V
7	0.459	R	16predict	0.59	V
15	0.459	V	9b	0.557	R
4b+4e	0.41	I	4b+4e	0.525	I
16predict	0.393	V	7	0.508	R
16	0.393	V	14	0.508	V
14	0.344	V	12c+12f	0.492	V
6	0.262	R	4c+4f	0.475	I
17b(ii)	0.262	V	17a	0.475	V
4c+4f	0.213	I	16	0.459	V
12c+12f	0.213	V	6	0.361	R
17a	0.213	V	4a+4d	0.344	I
4a+4d	0.164	I	8	0.295	R
8	0.164	R	17b(ii)	0.164	V

Table 4.46: Comparing facility values of common questions in pre- and post-test

There was an increase in facility values in going from the pre- to the post-test (see also Table 4.2). Comparing the common questions in both tests, this increase was evident in all questions except for Qn 17b(ii) (p.d. across an open switch). It was indeed expected that more students could manage a correct answer at the post-test stage. The comparison also shows a change in rank for most questions in the post-test when compared to the pre-test. This was considered as a positive aspect reflecting how the teaching may have influenced students' ideas, making some questions easier to solve whilst exposing the complications of others.

Details about possible changes in students' ideas in specific questions asked are dealt with in the following sections.

4.5.3 Microscopic views of circuit

4.5.3.1 Electric charges and where they reside

Considering Qn 4(a) and Qn 4(d) which probed students' views regarding electric charges and whether these reside only in the battery, the data indicated that more students answered correctly in the post-test (see Tables 4.47 and 4.48).

		Qn4(a) (post-test)		Total
		Correct	Incorrect	
Qn4(a) (pre-test)	Correct	8*	7	15
	Incorrect	14	32	46
Total		22	39	61

Table 4.47: Results for Qn 4(a) on the pre-test and post-test

		Qn4(d) (post-test)			Total
		Correct	Incorrect	Missing	
Qn4(d) (pre-test)	Correct	23*	5	1	29
	Incorrect	15	17	0	32
Total		38	22	1	61

Table 4.48: Results for Qn 4(d) on the pre-test and post-test

The results in Table 4.49 show that after the teaching 21 students (34%) still saw electrons in the battery only, before the circuit is connected.

		Qn 4(d) (post-test)			Total
		Correct	Incorrect	Missing	
Qn 4(a) (post-test)	Correct	21*	1	0	22
	Incorrect	17	21	1	39
Total		38	22	1	61

Table 4.49: Results for Qn 4(a) and Qn 4(d) during the post-test

Moreover, in the answers to parts (c) and (f), more than a quarter indicated that they did not (or at least, not fully) understand that charges move *everywhere and together* around the circuit, once the circuit is closed (see Table 4.50).

		Qn 4(f) (post-test)		Total
		Correct	Incorrect	
Qn 4(c) (post-test)	Correct	29*	9	38
	Incorrect	9	14	23
Total		38	23	61

Table 4.50: Results for Qn 4(c) and Qn 4(f) on the post-test

Combining the results to parts (a), (d), (c) and (f) in Table 4.51 shows that many students still did not have a mental model of charge movement in a simple circuit, based on the idea that all wires are 'full' of mobile charges which move together when a p.d. is applied.

Combination of responses to parts (a), (d), (c), (f)	Number of students pre-test	Number of students post-test
All parts correct	8	16
3 parts correct	7	13
2 or more parts *incorrect*	32	31
All parts incorrect	14	11

Table 4.51: Combination of responses to parts (a), (d), (c) and (f) of Qn 4

4.5.3.2 Summary of results for microscopic views of the electric circuit

While improvements on this item were observed, problems persisted. Many students still viewed the battery as the source of the charges which move round the circuit creating the current.

4.5.4 Mental models of current

4.5.4.1 Ideas used at the post-test stage

As in the pre-test, most students appeared either to use the CC (current conservation) or ACC (attenuation conventional current) model.

In Qn 1, 'Current at points (a) and (b)', 19 students moved to a correct CC view in the post-test (see Table 4.52).

		Qn1 (post-test)		Total
		Correct	Incorrect	
Qn1 (pre-test)	Correct	38*	2	40
	Incorrect	19	2	21
Total		57	4	61

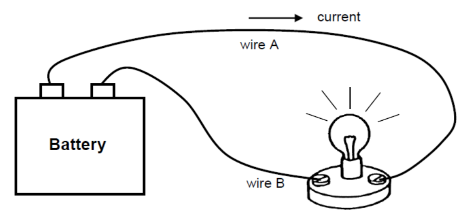
Table 4.52: Pre-test and post-test results for Qn 1

In Qn 3, 'Picture of the battery and bulb' (Figure 4.18), 17 corrected their pre-test answers and moved to the scientific model, but 6 regressed from the conservation model to an attenuation model. Four students used attenuation in both tests (see Table 4.53).

Qn3

A battery is connected to a bulb. The bulb is lit.

There is an electric current in wire A **from the battery to the bulb**.



(a) What can you say about the **electric current** in wire B?
Choose one answer.

i	There is an electric current in wire B **from the battery to the bulb**.
ii	There is an electric current in wire B **from the bulb to the battery**.
iii	There is **no** electric current in wire B.

(b) How can you explain this?
Choose one answer.

i	There is an electric current through one wire to the bulb. It is **all** used up in the bulb, so there is **no current** in the other wire.
ii	There are **two** electric currents from the battery to the bulb. They **meet** at the bulb and this is what makes it light.
iii	There is an electric current through one wire to the bulb. **Some** of it is used up in the bulb, so there is a **smaller current** going from the bulb to the battery in the other wire.
iv	There is an electric current through one wire to the bulb. It **all** passes through the bulb and back to the battery through the other wire.

Figure 4.18: Qn 3 - 'Picture of battery and bulb'

		Model Qn3 (post-test)			Total
		CC	A	U	
Model Qn3 (pre-test)	CC	26*	6	0	32
	A	10	4	3	17
	U	7	4	1	12
Total		43	14	4	61

Table 4.53: Pre-test and the post-test results for Qn 3

Consistency in the use of the CC model on both Qns 1 and 3 in the post-test was shown by 42 students (69%; see Table 4.54). Eleven students, however, did not use the conservation model in Qn 3. This was rather surprising. Reasons for this inconsistency may perhaps be attributed to the long description of the options in Qn 3(b), perhaps confusing the students, but this is speculative.

		Model Qn3 (post-test)			Total
		CC	A	U	
Model Qn1 (post-test)	CC	42*	11	4	57
	ACC	1	3	0	4
Total		43	14	4	61

Table 4.54: Post-test results for Qn 1 and Qn 3

On the other hand, the data for Qn 9'(a), 'Current conservation within a parallel branch' shows that while 40 students had conserved current in a parallel branch in the pre-test, the number now increased to 51 in the post-test. Of the latter number, 50 students were found to have consistently also used the CC model in Qn 1 (see Table 4.55).

		Qn9'(a) (post-test)			Total
		CC	ACC	AEF	
Qn1 (post-test)	CC	50*	6	1	57
	ACC	1	3	0	4
Total		51	9	1	61

Table 4.55: Comparing mental models of current in post-test Qn 1 and Qn 9'(a)

4.5.4.2 Summary of students' views of current

In the post-test questions probing models of current, including current within a parallel branch, more students were found to have conserved the current more consistently. There was strong evidence that many students now understood the CC model.

4.5.5 How resistances control the current

4.5.5.1 Resistances connected in parallel

Analysis of responses to questions probing ideas about resistance immediately pointed to persistence of problems with understanding in this area. Moreover, the data indicated more frequent use of specific mental models.

In Qn 9'(b) (the same as 9(b) in the pre-test) dealing with parallel resistors, while there were moves from incorrect to correct answers as to how resistances within the branch affect the splitting of current at a junction, there were as many moves in the opposite direction, with students believing that current splits equally at a junction, irrelevant of the resistances within the branches. Twenty four students were consistently correct in both tests (see Table 4.56). The results show that confused views of resistance effects prevailed, with students perhaps focusing on current and ignoring resistance. This was unexpected since students had used Kirchhoff's laws during the course.

		Answers for QN9'(b) post-test		Total
		Correct	Incorrect	
Answers for Qn9(b) pre-test	Correct	24*	8	32
	Incorrect	10	19	29
Total		34	27	61

Table 4.56: Comparing pre-test and post-test answers to Qn 9(b)

4.5.5.2 Evidence of a deep-seated alternative conception

The results from the analysis of Qn 6, 'Adding an equal resistance in series' are shown in Tables 4.57 and 4.58. Figure 4.19 also compares, at a glance, results in the pre-test and the post-test for Qn6.

		Qn6(b) (post-test)				Total
		ii	iii	iv	v	
Qn6(a) (post-test)	i	1	0	1	0	2
	ii	0	22 (BAT)	0	0	22
	iii	22*	0	3 (R-TAKE)	12 (SHARE)	37
Total		23	22	4	12	61

Table 4.57: Results for Qn 6 in the post-test

		Model Qn6 (post-test)						Total
		SCI(R)	R-TAKE	SHARE	More of A, more of B	BAT	U	
Model Qn6 (pre-test)	SCI(R)	8	0	1	1	6	0	16
	R-TAKE	0	1	1	0	6	1	9
	SHARE	5	1	5	0	2	0	13
	More of A, more of B	0	0	1	0	1	0	2
	BAT	1	0	1	0	2	0	4
	U	8	1	3	0	5	0	17
Total		22	3	12	1	22	1	61

Table 4.58: Comparing mental models in the pre-test and the post-test for Qn 6

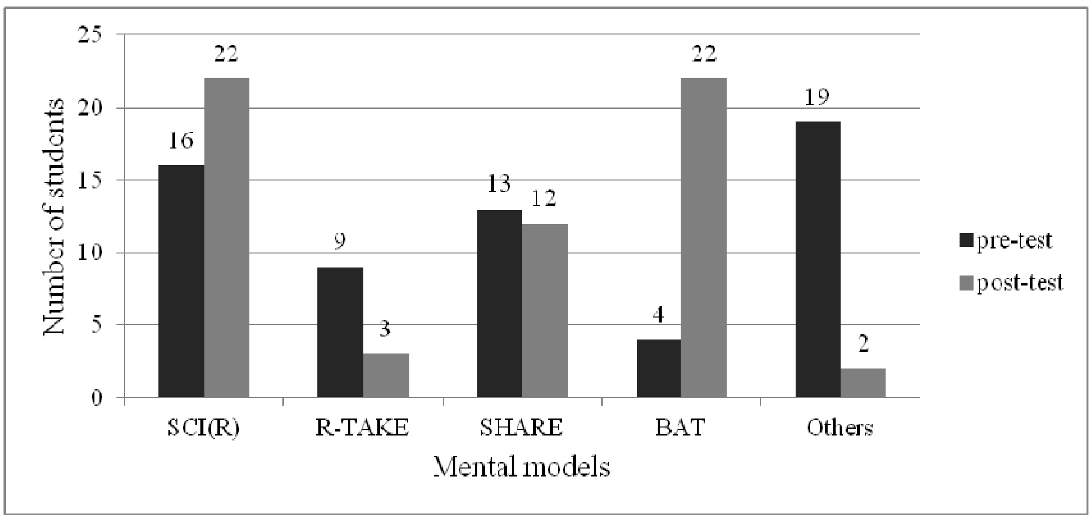


Figure 4.19: Mental models in pre-test and post-test for Qn 6 - 'Adding an equal resistance in series'

These results indicate that:

- more students now answered correctly;
- the use of the BAT model (same battery, same current) was now very pronounced.

The BAT model thus seemed reinforced with teaching – a result which was not mentioned in previous research studies.

4.5.5.3 Use of the BAT model in other questions

- In Qn 7, 'Increasing the variable resistance', the BAT model was again amongst students answers, even if it was used to a much smaller extent than in Qn 6 (see Tables 4.59 and 4.60).

		Qn7(b) (post-test)					Total
		i	ii	iii	iv	Missing	
Qn7(a) (post-test)	ii	0	0	1	5 (BAT)	0	6
	iii	1	31*	17	5	0	54
	Missing	0	0	0	0	1	1
Total		1	31	18	10	1	61

Table 4.59: Results for Qn 7 in the post-test

		Model Qn7 (post-test)				Total
		SCI(R)	BAT	R-TAKE	U	
Model Qn7 (pre-test)	SCI(R)	20*	1	6	2	29
	BAT	4	2	1	0	7
	R-TAKE	3	2	7	2	14
	U	4	0	3	4	11
Total		31	5	17	8	61

Table 4.60: Comparing pre-test and post-test mental models in Qn 7

There was indeed a striking difference between students' use of the BAT model in Qn 6 and Qn 7. It could be that in Qn6, the use of the variable resistance symbol and the explicit indication in the question that R is ***increased*** may have helped students to focus more on the resistance increase, making the R-TAKE model more appealing, in this case, than the BAT model.

- In Qn 8, 'Adding an equal resistance in parallel', the use of the BAT model was again quite pronounced (see Table 4.61 and Figure 4.20). Moreover, choice option iii/ii in Qn 8 may well provide indirect evidence of the use of ideas consistent with the BAT model, since when choosing these options, students may have seen the same current from the battery now passing partly through the extra path added, thus predicting that the current gets smaller.

		Qn8(b) (post-test)			Total
		i	ii	iii	
Qn8(a) (post-test)	i	0	18*	2	20
	ii	0	7	22 (BAT)	29
	iii	3	8	0	11
	Missing	0	1	0	1
Total		3	34	24	61

Table 4.61: Results for Qn 8 in the post-test

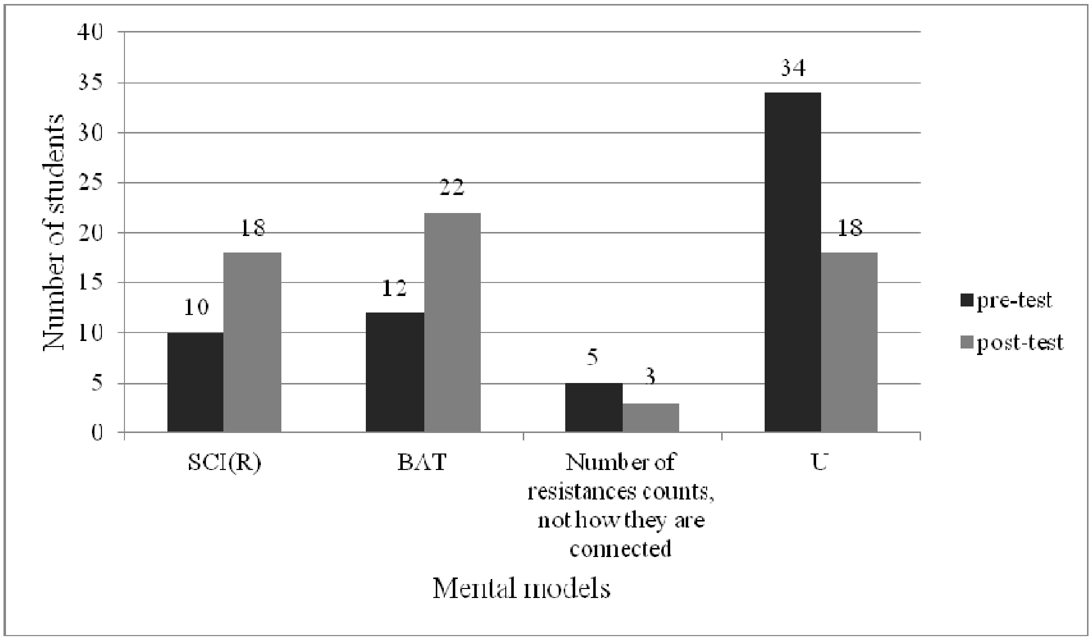


Figure 4.20: Mental models in pre-test and post-test for Qn 8 - 'Adding an equal resistance in parallel'

Moreover, the data in Table 4.62 shows that a good number of students who gave an unclassified answer in the pre-test used ideas consistent with the BAT model in the post-test, thus giving little importance to the number of resistors, or the manner in which they were connected.

		Model Qn8 (post-test)				Total
		SCI(R)	BAT	More of A, more of B	U	
Model Qn8 (pre-test)	SCI(R)	8*	0	0	2	10
	BAT	2	4	1	5	12
	More of A, more of B	1	3	0	1	5
	U	7	15	2	10	34
Total		18	22	3	18	61

Table 4.62: Models in pre-test and post-test for Qn 8 - 'Adding an equal resistance in parallel'

4.5.5.4 Consistency in the use of the BAT model

Comparing the mental models used in Qn 6 and Qn 8 during the post-test (see Table 4.63) shows that 17 students (28%) used the BAT model consistently in both questions. Consistency in the use of these ideas in the pre-test was certainly not as high. Only 4 students (7%) had used BAT in Qn 6 during the pre-test (see Table 4.23).

		Model Qn8 (post-test)				Total
		SCI(R)	BAT	More of A, more of B	U	
Model Qn6 (post-test)	SCI(R)	10	4	2	6	22
	R-TAKE	1	0	0	2	3
	SHARE	5	0	0	7	12
	More of A, more of B	0	1	0	0	1
	BAT	1	17	1	3	22
	U	1	0	0	0	1
Total		18	22	3	18	61

Table 4.63: Mental models in Qn 6 and Qn 8

4.5.5.5 Summary of students' views of how resistance controls the current

The data indicated that about half the sample could still not understand how resistances in parallel branches control the current within each branch. Moreover, while there was an increase in the overall number of correct responses, there were also shifts from scientific models to alternative ideas. The BAT model was shown to be one which students used more at the post-test stage, compared to the pre-test. This could be one factor hindering students' understanding of how resistance controls the current. In fact, both the battery and the resistance determine the current in a circuit. While the battery determines the strength of 'the push', the resistance controls the rate of flow of charge. Some students may not distinguish between these two forms of control, hence the confusion.

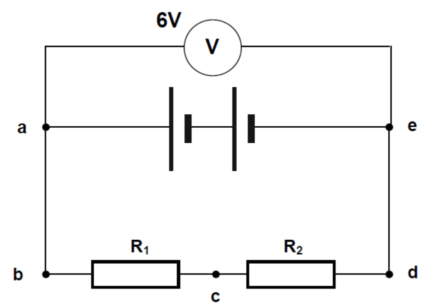
4.5.6 Conceptualization of p.d.

4.5.6.1 P.d. across ideal connecting wires

Problems in Qns 12'(b) and 12'(c) (Figure 4.21) still persisted. Some students still did not see that the p.d. across ideal connecting wires is zero.

Qn 12'

The circuit consists of some batteries connected to two resistors R_1 and R_2.
A voltmeter connected across a and e reads 6V.



For each question, choose one answer. Mark your answer on the answer sheet.

		More than 6V	6V	Less than 6V	Zero
(a)	What is the potential difference (pd) between points b and d?				
(b)	What is the pd between points a and b?				
(c)	What is the pd between points d and e?				

Figure 4.21: Qn 12' - 'p.d. across resistances and ideal connecting wires'

Only half the sample gave a correct answer to both part questions (b) and (c) (see Table 4.64), but this was an improvement over the pre-test results. Only 13 students (21%) had been consistently correct at that time.

		Qn12'c (post-test)				Total
		>6V	6V	<6V	Zero	
Qn12'b (post-test)	6V	1	13	6	4	24
	<6V	0	0	6	0	6
	Zero	0	0	0	30*	30
	Missing	0	0	1	0	1
Total		1	13	13	34	61

Table 4.64: Results for Qn 12'(b) and Qn 12'(c)

4.5.6.2 A voltmeter registers a difference of 'something' between two points

Answers to Qn 12'(a) showed that 50 students (82%) saw points 'a' and 'e' as equivalent points to 'b' and 'd', with the same p.d. across them. This also showed improvement over the 40 students (66%) who had answered correctly in the pre-test (see Figure 4.22). Looking at this part question alone, the impression was that many students were now seeing p.d. as some difference between points, as read by a voltmeter.

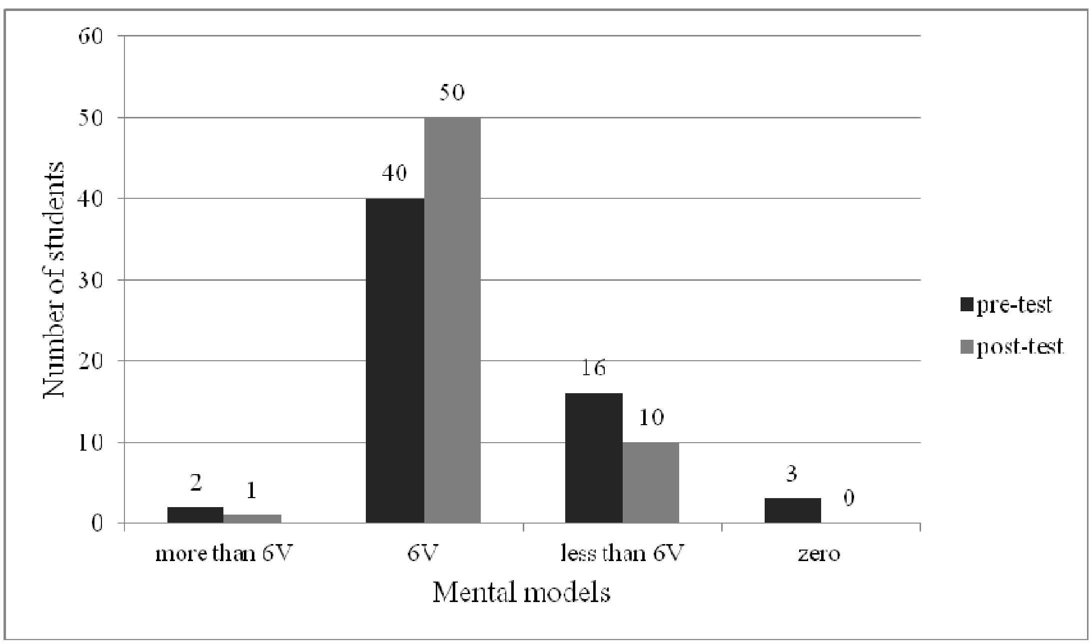


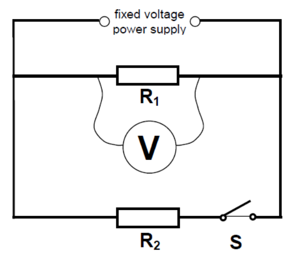
Figure 4.22: Responses to Qn 12'(a) - 'p.d. across equivalent points'

Qn 18

In this circuit, the power supply has a fixed voltage output.

The resistors R_1 and R_2 are connected as shown.

The switch, S, is open.
There is a reading on the voltmeter connected across R_1.



The switch is then **closed**.

(a) What happens to the reading on the voltmeter?
Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller.

(b) How would you explain this?
Choose one answer.

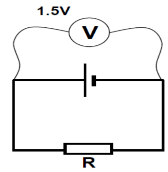
i	The voltage is now shared between the two resistors.
ii	R_1 is connected directly across the terminals of the power supply. So the voltage across it is always equal to the power supply voltage.
iii	The total resistance in the circuit is now bigger, so V increases (as V=IR).

Figure 4.23: Qn 18 - 'p.d. across a resistor, adding another resistor in parallel'

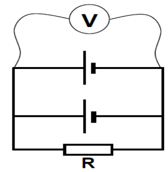
Qn 18, 'p.d. across a resistor, adding another resistor in parallel' and Qn 19, 'Addition of a battery in parallel with the first – voltmeter reading' both probed whether students still recognized equivalent points in a circuit having the same p.d. across them. This time another component, a resistor and a battery respectively, was added in parallel with the first. Students were told that the output voltage was constant in all questions. Both questions had *not* been asked in the pre-test, and while comparison of performance in both tests was not possible, yet these 'new' questions were meant to help clarify and probe deeper into students' understanding of p.d., since the course of study had elaborated a lot about this concept. Students were expected to realize that in both cases, the voltmeter reading would remain unchanged (see Figures 4.23 and 4.24).

Qn 19

In this circuit, a battery is connected to a resistor R.
The voltmeter reads 1.5V.



A second identical battery is now added, like this.



(a) What is the reading on the voltmeter now?
Choose one answer.

i	3 V
ii	1.5 V
iii	0.75 V
iv	zero

(b) How would you explain this?
Choose one answer.

i	Two batteries 'push' harder than one on its own.
ii	The voltmeter measures the potential difference across each battery, which stays the same.
iii	The second battery pushes against the first one.
iv	The two batteries transfer more energy to the resistor every second.

Figure 4.24: Qn 19 - 'Addition of a battery in parallel with the first: *Voltmeter reading*'

The results in Tables 4.65 and 4.66 indicate the ideas students were using in these questions.

Answer to Qn18(a)	Answer to Qn18(b)	Mental model consistent with answers	Mental model code	Number of students	Percentage (N=61)
ii	ii	p.d. as some difference between two points	SCI(p.d.)	47*	77%
i	iii	Number of components counts and not how they are connected	MORE of A, more of B	2	3%
ii/iii	i	p.d. as 'flow': p.d. is shared between Rs in parallel	p.d.FLOW(I)	1/7	2%/12%
ii/iii	iii	Unclassified	U	3/1	5%/2%

Table 4.65: Results for Qn 18 - 'p.d. across a resistor, adding another resistor in parallel'

Answer to Qn19(a)	Answer to Qn19(b)	Mental model consistent with ideas	Mental model code	Number of students	Percentage (N=61)
ii	ii	p.d. as some difference between two points	SCI(p.d.)	29*	48%
i	i	Number of components counts and not how they are connected	More of A, more of B	10	16%
i	iv	p.d. as 'flow': p.d. in terms of energy supplied to the circuit	p.d.FLOW(E)	2	3%
iv	iii	p.d. as 'flow': batteries push against each other (local reasoning)	p.d.FLOW(B)	8	13%
Others			U	12	20%

Table 4.66: Results for Qn 19 - 'Addition of a battery in parallel with the first: *Voltmeter reading'*

Looking at these results, the initial impression that **many** students saw p.d. as 'a difference of some sort' between points now started to become less certain. When another resistor was added in parallel with the first, some students' ideas shifted towards sharing of p.d. When another battery was added in parallel with the first, some students' answer choices were linked with either an increased p.d. or a cancellation effect of two batteries working against each other.

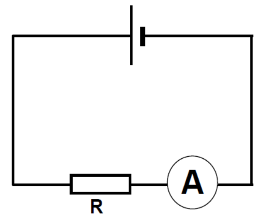
These results seem to indicate that some students may have understood p.d. as 'some' difference between points, but that their understanding may not have been deep enough to let them see this in all contexts. When a change is made to a circuit, this becomes too much of a distractor, with students intuitively looking mainly at what is changing, often giving an answer based on local reasoning. The circuit is thus not looked at globally (see Closset (as cited in Millar and King, 1993); Shipstone, 1984; Shipstone 1985).

4.5.6.3 Further evidence of the effect of distractors

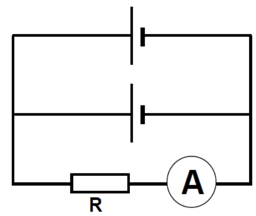
Qn 20, 'Addition of a battery in parallel with the first: Ammeter reading' (see Figure 4.25) was seen as complementing Qn 19 since it extends the idea of constant p.d. across two points when a second battery is connected in parallel with the first, while expecting students to realize also that the current through R remains the same.

Qn 20

In this circuit, a battery
is connected to a resistor R.
There is a reading on the ammeter.



A second identical battery is
now added, like this.



(a) What happens to the reading on the ammeter?
Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller.

(b) How would you explain this?
Choose one answer.

i	Two batteries 'push' harder than one on its own.
ii	The potential difference across the resistor is still the same.
iii	The second battery pushes against the first one.
iv	Two batteries supply more energy every second.

Figure 4.25: Qn 20 - 'Addition of a battery in parallel with the first: *Ammeter reading*'

Analyzing Qn 20 in the same way as Qn 19 and comparing the data (see Table 4.67) it can be seen how much harder the students found it to transfer their idea of constant p.d. to predict that the ammeter within the branch would show the same reading. Out of 29 students (48%) answering correctly in Qn 19, only 9 students (15%) answered correctly and consistently in Qn 20.

		Model Qn20 (post-test)					Total
		SCI(p.d.)	More of A, more of B	p.d.FLOW(E)	p.d.FLOW(B)	U	
Model Qn19 (post-test)	SCI(p.d.)	9*	12	7	1	0	29
	More of A, more of B	0	7	3	0	0	10
	p.d.FLOW(E)	0	0	2	0	0	2
	p.d.FLOW(B)	1	3	0	5	0	9
	U	3	4	0	1	3	11
Total		13	26	12	7	3	61

Table 4.67: Mental models in Qn 19 and Qn 20

Rather than focusing on the constant p.d. across points, students tended to look at the change within the circuit, that is, the extra battery added in parallel. Students moved from scientific answers in Qn 19, to answers in Qn 20 indicating they 'saw' the larger number of batteries as pushing harder, or supplying more energy, ignoring the global effect of the circuit as a system. This may once again be seen as an extension of basic causal reasoning, with students finding it difficult to predict that changing something results in no change in the quantity being asked about.

4.5.6.4 P.d. not distinguished from current

Analyzing Qns 15 and 16, 'p.d. across equal and unequal parallel resistors' one can see that while there was an overall improvement since the pre-test stage, in terms of frequency of scientific answers, yet some students were still using unhelpful ideas which they had used in the pre-test.

When students' individual answers in the pre- and post-test were compared (see Table 4.68), it was found that 16 students (26%) held on to their correct and incomplete answers, while a substantial number moved to this from other views, including the 'scientific and complete' category. Some kept their alternative views, while others regressed, going from a scientific incomplete answer in the pre-test, to one based on alternative views in the post-test. Some mentioned having the same voltmeter reading because of identical resistances, or referred to equal 'splitting' or 'sharing' of the supply voltage between resistances.

		Model Qn15 (post-test)				Total
		SCI(C)	SCI(D)	p.d.FLOW(I)	U	
Model Qn15 (pre-test)	SCI(C)	0	4	0	0	4
	SCI(D)	3	16	4	1	24
	p.d.FLOW(I)	4	11	6	6	27
	Missing explanation	1	2	0	1	4
	U	0	1	0	1	2
Total		8	34	10	9	61

Table 4.68: Comparing pre-test and the post-test models in Qn 15

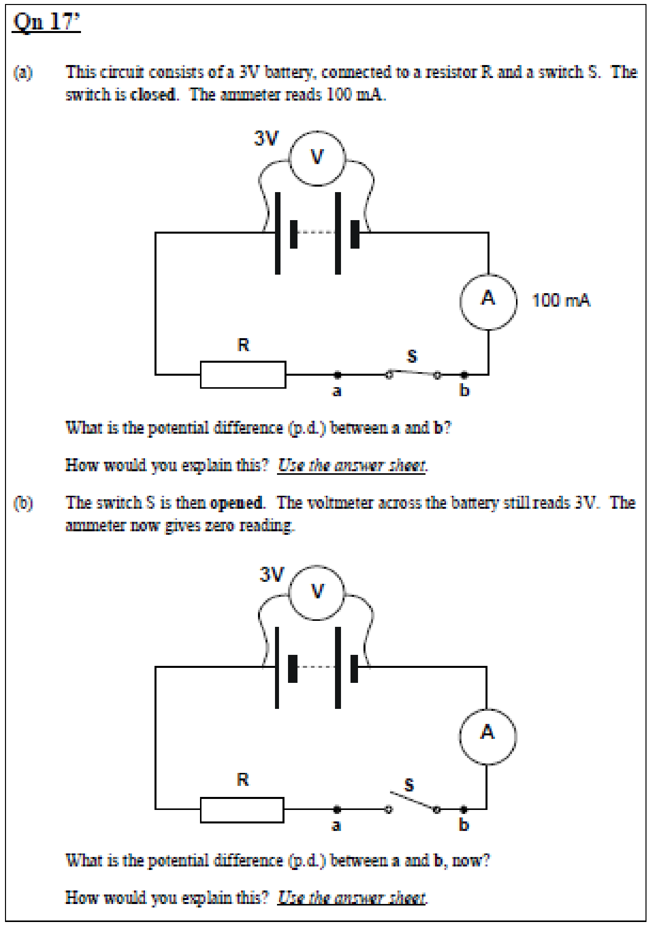
The results for Qn 16 were again along much the same lines as for Qn 15, though with unequal resistances, understanding seemed, as in the pre-test, slightly worse. It was more difficult to visualize equal p.d. across equivalent points in the circuit when the resistances within the parallel branches were unequal (see Table 4.69). Answers based on ideas of direct or inverse proportionality between resistance and voltage started to appear, as in the pre-test.

		Model Qn16 (post-test)				Total
		SCI(C)	SCI(D)	p.d.FLOW(I)	U	
Model Qn15 (post-test)	SCI(C)	4	1	1	2	8
	SCI(D)	1	21	4	8	34
	p.d.FLOW(I)	0	1	4	5	10
	U	0	0	0	9	9
Total		5	23	9	24	61

Table 4.69: Models in Qn 15 and Qn 16

Globally, the answers to both of these questions pointed towards the fact that either students could predict the voltmeter readings correctly and provide a complete/ incomplete/inadequate explanation for their prediction, or else students split the supply voltage. This splitting of the voltage indicated that either the circuit was being treated like a series circuit (see Millar & Beh, 1993) or more likely that the voltage was being looked at as if it were current. Overall, it can be said that 27 students (44%) seemed to visualize p.d. consistently as ‘some difference’ between points. Others saw p.d. as ‘some kind of flow’.

Data from Qn 17’ ‘p.d. across an open and closed switch’ (Figure 4.26), further confirmed that many students still did not distinguish voltage from current.


Qn 17’

(a) This circuit consists of a 3V battery, connected to a resistor R and a switch S. The switch is **closed**. The ammeter reads 100 mA.

What is the potential difference (p.d.) between **a** and **b**?

How would you explain this? *Use the answer sheet.*

(b) The switch S is then **opened**. The voltmeter across the battery still reads 3V. The ammeter now gives zero reading.

What is the potential difference (p.d.) between **a** and **b**, now?

How would you explain this? *Use the answer sheet.*

Figure 4.26: Qn 17’ - ‘p.d. across an open and closed switch’

Qn 17’ asked for an explanation of students’ answers. Interpretations of students’ responses with explanations for Qn 17’(a) and (b) are shown in Tables 4.70 and 4.71, respectively.

(N=61)						
	Answers to Qn 17'(a)					
Prediction	Correct and complete	Correct but incomplete	Restating answer	Unclassified	Using alternative views	Missing explanation
0 volts	13*	10*	4	1		1
3 volts				14	1	6
Less than 3 V				3	1	
More than 3 V				1		
0.1R				1		
2.7 V					1	
Missing prediction						4

Table 4.70: Answers to Qn 17'(a) - 'P.d. across a closed switch'

(N=61)			
Answers to Qn 17'(b)	Prediction		
Explanation	0 Volts	3 Volts	missing
No current flowing	34		
correct and complete		1*	
correct and incomplete		5*	
restatement		3	
Unclassified	5		
with alternative framework	6		
missing explanation	2	1	4

Table 4.71: Answers to Qn 17'(b): 'P.d. across an open switch'

In the answers to part (a), some explanations revealed how language may be looked at as a most imperfect tool (Holt, 1982). Some students used words with different meanings interchangeably in their writing, and others did not describe their views in detail, leaving much to the interpretation of the researcher.

'(0 volts)' 'There is no resistance between 'a' and 'b', therefore no change in p.d.'

(Comment: The student used 'p.d.' when he should be referring to potential.)

'(0 volts)' 'All voltage is used up by the resistor.'

(Comment: The part of the answer: 'voltage is used up', gives the impression that the student saw something like 'energy' being used up.)

'(Less than 3V)' 'R decreases the rate of flow.'

(Comment: There is a hint of current attenuation in the student's idea - the decreased rate of flow resulting in something 'less than 3V'.)

Answers to part (b), for the p.d. across an open switch, show that more than half the students (34; 56%) still stated that there can be no p.d. if no current is flowing. Some students repeated the answer they had given in the pre-test, supporting it with their alternative idea about when p.d. exists, thus:

'(0 volts)' 'No current, therefore no p.d. across the points.'

The ability to distinguish p.d. from current was rare indeed.

Other explanations gave evidence of how students 'saw' or at least described voltage as current.

'(0 volts)' 'No p.d. *is passing* in the wire.'
'(0 volts)' '*No voltage will pass,* if the current is open.'
'(0 volts)' '*No voltage flows* in an incomplete circuit.'

Many students still related p.d. to something that flows or moves through a circuit. Not much had changed since the pre-test stage.

4.5.6.5 Summary of how students conceptualized p.d.

In questions which may be considered simple and direct, like Qn 12'(a), 82% of the students could easily predict the p.d. across two points by quoting the voltmeter reading across equivalent points.

When changes in the circuit were proposed, there was evidence of students who focused on the change rather than on how the circuit behaves as a system. Data specific to

Qns 18 and 19 indicated that 23% of the sample reacted in this way, proposing a view of p.d. as something that flows, splitting up at junctions or being shared between resistances. Ideas related to p.d. as flow of energy were also held.

Overall, p.d. was either looked at as ‘some difference between points’ or as ‘something which flows’. While some improvements were evidenced in students’ answers since the pre-test, yet, 56% of the students still stated they saw no p.d. if there was no current in the circuit. Many still did not distinguish p.d. from current, showing that the evolution from a flow model to a difference model was hard to accomplish, even after teaching.

4.5.7 Summary of post-test results

While more students answered correctly to questions about charges and where they reside, yet 34% of the student sample still visualized electrons in the battery only, before connecting the circuit. More than a quarter indicated their difficulty in understanding that charges move *everywhere and together* around the circuit, once the circuit is closed.

The only models of current students indicated were those of conservation (CC) or attenuation of conventional current (ACC). Many now used the CC model, with at least 70% of the students indicating consistent use of it in different questions.

Analysis of questions about resistance gave indications that ideas consistent with the SHARE (current being shared between the resistors) and the BAT (same battery, same current) models were popular with students. The BAT model was used consistently by 17 students in both Qns 6 and 8 (see Table 4.61).

In Qn 8, when a resistance was added in parallel, the post-test results indicated that a good number of students, who in the pre-test were proposing an answer that could not be classified as indicating any specific mental model now used the BAT model, thus giving little importance either to the number of resistors or the manner in which they were connected. The battery was the focus of attention. If the battery was the same, the current it pushed **into** the circuit was assumed the same. It seemed that the BAT model was a popular choice option with students – a model which could have been hindering understanding of how resistance controls the current. Moreover, for about 2% of the students’ who still lacked understanding of how resistance affects the current, this led to strong views about having equal splitting of the current along parallel branches, regardless of the resistance within each particular branch.

With regard to p.d., many students did not appreciate that when changes are made to a circuit, it is possible that the p.d. across two points does not change. Many students did not see 'a system' at work, but focused primarily on what was changing or being added to the circuit, basing their answers on *the change* and reaching incorrect conclusions. Moreover, having a majority of students splitting the supply voltage across parallel resistors, especially in Qn 16 with unequal resistances, suggested that many students had not yet clearly separated the idea of p.d. from that of current. Indeed Qn 17', 'p.d. across an open and closed switch', provided further evidence that, while many saw that when a current flows it is a resistance which has a p.d. across it, just as many believed that there can be no p.d. if no current flows.

4.6 Students' performance in the delayed post-test

4.6.1 Introduction

The aim of administering the delayed post-test was to find out whether the students retained the knowledge and understanding of what they had learnt through the course. The questions used in the delayed post-test were the same ones which had been asked in the post-test and the analysis was conducted in the same way as has been described in detail for the pre-test and the post-test. The following sections, briefly describe important findings.

4.6.2 Facility value results

4.6.2.1 Comparing facility values in the post- and delayed post-test

Table 4.72 shows the facility values in rank order for questions in the post- and delayed post-test. These tests consisted of the same questions. While the rank order of some questions, in terms of facility value, may have changed slightly from the post- to the delayed post-test, yet, globally, the facility values increased for the majority of the questions answered in the delayed post-test. Students thus performed better in the delayed post-test.

POST-TEST

Question number in the Question Bank	Facility Values	Code to item being tested: Current (I), Resistance (R), Voltage (V)
4b	0.984	
1a	0.934	
1b	0.934	
1	0.934	I
3a	0.934	
7a	0.885	
15predict	0.852	V
9'a	0.836	I
18a	0.836	
12'a	0.820	V
13a	0.803	
18b	0.770	
18	0.770	V
3b	0.738	
3	0.705	I
14a	0.705	
13 model	0.689	V
15 model	0.689	V
4c	0.623	
4d	0.623	
4f	0.623	
6a	0.607	
16predict	0.590	V
19b	0.574	
8b	0.557	
9'b	0.557	R
12'c	0.557	
4e	0.541	
19a	0.541	
4b+4e	0.525	I
7b	0.508	
7	0.508	R
14 model	0.508	V
12'b	0.492	
12'b+12'c	0.492	V
4c+4f	0.475	I
17'a	0.475	V
19	0.475	V
16 model	0.459	V
17'a model	0.443	V
6b	0.377	
4a	0.361	
6	0.361	R
4a+4d	0.344	I
8a	0.328	
8	0.295	R
20a	0.246	
21c	0.246	
20b	0.230	
21a	0.230	
20	0.213	V
21d	0.213	
17'b	0.164	V
21b	0.164	
21a+21b	0.148	V
17'b model	0.098	V
21c+21d	0.066	R

DELAYED POST-TEST

Question number in the Question bank	Facility Values	Code to item being tested: Current (I), Resistance (R), Voltage (V)
1b	0.934	
3a	0.934	
1a	0.918	
1	0.918	I
9'a	0.918	I
13a	0.885	
15predict	0.885	V
7a	0.869	
4b	0.852	
12'a	0.803	V
3b	0.787	
3	0.754	I
18a	0.754	
14a	0.721	
18b	0.721	
13 model	0.705	V
15 model	0.705	V
19a	0.705	
6a	0.672	
18	0.672	V
8b	0.656	
19b	0.656	
4f	0.623	
16predict	0.607	V
19	0.607	V
4d	0.59	
12'c	0.59	
4c	0.541	
7b	0.525	
12'b	0.525	
14 model	0.525	V
17'a	0.525	V
7	0.508	R
9'b model	0.508	
12'b+12'c	0.508	V
16 model	0.508	V
4c+4f	0.492	I
17'a model	0.475	V
4e	0.426	
6b	0.41	
8a	0.41	
6	0.393	R
8	0.393	R
4b+4e	0.377	I
4a	0.361	
4a+4d	0.361	I
21c	0.344	
20a	0.328	
17'b	0.311	V
21a	0.279	
20b	0.262	
17'b model	0.23	V
20	0.23	V
21d	0.197	
21b	0.18	
21a+21b	0.18	V
21c+21d	0.066	R

Table 4.72: Comparing facility values in the post-test and delayed post-test questions

4.6.2.2 Comparing facility values for common questions in all tests

PRE-TEST

Question number in the Question Bank	Facility Values	Code to item being tested: Current (I), Resistance (R), Voltage (V)
	Facility	Code
1	0.656	I
12b	0.656	V
15predict	0.574	V
9b	0.525	R
3	0.525	I
13	0.525	V
7	0.459	R
15	0.459	V
4b+4e	0.41	I
16predict	0.393	V
16	0.393	V
14	0.344	V
6	0.262	R
17b(ii)	0.262	V
4c+4f	0.213	I
12c+12f	0.213	V
17a	0.213	V
4a+4d	0.164	I
8	0.164	R

POST TEST

Question number in the Question Bank	Facility Values	Code to item being tested: Current (I), Resistance (R), Voltage (V)
	Facility	Code
1	0.934	I
15predict	0.852	V
12b	0.82	V
3	0.705	I
13	0.689	V
15	0.689	V
16predict	0.59	V
9b	0.557	R
4b+4e	0.525	I
7	0.508	R
14	0.508	V
12c+12f	0.492	V
4c+4f	0.475	I
17a	0.475	V
16	0.459	V
6	0.361	R
4a+4d	0.344	I
8	0.295	R
17b(ii)	0.164	V

DELAYED POST TEST

Question number in the Question Bank	Facility Values	Code to item being tested: Current (I), Resistance (R), Voltage (V)
	Facility	Code
1	0.918	I
15predict	0.885	V
12b	0.803	V
3	0.754	I
13	0.705	V
15	0.705	V
16predict	0.607	V
14	0.525	V
17a	0.525	V
7	0.508	R
9b	0.508	R
12c+12f	0.508	V
16	0.508	V
4c+4f	0.492	I
6	0.393	R
8	0.393	R
4b+4e	0.377	I
4a+4d	0.361	I
17b(ii)	0.311	V

Table 4.73: Comparing facility values for common questions on the three tests

Comparing the performance on the common questions in all tests (Table 4.73) it is evident that:

- the first seven questions which proved easy to answer in the post-test were still easy to answer on the delayed post-test, keeping the same rank order;
- Qn 17b(ii), 'p.d. across an open switch', probing students' understanding of the presence of p.d. without the presence of a current, remained very low in facility value and is last in rank on both post-test and delayed post-test;
- the facility value for questions relating to microscopic views remained low in all tests.

On a general note, while a good number of facility shifts occurred in going from the pre-test to the post-test, more stability in terms of facility was evidenced when comparing the post-test to the delayed post-test results. This implies that what was learnt was better internalized and retained at the later stages. When questions were directly related to ideas which could be recalled like, for example, 'increasing the resistance decreases the current', or 'adding a second battery in series increases the current', the facility values were high. As soon as questions started probing ideas related to resistance and p.d. across series and parallel resistors, the facility values started to drop. This was also evidenced in the qualitative analyses of the data, as the next sections shall continue to show.

The following sections look closer at changes observed in students' answers during the delayed post-test.

4.6.3 Did students 'see' the invisible now?

4.6.3.1 Performance on microscopic views of the electric circuit

Figures 4.26 and 4.27 compare the results for Qns 4(a) and 4(d), 4(c) and 4(f) respectively. It is clear that while the number of students answering correctly to both part questions (about one half) remained almost the same as in the post-test, yet the number of students choosing incorrect answers to both part questions increased.

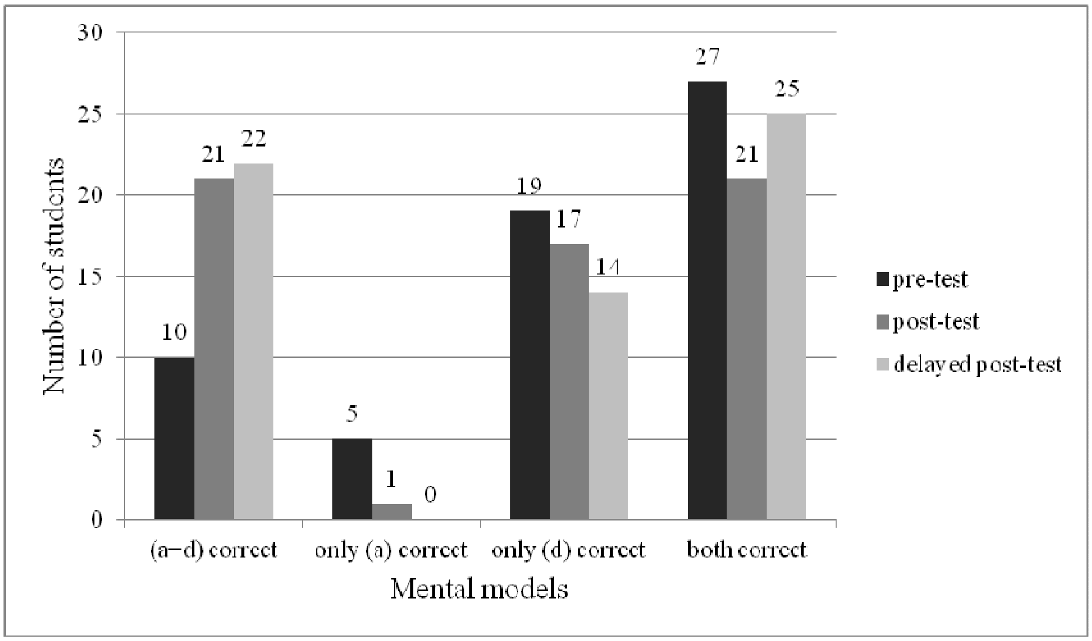


Figure 4.27: Comparison of performance in part Qns 4(a) and 4(d) (all tests)

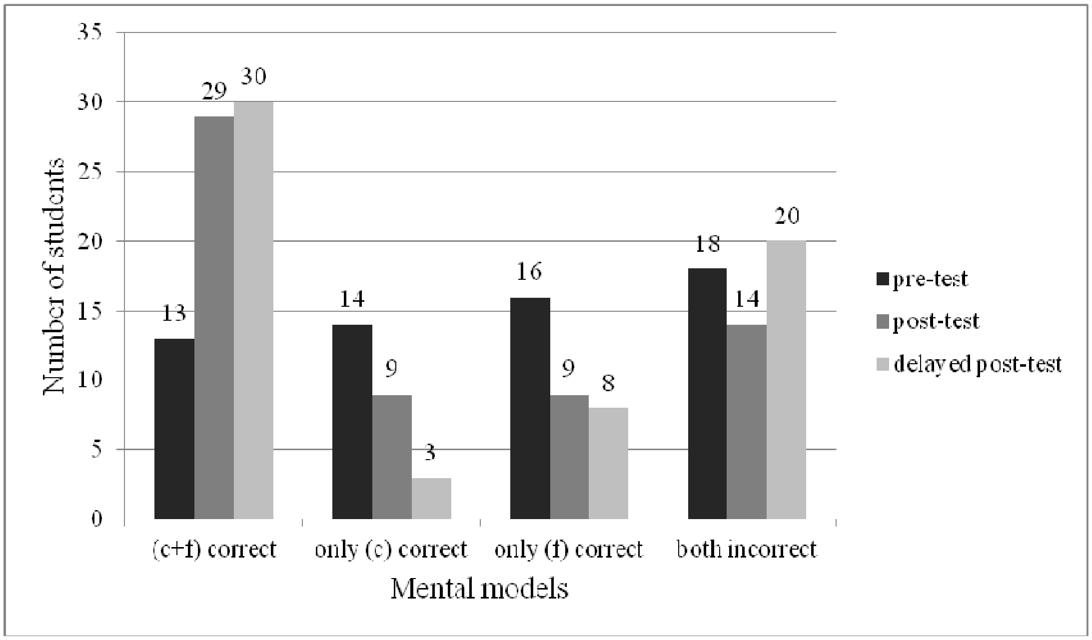


Figure 4.28: Comparison of performance in part Qns 4(c) and 4(f) (all tests)

Data indicated that there were as many students who progressed to a correct answer, as students who regressed to an incorrect view. Table 4.74 shows this for Qn 4(a).

		Qn4(a) (delayed post-test)		Total
		Correct	Incorrect	
Qn4(a) (post-test)	Correct	12*	10	22
	Incorrect	10	29	39
Total		22	39	61

Table 4.74: Post-test and delayed post-test results to Qn 4(a)

4.6.3.2 Summary on how students visualised charges in the electric circuit

While less than one third of the students gave evidence that they consistently saw charges present in the battery and in the wires all the time, these moving together after the circuit is connected, some other students regressed in their views since the post-test was administered. Even if a few students improved in their understanding of how the charges in the circuit behave, yet, all in all, the indication was that problems still persisted in this area. Students found difficulty understanding what they could not see.

4.6.4 Models of current used in the delayed post-test

4.6.4.1 Performance on questions probing models of current

Similarly to the post-test results, the majority of students conserved the current while only very few used attenuation.

In Qn 1, 87% of the sample retained ideas consistent with the current conservation (CC) model. A small number of students regressed to an attenuated view but the same number improved and conserved the current, such that 92%, in all, now used the CC model in this question (see Table 4.75).

		Model Qn1 (delayed post-test)				Total
		CC	ACC	AEF	U	
Model Qn1 (post-test)	CC	53*	2	1	1	57
	ACC	3	1	0	0	4
Total		56	3	1	1	61

Table 4.75: Mental models in the post-test and delayed post-test for Qn 1

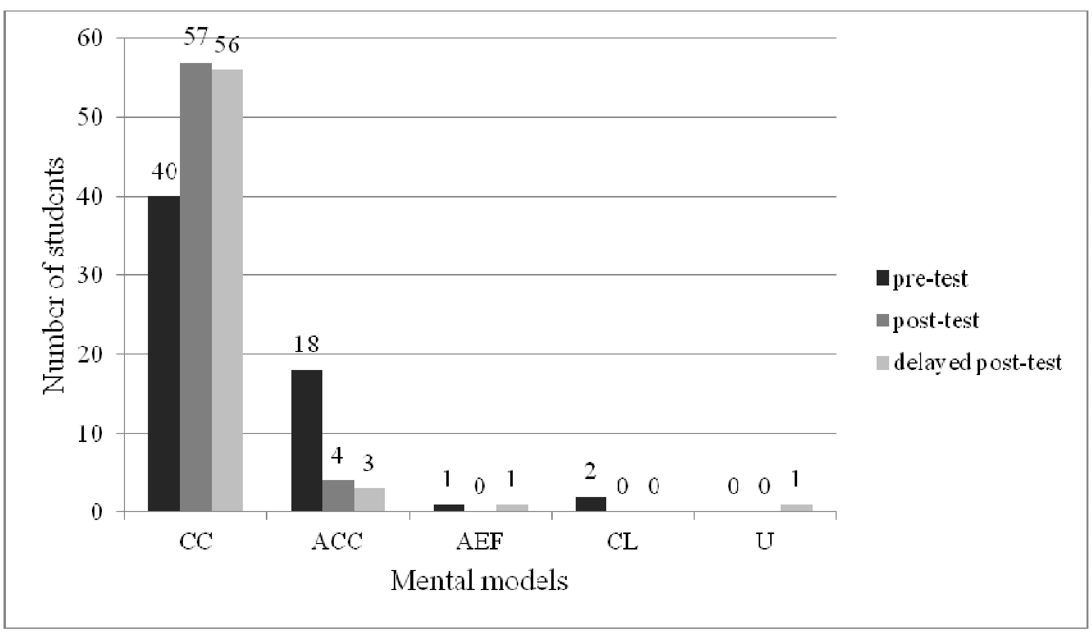


Figure 4.29: Mental models of current in Qn 1 - 'Currents at points (a) and (b)' (all tests)

Figure 4.29 compares performance on this question in the three tests.

Similar performance was observed in Qn 3, 'Picture of the battery and bulb', with 46 students (75%) now using ideas consistent with current conservation, compared to 43 students (70%) who had been correct in the post-test (see Figure 4.30 showing student performance in Qn 3 over the three tests).

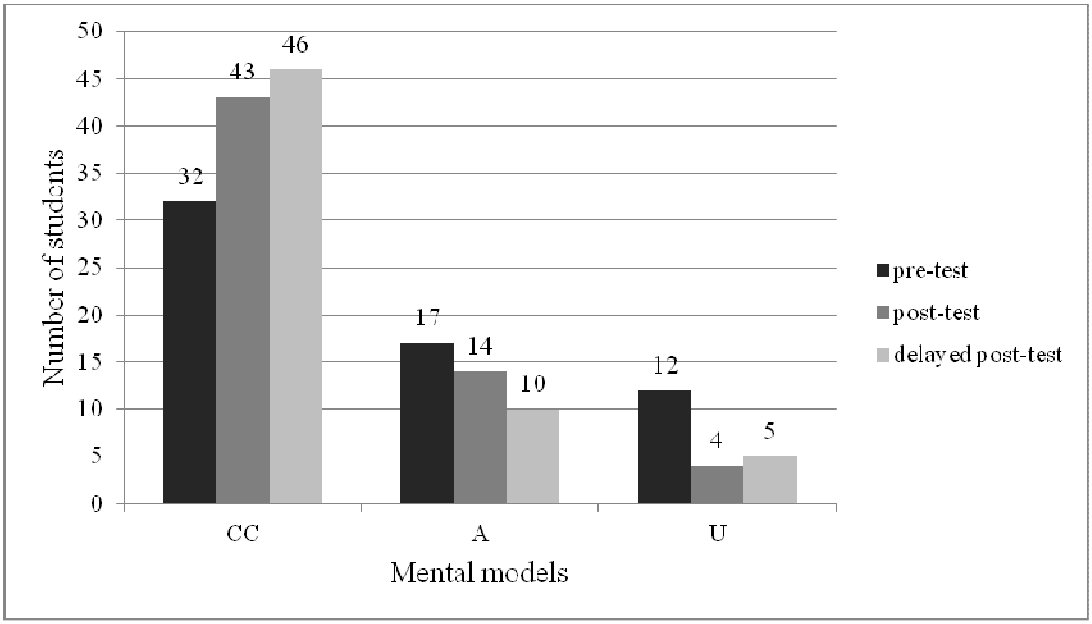


Figure 4.30: Mental models of current in Qn 3 (all tests)

More students now conserved current within a parallel branch. Results in Table 4.76, for Qn 9'(a), show the progress of 8 students (13%) moving from ideas consistent with attenuation in the post-test to current conservation in the delayed post-test. A majority of 57 students (93%) answered correctly (see also Figure 4.31).

		Qn9'(a) (delayed post-test)			Total
		CC	ACC	AEF	
Qn9'(a) (post-test)	CC	49*	1	1	51
	ACC	7	2	0	9
	AEF	1	0	0	1
Total		57	3	1	61

Table 4.76: Mental models in the post-test and delayed post-test for Qn 9'(a)

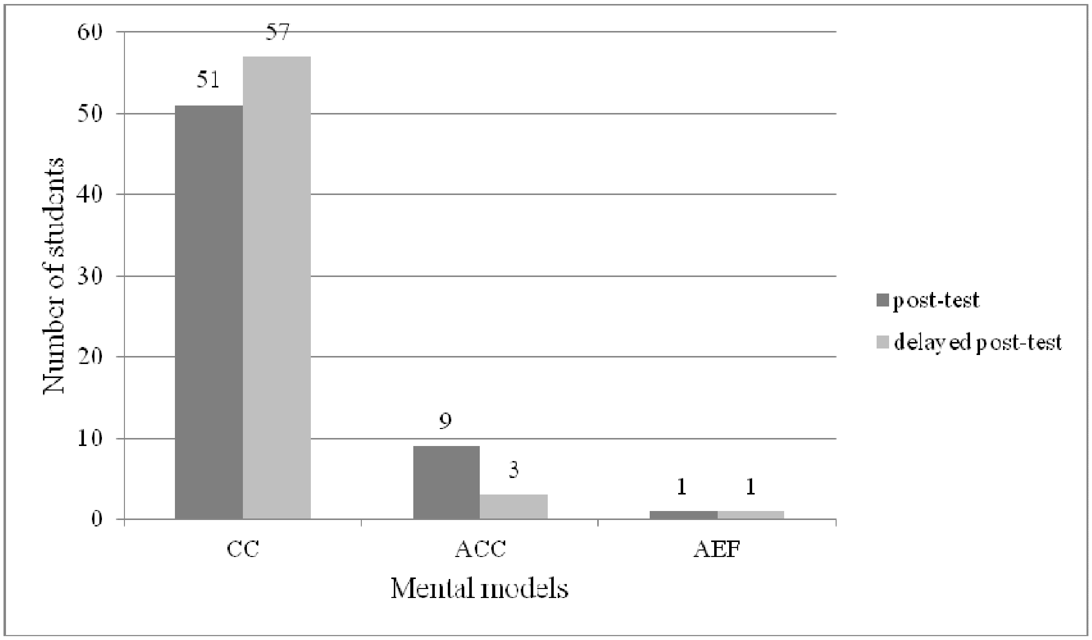


Figure 4.31: Comparing performance to Qn 9'(a) in post-test and delayed post-test

4.6.4.2 Summary of performance in questions probing models of current

While a few students moved from the use of the CC model in the post-test to the attenuation model in the delayed post-test, yet, it can be confidently said that a good number of students retained, and some more progressed to the CC model of current.

4.6.5 Understanding resistance and current control

4.6.5.1 Resistances in parallel branches

Students' responses to questions probing understanding of resistance once again helped to show that the concept of resistance remained rather poorly understood.

In Qn 9'(b), 'Parallel resistors' control of current', some students split the current equally at a junction, ignoring the effect of different resistances within the branches. Almost as many students moved towards a correct view as students moved away from it (see Table 4.77).

		Qn 9'(b) delayed post-test		Total
		Correct	Incorrect	
Qn9'(b) post-test	Correct	24	10	34
	Incorrect	8	19	27
Total		32	29	61

Table 4.77: Comparing answers to Qn 9'(b) for the post- and delayed post-test

4.6.5.2 Battery control versus resistance control in determining the current

Analysis of answers to Qn 6, 'Adding an equal resistance in series' and Qn 8, 'Adding an equal resistance in parallel', once again underlined a pronounced use of the BAT model. Figures 4.32 and 4.33 show the mental models inferred by students' answers to questions in all tests.

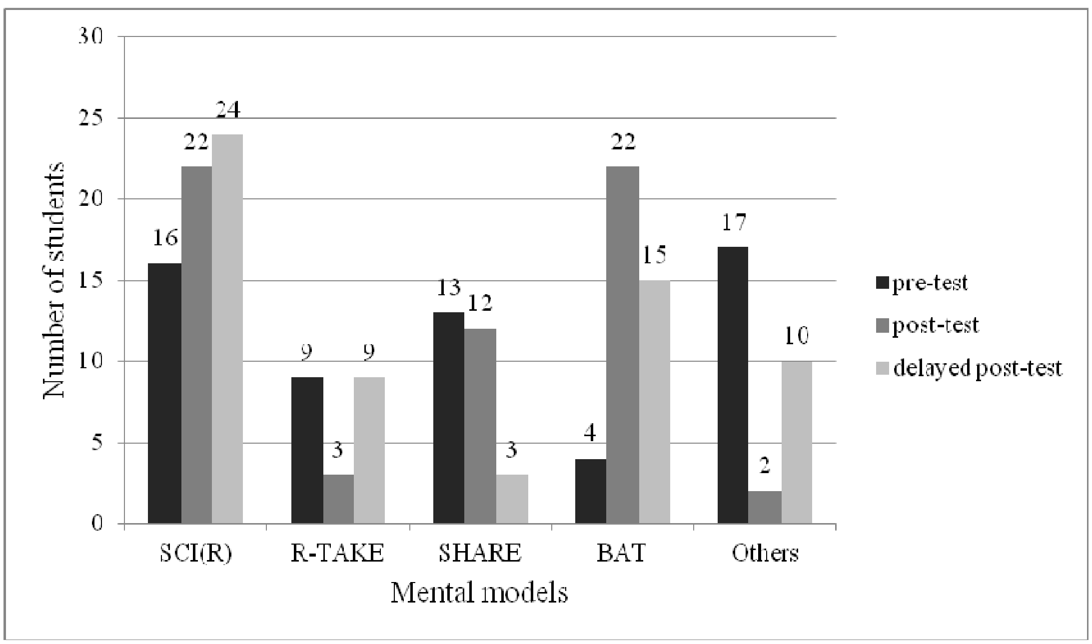


Figure 4.32: Mental models in Qn 6 (all tests)

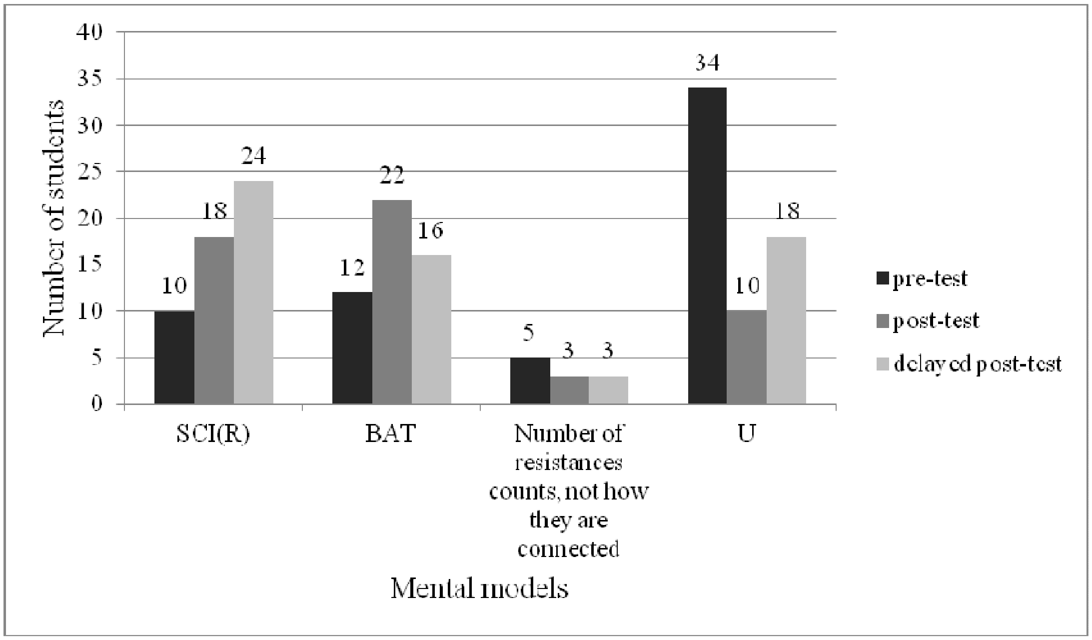


Figure 4.33: Mental models in Qn 8 (all tests)

In Qn 8: 'Adding an equal resistance in parallel', comparing models inferred in the post-test and delayed post-test (see Table 4.78), 14 students (23%) answered consistently in terms of the BAT model, confirming how strongly some students held on to this view.

		Model Qn8 (delayed post-test)				Total
		SCI(R)	BAT	R↑, I↓	U	
Model Qn8 (post-test)	SCI(R)	14*	1	0	3	18
	BAT	2	14	2	4	22
	R↑, I↓	2	0	1	0	3
	U	6	1	0	11	18
Total		24	16	3	18	61

Table 4.78: Mental models in the post-test and the delayed post-test for Qn 8

Moreover, the results in Table 4.79 show how 10 students (16%) used the BAT model consistently in both Qn 6 and Qn 8 during the delayed post-test.

		Model Qn8 (delayed post-test)				Total
		SCI(R)	BAT	R↑, I↓	U	
Model Qn6 (delayed post-test)	SCI(R)	16*	1	1	6	24
	R-TAKE	4	1	1	3	9
	SHARE	1	0	0	2	3
	BAT	1	10	1	3	15
	others	2	4	0	4	10
Total		24	16	3	18	61

Table 4.79: Mental models in Qn 6 and Qn 8

4.6.5.3 Summary of performance in questions probing understanding of resistance

More students could see that as resistance increases, current decreases. However, some students still inferred ideas consistent with the BAT model. These students focused more on the control of the current by the battery, forgetting the fundamentally important point that the current in the circuit is determined not only by the battery push but also by the control of this push by the resistance within the circuit.

4.6.6 Understanding p.d.

4.6.6.1 P.d. across ideal connecting wires

In the post-test the concept of p.d. was shown as being difficult to understand. Evidence had been provided to show that students either saw p.d. as ‘some difference between points’ or as ‘something which flows’. In the delayed post-test these ideas prevailed.

In Qns 12’(b) and (c) only half the students gave correct answers and recognized zero p.d. across the connecting wires (see Table 4.80).

		Qn12'(c) (delayed post-test)			Total
		6V	<6V	Zero	
Qn12'(b) (delayed post-test)	>6V	1	0	0	1
	6V	12	5	5	22
	< 6V	1	5	0	6
	Zero	1	0	31*	32
Total		15	10	36	61

Table 4.80: Results for Qn 12'(b) and (c)

Comparing results for Qn 12'(c) for both post-test and delayed post-test (Table 4.81), also shows that only half the sample answered correctly in both tests. This half seems to have retained their correct ideas. The other half could not 'see' zero p.d. across ideal connecting wires.

		Qn12'(c) (delayed post-test)			Total
		6V	<6V	Zero	
Qn12'(c) (post-test)	>6V	1	0	0	1
	6V	8	3	2	13
	<6V	5	3	5	13
	Zero	1	4	29*	34
Total		15	10	36	61

Table 4.81: Results for Qn 12'(c) during the post-test and delayed post-test

4.6.6.2 P.d. across equivalent points

In Qn 12', 'p.d. across resistances and ideal connecting wires', only 45 students (74%; see Table 4.82) in both tests, saw consistently that the voltmeter reading indicated the p.d. across equivalent points 'b' and 'd'.

		Qn12'(a) (delayed post-test)			Total
		>6V	6V	<6V	
Qn12'(a) (post-test)	>6V	0	0	1	1
	6V	0	45*	5	50
	<6V	1	4	5	10
Total		1	49	11	61

Table 4.82: Results for Qn 12'(a) in the post-test and delayed post-test

Qn 18, 'p.d. across a resistor, adding another resistor in parallel' also probed whether students could identify equivalent points and 'see' p.d. as a difference between those points. The results in Figure 4.34 show that a smaller number of students answered correctly in the delayed test, some students showing what had been pointed at in the post-test analysis, that choices were affected and related to the change suggested in the circuit. A slight regression of ideas towards unscientific views was detected in this question.

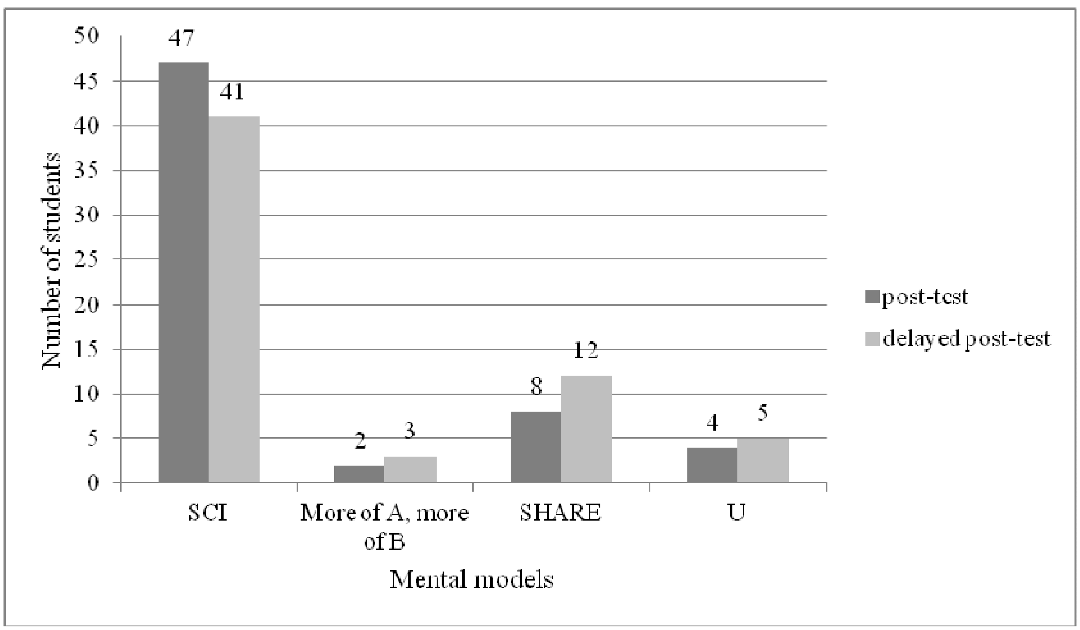


Figure 4.34: Performance on Qn 18 – 'p.d. across a resistor, adding another resistor in parallel'

Comparing the performance on Qn 18 and Qn 12'(a) in the delayed post-test, 35 students (57%, slightly more than half the sample) were consistently viewing p.d. as a difference between two equivalent points (see Table 4.83) in these questions. This number had been 39 (64%) in the post-test. A slight regression on views of p.d. towards the unscientific seems to be once again confirmed.

		Model Qn18 (delayed post- test)				Total
		SCI(p.d.)	SHARE(p.d.)	More of A, More of B	U	
Qn12'(a) (delayed post-test)	> 6V	0	0	0	1	1
	6V	35*	7	1	6	49
	<6V	6	3	2	0	11
Total		41	10	3	7	61

Table 4.83: Comparing results for Qn 12'(a) and Qn 18

Poor performance was also shown in Qn 19, 'Addition of a battery in parallel with the first: *Voltmeter reading*'. Even if more answered correctly compared to the post-test, only 37 students (61%) gave a scientific response to what the voltmeter reads when connected across similar batteries in parallel. Figure 4.35 compares mental models inferred by students' answer choices in the delayed post-test to the post-test answers a month earlier.

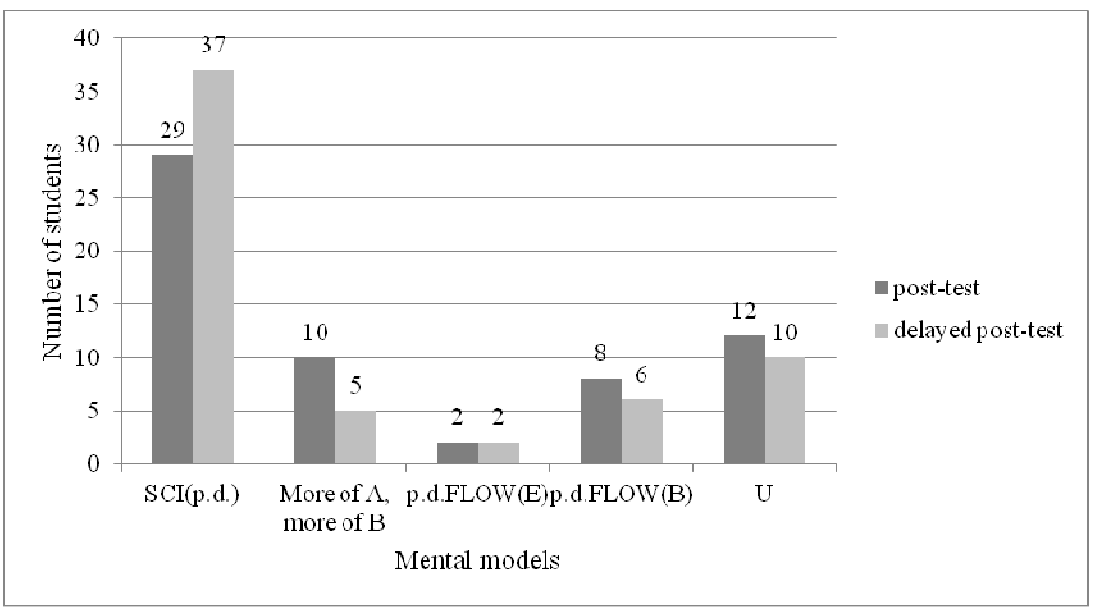


Figure 4.35: Qn 19 - 'Addition of a battery in parallel with the first: *Voltmeter reading'*

In Qn 20, 'Addition of a battery in parallel with the first: *Ammeter reading*', roughly the same number of students gave a scientific response to this question in both post-test and delayed post-test (see Figure 4.36) and more students now used the idea of batteries cancelling out each other's effect, or gave an unclassified answer.

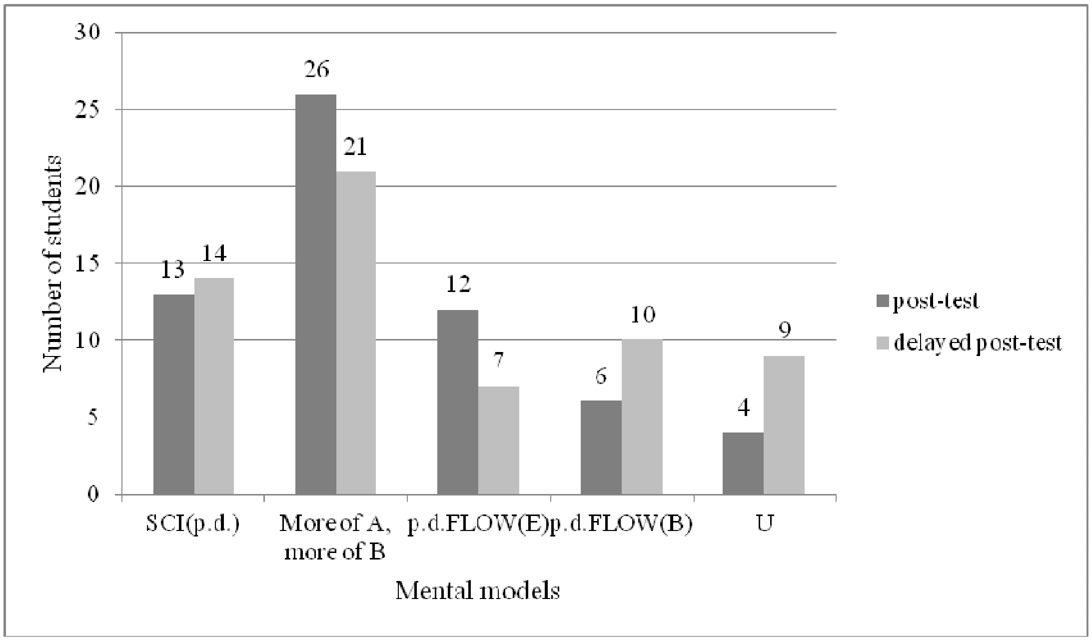


Figure 4.36: Qn 20 - 'Addition of a battery in parallel with the first: *Ammeter reading*'

Moreover, only 12 students (20%) saw that the same p.d. across the resistor translates into the same current through the resistor (Table 4.84). Analysis shows that only 5 of these 12 students had shown scientific ideas in both Qn 19 and Qn 20 on the post-test and had held consistently on to them. While this shows improvement over the post-test results, yet poor understanding of the concept of p.d. by most students was still evident.

		Model Qn20 (delayed post-test)					Total
		SCI (p.d.)	More of A, more of B	p.d.FLOW(E)	BAT	U	
Model Qn19 (delayed post-test)	SCI(p.d.)	12*	13	4	5	3	37
	More of A, more of B	0	4	1	0	0	5
	p.d FLOW(E)	0	1	1	0	0	2
	BAT	1	0	0	2	3	6
	U	1	3	1	2	4	11
Total		14	21	7	9	10	61

Table 4.84: Mental models in Qn 19 and Qn 20 during the delayed post-test

4.6.6.3 P.d. not distinguished from current

Approximately as many students as in the post-test could predict the voltmeter readings correctly in Qn 15a, 'p.d. across equal resistors connected in parallel' (see Table 4.85).

		Qn15 prediction (delayed post-test)		Total
		4V,4V	8V,8V	
Qn15 prediction (post-test)	4V,4V	3	4	7
	8V,8V	3	49*	52
	Missing	1	1	2
Total		7	54	61

Table 4.85: Qn 15 (prediction) on the post-test and delayed post-test

Only 8 students, however, gave a correct and complete response (see Table 4.86).

Answer to Qn 15 (a): Voltmeter readings prediction	Type of response	Number of students	Percentage (N=61)
8V , 8V	Correct and complete	8	13%
	Correct and incomplete	35	57%
	Correct part (a), restating answer in explanation	5	8%
	Explanation with alternative views	4	7%
	Unclassified	3	5%
4V , 4V	Voltage shared/split	2	3%
	Resistance in control of the voltage	4	7%

Table 4.86: Predicting voltmeter readings in Qn 15

In Qn 16, ‘p.d. across unequal parallel resistors’, the element of sharing or splitting of p.d., treating p.d. like ‘something which flows’, was again evident. Twenty eight students out of 37 were consistent in their correct voltage prediction in both post-test and delayed post-test (Table 4.87).

		Qn 16 voltage prediction (delayed post-test))					Total
		2V, 4V	3V, 3V	4V, 2V	6V, 6V	Others	
Qn 16 voltage prediction (post-test)	2V, 4V	4	0	1	5	1	11
	3V, 3V	2	0	1	1	0	4
	4V, 2V	1	1	2	1	0	5
	6V,6V	6	1	1	28*	1	37
	Others	1	0	0	2	1	4
Total		14	2	5	37	3	61

Table 4.87: Voltmeter reading predictions in post- and delayed post-test for Qn 16

Moreover, 37 students gave a correct voltage prediction in both Qns 15 and 16. The results in Table 4.88 clearly show that some students still found it very demanding answering correctly to Qn 16. P.d. was hard to visualize and model.

		Qn 16 voltage prediction (delayed post-test)					Total
		2V, 4V	3V, 3V	4V, 2V	6V, 6V	Others	
Qn 15 voltage prediction (delayed post-test)	4V, 4V	4	2	1	0	0	7
	8V, 8V	10	0	4	37*	3	54
Total		14	2	5	37	3	61

Table 4.88: Voltage predictions to Qn 15 and Qn 16

The analysis of Qn 17', 'p.d. across an open and closed switch', indicated a slight overall improvement over the post-test results, especially in part (a), where students had to say that there is no p.d. across a closed switch (see Table 4.89). Twenty three students had been correct in the post-test, and now it was 29.

(N=61)							
Answers to Qn 17 (a): 'p.d. across a closed switch' (delayed post-test)							
Prediction	Correct and complete	Correct and incomplete	Restatement of the answer	U	Showing alternative ideas	Missing explanation	All missing
0 Volts	19*	10*	3				
3 Volts				16	5	1	
Less than 3V					1		
More than 3V							
Others				1	1		
All missing							4

Table 4.89: Answers to Qn 17'(a) - 'p.d. across a closed switch' during the delayed post-test

In part (b), however, only 14 students were correct in their answer, indicating 3V as the p.d. across an open switch - a p.d. equal to that of the battery (see Figure 4.37). This showed a 13% improvement over the number of correct answers in the post-test. Even so, when 33 students (about half the sample) still stated that with no current flowing, no p.d. could exist, the performance in this question left a lot to be desired.

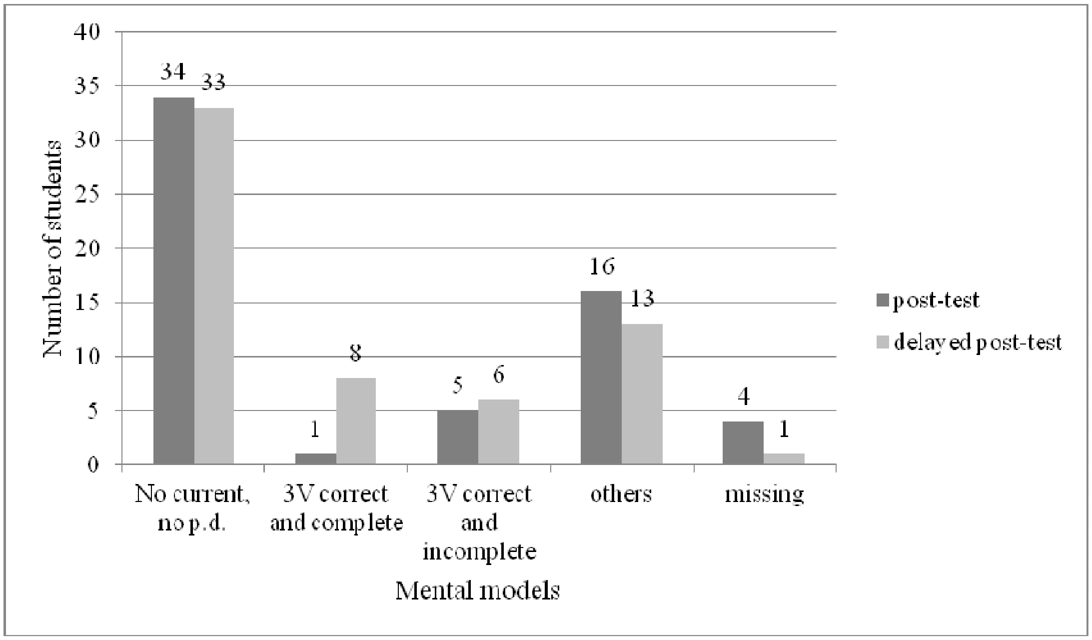


Figure 4.37: Answers to Qn 17(b) – 'p.d. across a closed switch'

4.6.6.4 Summary of students views of p.d.

Evidence indicated that performance on questions dealing with p.d. across equivalent points in a circuit had, on an average either remained the same or was slightly poorer in some questions.

More students could now answer correctly to zero p.d. across a closed switch, but many (more than one half) still had problems acknowledging that p.d. can exist without a current. It was difficult for a large number of students to see p.d. as an imbalance of charge between points and to thus distinguish it and describe it differently from current.

4.6.7 Conclusion from the delayed post-test results

Looking at the results of the delayed post-test globally, one cannot say that performance in the delayed post-test corroborated the view expressed by Fleer (1994) that students generally regress from the scientific ideas gained during teaching, after some time has elapsed. Indeed, in most questions the number of correct answers increased, even if by only a small amount. It should be borne in mind that, at the time of the delayed post-test, the students in this sample were close to sitting an important national examination in Physics. This may explain why students performed slightly better at this stage, since they may have been more serious about their work, as the examination was fast approaching. It has also been shown that it was not always the same students answering correctly over the two tests. While some students were consistent in their views even after one month elapsed, the ideas of some other students shifted from or towards the scientific view. Furthermore, evidence has shown that some students persisted with their unscientific views.

The following is a summary of the main findings:

- most students showed they now reliably used ideas consistent with the conservation of current (CC) model;
- less than one third of the students showed that they consistently saw charges present in the battery and in the wires all the time, these moving together after the circuit is connected. Problems with microscopic views persisted;
- about one third of the students could not see resistance as a control of the current, **together** with the battery push;
- the BAT model seemed more popular compared to other alternative views;
- some regression was shown in dealing with p.d., with about half the sample still believing that p.d. cannot exist without a current.

4.7 Comparing the overall performance of Cohort 1 in all tests

The previous sections in this chapter looked in detail at students' answers and the mental models students appeared to be using in relation to current, resistance and p.d. The following sections compare statistical results from the analysis of students' test scores in the three tests.

Students' performance on the **common** questions in the tests was looked into to check whether students improved in their overall performance related to the ideas which were probed by these questions (see Table 4.90).

(N=61)				
Diagnostic Test	Mean score out of 19	Standard deviation	Mean score as a percentage of the total score	Standard deviation of the percentage scores
Pre-test	7.4	4.0	39.0 %	21.1
Post-test	10.4	3.7	55.0 %	19.4
Delayed post-test	10.8	3.9	56.8 %	20.7

Table 4.90: Results considering the common questions asked in all tests

The rise in the mean score from 39.0% in the pre-test to 55.0% in the post-test shows an improvement in performance after the teaching, on the common questions asked. The results for the delayed post-test show no regression in overall performance on these questions.

The results in Table 4.91 show that correlations between the test scores, considering only the **common** questions, were statistically significant at the 1% level. These results show that the students who had been performing well at the start of the course continued to do well, while those students who had been performing poorly, still showed a tendency for low performance in the post-test and delayed post-test, even if their understanding may have improved somewhat through the course.

N=61		
Correlation for the students' scores on the common test questions/19	Pearson Correlation Coefficient	Sig. (1-tailed)
Pre- / post-test mark	0.65	<0.01
Pre- /delayed post-test mark	0.50	<0.01
Post- / delayed post-test mark	0.73	<0.01

Table 4.91: Correlation of the students' scores on the common questions in the pre-, post- and delayed post-test

Table 4.92 shows the paired t-test results for differences between the pre-test and post-test and between the post-test and the delayed post-test scores. The results for the first pair of tests indicated that students made a significant improvement over time ($t = 7.3$, $df = 60$, $p < 0.01$, one-tailed). The difference in the results of the post-test and the delayed post-test was not significant ($t = 1.0$, $df = 60$, $p > 0.05$, one-tailed).

	Difference in score		t	df	Sig. (1-tailed)
	Mean	Standard Deviation			
Post-test – pre-test	3.0	3.2	7.3	60	<0.01
Delayed post-test – post-test	0.3	2.8	1.0	60	0.17

Table 4.92: Results of t-tests between post/pre-test and delayed post/post-test (all questions)

The t-test was used in the above analysis, treating the scores in the diagnostic tests as interval level data (Brace, Kemp, Snelgar, 2006). Since this was slightly uncertain, the Wilcoxon test of paired differences was also used to check for the level of significance. This check confirmed the t-test results. In this chapter and also in later ones, whenever t-tests were performed, they were checked using the Wilcoxon or Mann-Whitney test, as appropriate, to compare the levels of significance. In all cases, these checks confirmed that the results were very similar in terms of level of significance. For this reason, only the t-test results are presented.

It was also important to examine how test scores on the different groups of questions changed in going from one test to the next. This indicated which part of the topic was being understood by students and which part was creating problems in students' learning. The changes in the mean scores within each group of questions in the diagnostic tests are shown in Table 4.93.

(N=61)								
Diagnostic test	Group A (microscopic views)		Group B (Models of current)		Group C (How resistances control current)		Group D (Conceptualization of p.d.)	
	Mean %	Standard Deviation	Mean %	Standard Deviation	Mean %	Standard Deviation	Mean %	Standard Deviation
Pre-test	26.2	31.7	70.2	30.4	44.9	26.2	53.2	22.8
Post-test	44.8	31.0	82.5	27.6	43.0	33.6	46.8	18.9
Delayed post-test	41.0	35.7	86.3	21.4	45.1	34.7	50.2	20.9

Table 4.93: Means as a percentage for the question groups in all tests (all questions)

These results are in clear agreement with the results from the detailed qualitative analysis presented in the previous sections. While students still found problems with microscopic views, yet they improved in the use of current conservation views. Treating resistance as a control of the battery push can be seen to have remained difficult for students to grasp. Moreover, in Group D, a lower percentage mean resulted for the post-test questions, when more questions were asked probing p.d. An increase in the percentage mean score was observed in the delayed post-test on this group, but this score was not as high as for questions in group B, implying that the current concept was more easily understood by students when compared to the concept of p.d.

4.8 Conclusion to the analyses of the PDTs (Cohort 1)

The analysis of the results from the 3 diagnostic tests gave some important indications.

Students showed progress in understanding that current is conserved, with at least 70% of the sample indicating ideas consistent with the current conservation (CC) model in the post-test, many holding on to this view in the delayed post-test. Such progress however, was not shown when dealing with microscopic views, resistance and p.d.

In dealing with what happens in the battery and wires, it was shown that more than two thirds still held the idea that the battery carries all the charges and pushes them into the wires when the circuit is complete. These students did not find it easy 'to see the invisible'. Teaching had not helped enough in this regard.

In tackling questions related to resistance, some students started by indicating a tendency to use the SHARE (current sharing between resistances) and BAT (the same battery supplies the same current) models in the pre-test. This 'tendency' seemed to evolve into a strong view for some, who showed that they put their focus mainly on what they thought the battery alone could do to the circuit. The BAT model was in some cases used consistently, even after teaching – a result which is not indicated in previous literature. Students who inferred the BAT model ignored the effects of other components in the circuit. The impression was that local reasoning rather than 'a system' approach was still favoured by some students, with these showing a poor ability to understand the idea of resistance as a control of the current, together with the battery push. In students' early years, they learn that for an electric toy to work it needs a battery. For a car engine to start, a battery is needed. Any other apparatus making use of a current requires a voltage supply. All this helps to highlight the importance of 'the battery', perhaps more than it does for the importance of other circuit components. This highlight may then be in itself an element which promotes the use of unhelpful ideas like the BAT model.

Students certainly did not find p.d. easy to master, showing a regression of ideas when dealing with related questions. Some indicated splitting of p.d. at junctions between parallel branches, treating p.d. much the same as current. Apart from the view indicating a difference between points, students showed use of ideas related to something which flows. Some students seemed not to distinguish p.d. from potential and from current.

As can be seen, the analysis of the PDTs gave an interesting picture of ideas consistent with mental models which were popular with students and which were not always scientific. The interviews carried out with some of the student sample were meant to go deeper into what students 'see' when they think of how the circuit works, and what hinders progress. The next chapter describes the results of these interviews.

Chapter 5 Interview Study: Cohort 1

5.1 Introduction

While the analysis of the Physics Diagnostic Tests (PDTs) in Chapter 4 gave indications of ideas students use as they learn about circuits, yet a clearer view of the mental models students adopt was obtained when students' ideas were backed up by more in-depth information obtained from interviews. This chapter analyses the results of four one-to-one interviews conducted with each of 9 students from Cohort 1 (see section 3.8.4.1 for details about the interviewees and their selection). All student names indicated are pseudonyms. The interviews were conducted after students did the pre-test, and while the teaching was in progress. While the interview schedules are included in Appendix 8, the questions asked and the respective circuit diagrams used with the students are also included in this chapter, for ease of communication.

The 1st interview probed students views of what causes current, as well as models of current which students seem to hold. Ideas about how resistance affects the circuit were also probed, together with views related to the battery function.

The 2nd interview looked into how students deal with resistances in series and in parallel and the effects on the current in the circuit resulting from the different ways of connecting resistances.

The 3rd interview probed microscopic views using Qn 4 answers students had given in the PDTs, and looking at how these views may have changed after teaching. Moreover, views about meanings given to voltmeter readings were also probed, with the hope of finding out how students model potential and potential difference.

The fourth and last interview focused on whether students were able to separate the idea of potential difference (p.d.) from that of current.

All interviews were based on ideas which students had shown to find problems with in the pre-test. The timing of the interviews in relation to the teaching has already been indicated in section 3.8.8.

5.2 The 1st interview – Current in a simple circuit

5.2.1 The aims of the 1st interview

The 1st interview was aimed at probing students' ideas about how a simple circuit works. It was important to find out how students visualize what goes on in the electric circuit and how devices affect the current in that circuit. Details regarding what constitutes current, the function of the battery and the resistance, were all important to discover. Moreover, it was also important to get feedback about questions like the following:

- is the battery the only source of electrons which flow in the circuit or is it only there to provide the push for electrons to flow?
- what is the effect of having a resistance in the circuit? Does the resistance affect the circuit locally or globally?
- how do students model current?

5.2.2 Conducting the 1st interview

The 1st interview in a series of interviews is always of significant importance. It sets the path and tone for further interviews. During this interview, one of the primary objectives was to give an idea to the students of how the interviews were designed and how they would be conducted. In an era where students have become too used to having what they are saying or doing as being categorized as either 'correct' or 'incorrect', it was felt important to get the student to know and to speak to the interviewer in an informal way, trying to clearly explain their ideas. An environment had to be created which allowed the students to voice their thoughts, while reducing the dreaded pressure of making mistakes.

The ideas to be probed into dealt with issues which are usually covered and dealt with at the beginning of a basic course in current electricity. Focusing on 'simple' key ideas implied that there was a larger possibility that the situation dealt with would not be new to the student. Moreover, asking about 'simple' key ideas was thought of as being a better way towards reducing the complexity of the answers and their interpretation. While James (L), for example, said: *'I am going to find this a bit difficult!',* when asked for the mental picture of what goes on in the circuit presented, yet what the student said was taken as a pointer towards the perception of the difficulty that some students may have about the topic in question, or the problem some students have in explaining their ideas.

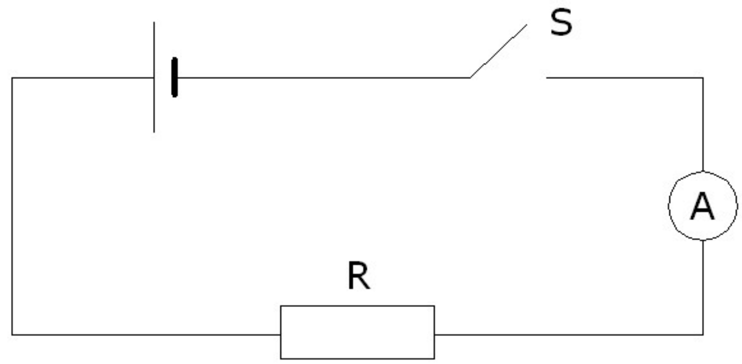


Figure 5.1: A simple circuit diagram

The circuit diagram shown in Figure 5.1, together with the actual circuit, was shown to the individual students. The students were asked:

- Describe <u>your</u> mental picture of what is happening in <u>this</u> electric circuit when S is switched on.
- What affects the ammeter reading? Why?
- What do you imagine is happening within the circuit? What mental model do you have as you give this answer?

In addition, a Predict-Observe-Explain (POE) task (see section 3.6.2.3 for details) was prepared, with questions probing further into the models of current flow students held (see section 5.2.6).

5.2.3 Ideas revealed about current

5.2.3.1 A general mental picture of something flowing

When students were asked for their mental picture of what happens in '<u>this</u>' electric circuit, their answers were indicative of the fact that they knew that something was *passing* or *flowing* through the circuit. Most of them mentioned 'electron flow' (Theri (A), Kyle (A), John (L), Chris (A), James(L), Mitch (H)) and 'the flow of charge of electrons' (Chris (A)). At times, the flow was referred to as a 'current' passing (Chris (A)) or 'coming out of the battery' (John (L) and Andi (L)). Some of the students were specific in their use of words indicating a *direction of flow*, saying that 'electrons pass from the negative to the positive side of the battery' (Kyle (A), Mitch (H)). Mari (L) said that 'the current passes and the voltage, together'. Robi (H) referred directly to the presence of 'a potential difference and because of it, a current passes', thus indicating the cause of the effect.

5.2.3.2 A cyclic sequential pattern to indicate flow

At the very start of the interview, as a general rule, the tendency was for the students to describe a '*cyclic sequential'* (see Grotzer and Sudbury, 2000, p. 7) process to indicate flow. The description was given verbally, sometimes with gestures and pointing towards the circuit diagram. The starting point was necessarily one end of the battery, with a description of what was flowing as passing sequentially through each device in the circuit and finally coming to the other end of the battery. 'There is a beginning and ending of sorts at the battery' (Grotzer and Sudbury, 2000, p. 7).

The following extract is an example of the way the process was described by Mitch (H).

> M: Electrons are passing from the negative side, through the switch, then into the ammeter and they pass through the resistance and go into the positive side of the battery.

The above describes a sequence of events, with a specific start and a finish.

John (L), who showed evidence of this sequential process from the start, also seemed heavily inclined towards local and attenuation reasoning, throughout the whole interview.

> J: If you use a bulb and you put it without a resistor, it shows a certain amount of brightness. With the resistor, the bulb has a lower brightness, but near the ammeter, a high brightness.
> I: Where do you put the bulb?
> J: Here after the resistor, the brightness will decrease.
> I: And if you put it somewhere else?
> J: Near the ammeter, for example, it would not have passed through the resistor, so the brightness would be more.

On the other hand, the initial cyclic sequential description was not necessarily backed up by an attenuation model by the other students. Chris (A) and Robi (H), for example, described no specific attenuation model at all. This indicates that some students are ready to describe the flow in the circuit in a sequential manner, even if they *don't* necessarily *see current as being attenuated*. Others use the same mode of description and they actually *believe* that the effects are experienced locally at the circuit devices, holding an attenuation view. The implication is, therefore, that the method of describing the flow of current is not automatically equivalent to the mental model of current held. Moreover, as expected, the analysis of the transcripts was indicating that not all the students held the same model of current, at this initial stage.

5.2.3.3 The importance given to the connecting wires

The connecting wires are certainly a requisite in any circuit. But, how did students regard the function of these wires in terms of current flow? Different mental pictures were made evident by the students, as different functions were attributed to the connecting wires.

Current results because of electrons in the connecting wires

Irrespective of their ability, some students saw the current as resulting because of the electrons present in the connecting wires alone. Theri (A) was an example of this. Electrons were seen in the connecting wires only and none were seen in the battery, with the latter being there to push the electrons in the wires and thus create current flow.

I: So what picture do you see?
T: Electrons in the wire are already there. When S is switched on, the battery gives a push, but it pushes according to what resistance there is in the circuit.

[And later on….]

I: So what is the battery exactly producing then?

[The student takes time to think.]

T: Maybe, how much it can push? I don't know!

Mari (L) initially only described the importance of the electrons in the wires for current formation because of the belief that 'the current is the free electrons already in the wires'.

Only when prompted to explain further, did the student go on to speak about the properties of the battery.

I: Does the battery have…?

M: Potential difference.
I: ....and electrons too?
M: Yes, it's a conductor otherwise there is no complete circuit.

Mari (L) also referred to the push from the battery – a push which the voltage was creating.

M: If R increases, it won't pass because there will not be any push from the voltage.

While the student acknowledged the battery push, the mental picture of current remained dominated by the electrons present in the wires.

Robi (H), initially, likewise saw the electrons in these wires as being the only source of current in the circuit but, as the questions from the interview generated more conflict, reservations that were held about this idea were indicated.

I: Do you see electrons in the wires?
R: Yes.
I: Do you see electrons in the battery? [I was trying to probe the student's ideas regarding the function of the battery in the circuit.]
R: The battery provides the energy for the electrons to move. I don't think there will be electrons there. So I see the electrons in and from the wires, moving and creating the current because of the potential difference.
I: Do you see a current in the battery? [This question was asked on purpose, to introduce some conflict.]
R: Hmmm, let me see! There are no electrons, I doubt whether there is a current!

[The student looked rather confused.]

I: What are you thinking?
R: I'm still thinking about it. Now I see that if there is a current, there must definitely be a connection inside the battery!
I: So?
R: So I am thinking, maybe I was wrong about what I said before that there is no current in the battery. [The student comes to this conclusion as a result of the conflicting ideas which were created through the interview.]
I: So what are your thoughts now?
R: Will there be a connection inside the battery, or not? I'm asking because I never studied anything about the inside of the battery – not in class! And I never opened one!

The student's confusion still seemed unresolved. An answer from me was expected as reassurance.

Current as a result of electrons in both the battery and the connecting wires

Other students like Mitch (H), for example, saw the electrons in the wires together with the charge in the battery as constituting the current.

I: So how do you see this current exactly?
M: I know that the current leaves the positive side and goes in the opposite direction to the conventional current.
I: But do you see these electrons that you have….
M: What do you mean: 'See'?
I: Because it is a picture which I wish you would describe to me. Do you see them as being somewhere specific?
M: Let me think, because there are already electrons in the wires. The free electrons not used in the bonding. And those help with the conductivity. The more there are, the more conductivity there is.

[And later ……]

M: The electrons are going round. There are electrons in the wires, the free electrons help with the conductivity.
I: You see electrons in the wires, then. Are there electrons in the battery?
M: Yes.
I: The electrons from the battery and those from the wires, do they form the current together or is there something else? I wish that you would explain this to me please.
M: The electrons from the battery, because they have like charges, will be pushed through the circuit. The electrons in the battery will have a stronger charge because of potential difference. And they push the free electrons in the wires to move through the rest of the circuit.

[And later on still…]

M: Both the free electrons in the wires and the ones inside the battery are being pushed, given energy and travel to the positive side.

The battery alone as the supplier of current

Other students said they believed that the charge/electrons/current emerged from the battery as the supplier of the current, offering different views about the role of the connecting wires. Many students had indicated they saw the battery as the sole supplier of charge in the pre-test (see section 4.4.2).

Andi (L) put all the focus on the battery and saw the current coming out of it, without ever mentioning the wires in describing current flow.

Kyle (A) saw no electrons contributing to the current coming from the wires.

I: So when you switch the circuit on, mentally what do you see?
K: When you switch on, it is as if you have a bridge. You have closed the gap and the flow begins.

The ammeter reads the current and then, the current passes through the resistance and goes back into the battery.

I: How does this happen?
K: Once the switch is opened again, the contact is broken and the flow around the circuit stops.
I: What more can you say about this flow?
K: The battery has all the charge in it…. Electrons etc., and as you close the switch there is a connection to the rest of the circuit.

Chris (A) saw the wires as necessary paths for the passage of the charges flowing out of the battery.

John (L) also saw the wires full of electrons coming from the battery alone.

I: So these electrons, did I understand you well? Do you see them as residing in the battery?
J: They must come from somewhere.
I: Do you see them as coming from anywhere else, or is it that they come out only from the battery?
J: From the battery only! I don't think they are in the wires. I don't know whether it is true or not.

[And again, later…]

I: So in the wires, are you seeing electrons?
J: Only the ones coming from the battery……….

James (L), on the other hand, did consider the wires but it was their resistance which was of underlying importance. The 'free' electrons within them were not seen as important for current flow.

J: A flow of electrons occurs and the ammeter reads the amount of current.
I: When you say: 'flow of electrons', from where is this coming?
J: From the cell, from the battery.
I: Explain more about the process.
J: They come out from the negative terminal. The electrons from the negative terminal, they do what I have just explained.
I: So where do you find these electrons?
J: They are also found in the wires, but I think [this is said with emphasis], the electrons come out of the battery. The wires offer some resistance too, I am sure.
I: So you said the wires have electrons too…..
J: No. I used the wrong word. The wires have 'free' electrons since they are metal…, but these have nothing to do with the electrons of the battery, no?

J: I'm thinking a bit! Eh… I don't think that the ammeter reads the electrons found in the wires of the metal.

Later James (L) made a spontaneous use of an analogy which helped him explain his model of current.

I: So how do you see current?
J: I see it as electrons passing through the wires.
I: Passing through the wires, like what? What is your mental picture?
J: My picture is that electrons are the cars. That is how I compare it. The wires are the roads. If the road is wide, more cars will pass. If wires are thicker, more electrons can flow.

In summary, these interview extracts show that at the start of the course, students of low or average ability were either saying that the electrons in the wires alone, or that the charge from the battery alone, constituted the electric current. One of the high ability students had a strong idea from the start that both the electrons in the wires and the charges in the battery contributed towards current formation. The other student started off having the idea that only the electrons in the wires were important for the flow of current, yet conflicting ideas arising during the interview shifted the student's view towards the presence of some 'connection within the battery' (Robi (H)), for current to flow. For this student, ideas related to the battery and more specifically to the battery symbol in common use, created some confusion in the student's mental picture held. The student said that this confusion had persisted since previous years. Indeed, the student claimed that his knowledge of battery construction and how the battery works was poor. The student asked the interviewer for clarification of how things work.

5.2.3.4 The role of the battery

For some students, as in the case of Theri (A), the battery was required to provide the forward 'push' or the energy required for the electrons to move. John (L) saw this energy as being transferred from one electron to the other. Chris (A) used a car and garage analogy, putting the focus on the cars coming out of the garage. The student never really mentioned the 'push', however, the idea of energy was implicit since the cars were moving. Even when students refer to the battery as the 'driver' of the current, as in the case of Andi (L), a 'push' or some force is implicit. Mari (L) and Robi (H) explained that the push was the effect of the potential difference.

On the other hand, there were students who did not mention the push. The idea was conveyed that once the circuit was complete, the flow occurred naturally.

Kyle (A) saw the battery as some kind of charge storage which could supply the current flow.

> K: The charge is stored in the battery and when S is on, this means that *the circuit is complete and electrons can then flow, leave the battery, go round the circuit and come back to the battery.*
> I: So there are no electrons in the wires?
> K: No! *The wires do not have charge in them because if you connect the ammeter to the wire, it won't give you a reading.*

The above extract shows that Kyle (A) had the evident expectation that if the wires had electrons in them, then connecting them to an ammeter, the latter should give a reading. No 'battery push' idea was exposed. What was made implicit was the idea that flow did not necessitate the presence of the battery push. It was rather the importance of the complete circuit alone which was being emphasized as a requirement for current flow.

Some students could imagine and speak of the attraction between the charges. Potential difference was also referred to but, it is important to note that the electric field which exists between battery terminals was not mentioned, at this stage.

5.2.3.5 A summary of ideas about what makes current

In an effort to make the picture representing the student responses easier to describe and to get an overall view, the results were compiled in Table 5.1.

Student Code	Pictures electrons in wires	Comment	Pictures electrons in battery	Comment	What makes the current?	The role of the battery
Andi (L)			✓		Current from the battery	Battery drives the current
John (L)			✓		Electrons from the battery	Voltage provides a push
James (L)	✓	Electrons in wires just there to offer resistance	✓		Electrons from the battery	Battery supplies charge for the flow of current
Mari (L)	✓			Says there is *charge* in the battery, for the circuit to be complete	Electrons from the wires	Voltage provides a push
Kyle (A)			✓		Charge from the battery	Battery stores the charge. No push is mentioned
Theri (A)	✓				Electrons from the wires	Battery provides a push
Chris (A)		Wires seen as paths for the flow of charge	✓		Electrons from the battery	Battery like a garage storing charge. Voltage depending on strength of the current
Mitch (H)	✓		✓		Electrons from both battery and wires	Battery provides a push
Robi (H)	✓ (as a start)		✓ (later on)	At the end, questions whether charge is present in battery.	The movement of electrons in the wires and the shift of ions within battery is mentioned. Student is still rather unsure of what is happening in the battery	Battery provides a p. d. because of a charge difference between the terminals

Table 5.1: The formation of current in a closed circuit

The results show that more of the low and average ability students pictured the current as flowing out of the battery in which it was stored. It is the high ability students who saw either immediately or as a result of the interview that the charges from all parts of the circuit were moving for a current to be established. With regard to the battery, not all students found it relevant to mention the importance of the ‘push’ which needs to be supplied for current flow. At this stage, some just only looked at the importance of having a complete circuit for current flow.

5.2.4 A picture of resistance

Students easily said that resistance controls the current flow.

Some described it as ‘friction’ stopping the electrons. Others mentioned an opposition to the flow and referred to the presence of the resistance as reducing the attraction of the electrons from the positive end of the battery. The word ‘blockage’ was also used. Sometimes descriptions related to length and area of a resistance wire. Some described the resistance as ‘taking the voltage’ or ‘taking energy from the current’. These ideas seemed linked with the R-TAKE model of resistance referred to in Chapter 4.

Moreover, some students, independent of their overall ability in performance, used analogies to describe the way resistance affects the current in the circuit. It may seem that as Chris (A) put it, ‘One can better explain (resistance) this way’. Resistance was compared to a gate or a crowd of people, or looked at as ‘narrowing the road’ or ’narrowing a gap’.

5.2.5 Factors affecting the current

All the students interviewed found it relatively easy to state that as the voltage is increased, the current in the circuit increases. All students, except for one from the low ability group, also found it easy to state that as the resistance increases, the current in the circuit decreases.

5.2.6 The Predict-Observe-Explain task

5.2.6.1 The aim of this task

As already explained in section 5.2.2, this POE task was conducted with the aim of probing into students’ mental models of current flow in a circuit.

5.2.6.2 The circuit used and questions asked

The circuit diagram shown in Figure 5.1 was shown to the students, who were also supplied with the necessary apparatus to construct the circuit. The POE technique was then used to probe students' ideas. The students were asked the following questions:

- If you switch S on, what would you notice? Why?
- Will it make a difference to the ammeter reading if the position of the ammeter is changed and it is placed on the other side of the resistance? Why?

5.3.6.3 The results of the POE task

Students' responses have been summarized as shown in Table 5.2. Some comments which were deemed relevant to students' ideas exposed through the interview have also been added, trying to make the picture students were indicating more complete.

Student code	Predicting ammeter reading / (Current model)		Explanation of observation	Comments
	Same/ (Conservation)	Different/ (Attenuation)		
Andi (L)	✓		None	Shows recall of information, with no causal reasoning offered
John (L)	✓ Using resistors	✓ Using bulbs (Attenuation is the model of current when a bulb is used)	Recalls teacher advice for a series circuit	Recalls ideas from secondary school; Problems relating resistances to bulbs
James (L)		✓	No interpretation was possible	
Mari (L)	✓		None	Admits being mixed up
Kyle (A)		✓	Mixing voltage with current	Mixed up ideas
Theri (A)	✓		Convinced in prediction	
Chris (A)	✓		Convinced in prediction	
Mitch (H)	✓		Convinced in prediction	
Robi (H)	✓		Always saw it like this in a series circuit.	No causal reasoning was offered

Table 5.2: Mental models of current indicated by the students

This POE task was meant to check the idea of whether students mentally pictured conservation of current, in a simple circuit. Considering that this sample consisted of students at post-secondary level, one would have expected that they would have a good grasp of the idea. These results agree with previous literature on this topic that some students, even those at post-secondary level, still hold views of current flow which are not scientific (e.g. Borges and Gilbert, 1999; Shepardson and Moje, 1999). After observing the result of the experiment, some students were still not able to offer an explanation. Similar to what usually happens in such circumstances, some students still tried to state some reason for the observation, even if the reason was not a valid one, or one which was hardly making sense in explaining *why* current was being conserved. These students did not show that they could 'see' the circuit as a system. The following extract, taken from one of the transcripts is an example of this.

James (L) had wrongly predicted that changing the position of the ammeter, would give a different reading for current. Upon observing the experimental results:

> J: It stays the same. So it doesn't make a difference. The current remains the same, no?
> I: But you are saying this after we saw the experiment. Why did the result show us this? How do you explain it?
> J: Why did it happen!? Because the resistance is what varies with the voltage, no? Since V = IR, so the more R varies, the more V varies. So if you were to vary V in this circuit, changing the position of a voltmeter, connected instead of the ammeter, then you would see a change in voltage.

Even if the interview was being conducted in an informal manner, it was felt that the student was still being somewhat threatened by the questions being asked. The student was trying to cover up not being able to offer a good explanation with valid reasons. The equation V = IR was being referred to but what was being said did not relate to what was being asked. Simons and Lewis (as cited in Cohen et al., 2001) "indicate that children will tend to say anything rather than nothing at all, thereby limiting the possible reliability of the data" (p. 279). It is felt, however, that the reliability of the data being gathered in <u>this</u> case was not being limited in the way described by Cohen et al. (2001) since it was quite evident to the researcher that what the student was saying was just being said to fill in the gap of time. The situation would have been different if the data were given a wrong interpretation, thus blurring the results, rather than just being understood for what it was - a student who did not have ideas that helped in stating a valid explanation with reasons for what was being observed.

Another observation was that while some students could recall instruction related to current conservation from a few years earlier on, yet they could not mentally visualize why things worked out that way. The words were pronounced and the idea looked scientific, yet the mental model was either not there or just could not be explained. The following extracts are evidence of this.

Andi (L):

> A: It will be the same ammeter reading. All is in series. I cannot see a reason for it, for how to explain it.

[And later…]

A: Maybe I say this because that is what I have been taught.

Likewise, John (L) could only say the following:

J: In Form 3 (secondary class), the teacher had said that connecting the ammeter in whatever position it would give the same reading, as long as it was a series circuit.

The above seems more of a recall situation, rather than one which shows the understanding of a system at work.

The examples quoted above are in stark contrast with the following extract which shows that the student did not only have the ability to state that current was conserved but also to show conviction of the picture being imagined. This fact supports the idea that deeper understanding can take students further in developing their imagination.

In the following quote, Theri (A) was answering to the question of whether there would be a change in the ammeter reading when its position with respect to the resistance was changed.

T: No, I don't think so. It still reads 3.1mA because I don't imagine a big flow of electrons coming to the resistance, then once at the resistance it controls the current! I mean the current is the same all through the circuit.'

In the case of Chris (A), what was being imagined could also be well explained using analogical reasoning.

C: There is one road. Cars are passing. R is a tunnel or a narrower road but the same amount of cars pass through.

It is clear that in these examples, the students could visualize the model they were using, of the same current through the circuit immediately as the switch was closed, and not just recalling information.

Also worth noting is the case where one of the students, namely John (L), was confused in deciding between the ideas of conservation and attenuation because of the difficulty that was encountered in dealing with resistances and bulbs. It seemed that this was one reason, at least, for the lack of possible scientific model appreciation. Heller and Finley (as cited in Grotzer and Sudbury, 2000), found that sequential models in which bulbs 'use up' current were the most common type of model amongst the elementary and middle school teachers whom they studied. This might indicate that the difficulty John (L) found related to bulbs could have possibly been ‘inherited’ from some earlier classroom situation.

5.2.6.4 Overall comments based on the POE task

Students’ answers in this part of the interview were similar to previous answers described in section 5.2.3.2. One important aspect of this POE task, which was also evident through other POE tasks thereafter, was that it could be considered both by the interviewer and by the interviewee as a teaching/learning session. The importance of “regarding the interview as an interchange of views between two (or more) people, on a topic of mutual interest, sees the centrality of human interaction for knowledge production” (Cohen et al., 2001, p.265). The interviewer made use of this important aspect of the POE, especially to promote the motivation for thinking aloud, on the part of the interviewee. The interviewee seemed to be more at ease, once the experience of a tutorial session started to unfold, as opposed to a structured interview with alternating questions and answers.

After having experienced the POE technique, students realized how important it is to reflect on the reasons for why things work the way they do. The reason behind what was happening in the circuit, and why it was happening, was already there for some students but not for others. The latter had the opportunity to realize that there was a gap in their understanding and could thus try to think about their original views further and to resolve any conflicts that might have arisen.

The idea probed by this POE is considered by many a scientist, including science teachers, as a relatively simple one. Having observed the results, the possibility of understanding the current concept increased, with students using scientific ideas when required. Moreover, the unscientific views shown by some students in their predictions, point towards the importance of having students deal with simple experiments of this type earlier in their course of studies, allowing time for ideas to sink in and for mental pictures to develop, in order to reinforce deeper understanding.

5.2.7 Summary of students’ ideas exposed during the 1st interview

When students were asked about *what contributes* to *the formation of current*, the following ideas were indicated, namely:

- current because of movement of electrons in the wires;

- current because of movement of charges initially present in the battery;
- current because of the presence of charges in both the wires and in the battery.

When students were talking about *what makes the charges flow*, they came up with the following ideas, namely:

- movement requiring a push, once the circuit is complete;
- movement without a push, as long as there is a complete path.

Resistance was described in different ways. Some students described it as *an object, using analogical reasoning*:

- a gate or a crowd to control the rate of passing of current;
- a narrow road;
- a blockage.

When referring to the actual *function* of the resistance, one could not help but describe the notion of *a process - a 'doing thing'*:

- Suppressing / opposing the current flow
- Reducing the flow of electrons
- Reduction in the attraction of the electrons to the positive battery terminal – (while the presence of an electric field might be thought to be indicated here, yet students did not mention the field directly and therefore may not have been visualizing it.)
- Friction – a force opposing the flow

With regard to the models of current, it can be said that the main current models detected were:

- Conservation, and
- Attenuation.

Attenuation views were held when students had ideas that mentally pictured charges moving *in sequence* from one component to the next, and when students looked *locally* at a component effect rather than seeing the system.

Finally, focusing on the microscopic views students described, it can be seen that there were differences shown in the way students thought about what makes current. Such thoughts from students seem to be only fairly emphasized in earlier work related to simple circuits. On the other hand, without really wanting to, anyone dealing with electricity and simple circuits inevitably formulates ideas of what is going on in the circuit, as current flows. Such ideas form the basis of understanding of the topic, so they are important to follow and explore. For this purpose, the ideas students exposed through the interview, related to what is happening microscopically, have been put together and summarised in the schematic diagram shown in Figure 5.2, in an attempt to indicate possible thinking pathways students followed while describing ideas about current formation.

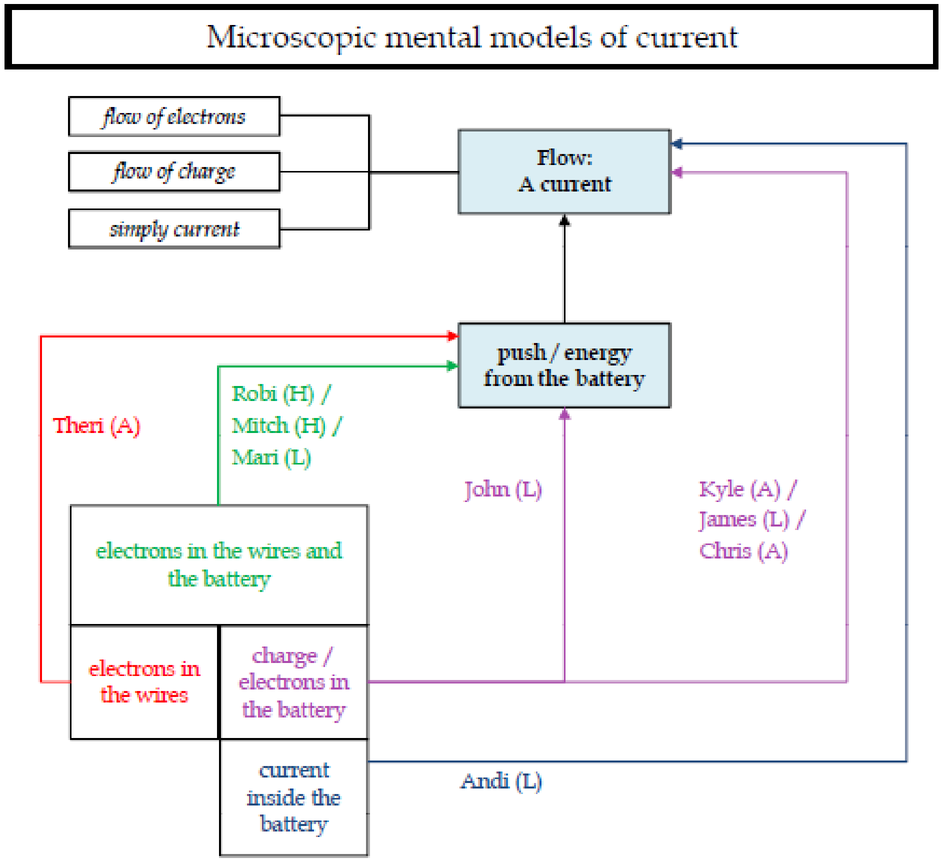


Figure 5.2: Students' ideas of how current forms in a closed circuit

5.3 The 2nd interview – Resistances in series and in parallel

5.3.1 The aims of the 2nd interview

The main aim of this interview was to see what mental picture students could offer of how resistance changes, if at all in their opinion, when two resistors were connected first in series and then in parallel. Is it the number of resistors connected in the circuit which counts, or is it the way in which resistors are connected which must also be considered? Moreover, even if students' prediction was not correct, the idea was to capture students' thoughts as to why the changes observed were happening.

5.3.2 Conducting the 2nd interview

In order to put the students at ease, short similar questions based on models of current, as were asked in the previous interview were prepared to be asked again, at the start of the 2nd interview.

Earlier through the year, the students had attended lectures dealing with how resistors can be connected in series and in parallel. Part of the lecture had dealt with how to compute the total resistance in series and parallel circuits. The students had been instructed in the use of the relevant equations, namely that:

- for resistances in series: R1 + R2 = R total; and
- for resistors in parallel: $^1/_{R1} + {}^1/_{R2} = {}^1/_{R\ total}$, from which the total resistance may then be calculated.

These equations had been derived by dealing with the respective circuits and examining current flow in the circuits, and within circuit branches where applicable, as well as discussing potential differences across resistors. Thus, at the time of the interview, students were *expected* to have been adequately instructed as to how to deal with resistances in series and in parallel and then to make conclusions regarding the current flowing through the respective circuits.

The interview was once again conducted using the POE technique. The students were shown the circuit diagrams shown in Figures 5.3 and 5.4 respectively, and allowed to set up the actual circuits and observe results.

The interview started with a focus on the series circuit. The students were asked whether changing the position of the ammeter connection shown in Figure 5.3 would have an effect on the ammeter reading. This was done so that this interview would be linked to what had been discussed during the last interview, a week earlier.

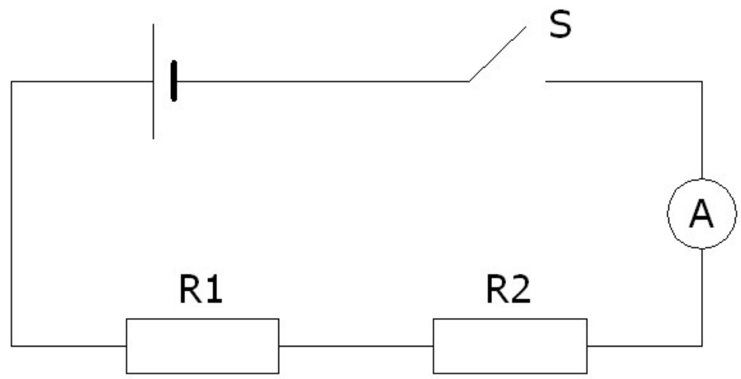


Figure 5.3: Circuit diagram showing resistances connected in series

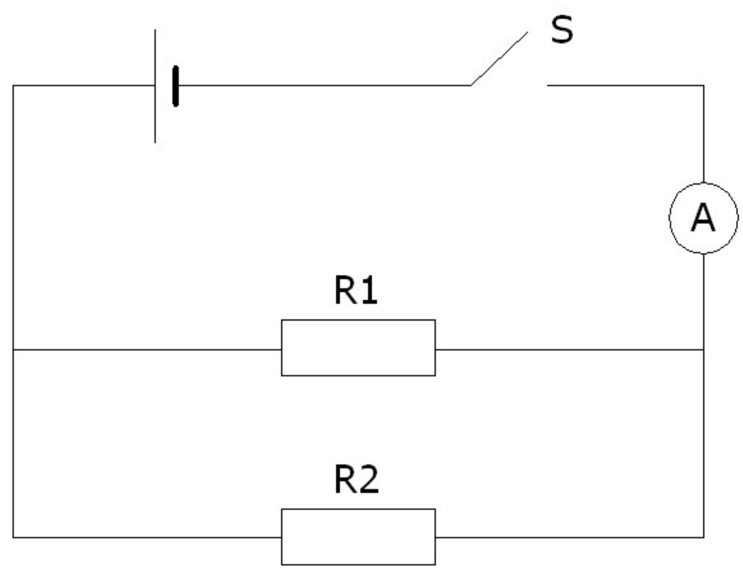


Figure 5.4: Circuit diagram showing resistances connected in parallel

The students were asked the following questions:

- In the circuit shown in Figure 5.3, using two equal resistors, what happens when S is switched on? Why? Would the ammeter reading change if we change its position?
- In the same circuit, if we increase one of the resistors, what happens and why?
- Using the same two equal resistors as in the first part, but now we connect them as shown in Figure 5.4, what happens to the ammeter reading? Does it increase, stay the same or decrease? Why?

After observing the results:

- Can you describe your mental picture for why this is happening?

5.3.3 The results of the 2nd interview

5.3.3.1 Reasoning difficulties with resistances connected in parallel

Students made it evident that after the last interview, a week earlier, they had no problems, now, in understanding current conservation. Moreover, it also seemed easy for students to predict that once one of the resistances connected in series was increased, then, the ammeter reading would be less.

It seems, however, that a problem was mainly encountered when the two resistances were connected in parallel. Students' predictions and the reasons for them, together with alternative reasons provided after observation of the experiment, are shown in Table 5.3. Some comments have also been included.

Student code	Prediction for Ammeter reading: increases decreases stays the same	Reason for prediction	Reasons, if applicable, after observation	Explanation	Comments
Andi (L)	Stays the same	Voltage is additive and the current on the ammeter remains the same	2 separate circuits explain the observation	2 separate circuits; uses the equation to confirm the answer	Sees the '2 paths' model
John (L)	Stays the same	Same in main circuit, less within a branch	After much indecision, finds a way out using equations	None offered	POE conflict and equations helped to change the idea that same Rs means same current
James (L)	Stays the same	The number of resistances are important and not how they are connected	Works backwards to see total R decreases. Also uses equation	None offered	Student still had doubts about the current conservation model
Mari (L)	Stays the same	Same in the main circuit, less within a branch	Suggests that the current is now through one R	Finally discovers the '2 paths' and sees more push on each resistance	Student very motivated to explain observation; sees the '2 paths' model recognising the same p.d. across both resistances
Kyle (A)	Stays the same	Sees same current dividing between the branches	Uses equations to explain	Just describes the observation	
Theri (A)	Less (Admits guessing!) Later says current increases	Uses the equation		Can only use the equation	
Chris (A)	Stays the same. Then quickly changes to current increases	Uses the equation		Sees the '2 paths' model	Refers to road analogy
Mitch (H)	Increases	Uses the equation		Sees the total resistance in parallel. Also sees the '2 paths' model	
Robi (H)	Increases	Resistance is less		Sees the '2 paths' model	Ideas were expressed fluently

Table 5.3: Summary of POE results for students' expectations of changes on the ammeter reading when two resistors previously connected in series are then connected in parallel

5.3.3.2 Predictions with reasons

When the students were asked what happens to the ammeter reading once the same resistances which were previously connected in series were now connected in parallel, there was a distinction between the answers from the students in the 3 categories. Students of low ability invariably said that the reading would remain the same. For these students it was the number of resistors in the circuit which was the issue and not the way in which the resistances were connected.

In prediction, James (L) said:

J: The ammeter reads the total amps in the circuit. As long as the resistances are not changed the ammeter reading stays the same.

We used the apparatus provided and first we connected the equal resistors in series. We noted 0.03A on the ammeter. We then connected the same resistors in parallel. Before we switched the parallel circuit on, the student laughed and said:

J: I so want to see the result!

Upon observing the result, James (L) had the following comments to add:

J: Now the reading is larger. It is 0.14A.
I: So what does it mean?
J: More current. Let me think for a while! So the resistance is less? That is how it turns out.

The student remained unconvinced for a while.

J: You did not vary the resistor. All we changed was the position of the resistors! (From being connected in series to being connected in parallel.)

However he later admitted that, had he not seen the ammeter reading when the changes were made to the circuit, he would not have been convinced that the total resistance is less when the resistors are connected in parallel.

The same idea was also expressed, as a start, by two students from the average group. One of them, Kyle (A), just like the students in the lower ability group, could only focus on the fact that it was the same resistances in the circuit, whereas the other one, Chris (A), immediately realized the mistake, and through numerical calculations saw that the total resistance offered by the two resistances connected in parallel would be less, thus the current would increase. The other average ability student, Theri, playfully guessed an incorrect answer but once urged to think about the situation more seriously, referred to the equations and gave a correct prediction.

The two high ability students, on the other hand, both gave the correct prediction immediately, using mental numerical calculations to check their answer.

The students who had given the right prediction were pleased to observe what they had expected, once the experiment was carried out. The other students were astonished at the result of the experiment. One student, Mari (L), tried to hold on to the erroneous prediction at all costs, providing supporting evidence showing that students hold on strongly to their intuitive ideas (White and Gunstone, 1992). The following extract shows how Mari (L) reacted:

> M: So the current is only passing through one resistor and not through the 2 resistors? I don't think that it is a good reason. I never heard of this though, but it is the only reason I can think of!

Mari (L) was encouraged to try the experiment using one resistance only in the circuit and when the ammeter reading was observed and found to be even different from the two previously observed readings, the conflicting ideas and motivation for learning were so strong that the student continued to search for an answer, until the following conclusion was reached:

> M: But here there are 4V from the source, on each R. That is what we say. Therefore, there is more push on each R. Before (meaning in the series connection) we had a 4 Volt push divided between the 2 resistors in series - 2 Volts on each R. Here we have more push and so this gives a larger current. It is as if (in parallel) you have 4 people, pushing the current through each R. So even if it is the same resistances, then there is a larger push, in parallel.

This student thus realized that the larger the p.d. across each resistance was providing a larger current through the resistance and, consequently, also through the whole circuit. He could model p.d. with the help of analogical reasoning.

The other students who had predicted incorrectly could only give a justification for the observations by numerically working out the value of the total resistance in the parallel circuit using the appropriate equation.

5.3.3.3 A qualitative reason for the observation

The strong point in favour of making this exercise worth undertaking was indicated by that part of the interview where the students were asked for a qualitative reason to explain why the total resistance in parallel would be less, thus allowing for an increase in the ammeter reading. While 2 students categorized as low ability could not offer any ideas at all and one student from the average group could just relate with numbers in providing an explanation, yet the other students, including some from the lower and average categories, managed to visualize an increase in current because of *two* paths which were now made available for the flow of current. The following is how Chris (A) described his reasoning:

> C: When in parallel, the resistance has been divided into two parts. The current can pass from two paths. More current passes now, compared to when the resistors were connected one after the other. If I compare this to roads, then I say that there are two roads of different width. You may pass through any one of them. They are not narrow roads taken one after the other. You have a choice from where to pass.

There were other similar answers. Two separate circuits were referred to by the students and this was a mental picture which students felt was convincing enough to explain the observation of the increase of current when the resistors were connected in parallel. It was an explanation which the students expressed with ease and confidence, once the experimental results were observed and a qualitative reason was asked for. The students were able to offer 'the 2 paths model' in a rather spontaneous fashion once they were led away from the use of numbers, by the interviewer. Millar and Beh (1993) also reported "an overwhelming preference" for their sample of 157 15-year old students, "to use the model/method 1 approach" (see Figure 5.5), in solving the problems asked related to resistances connected in parallel, even when "most students in" their sample were "not able to recall basic facts about voltages in parallel circuits"(p. 360). The model/method 1 approach "results from perceiving the circuit primarily in voltage terms, the most important feature being that both resistors have the same voltage across them" (p. 354). The relative ease with which students tend to look at resistances connected in parallel in terms of mono-circuits, even when their understanding of potential difference may not yet be so clear, points towards 'the 2 paths model' as an important model which can be discussed with students during the instruction of parallel circuits, with the aim of achieving deeper understanding of electric circuits in terms of models.

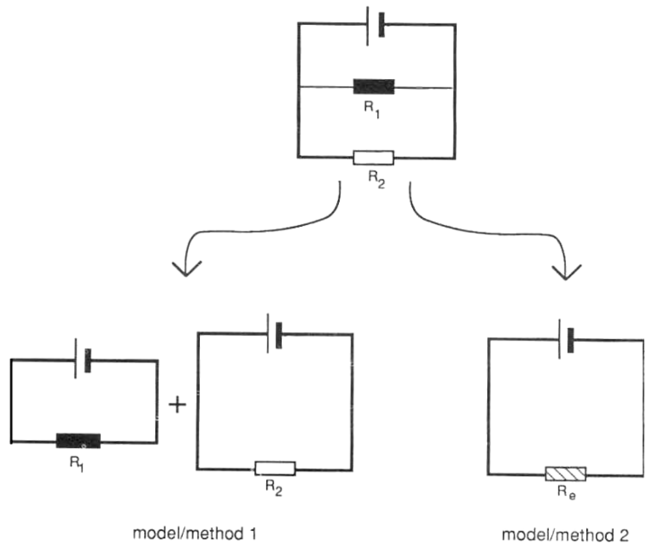


Figure 5.5: Two models of parallel circuits leading to two methods of tackling parallel circuit problems (Millar and Beh, 1993, p. 354)

One other point which is worth mentioning is that unless most students had been urged to discuss and to use the apparatus further to deal with any unscientific models they held, they would not have reached the final correct conclusions. This points towards the importance of having students' motivation increased as they are urged to think further through making use of the apparatus **themselves,** to solve **their** difficulties and test **their** ideas. Just using equations and instructing students in solving numerical problems is not enough for the understanding of key ideas in the subject. Cohen et al. (1983), McDermott and Shaffer (1992), Millar and Beh (1993) and van Aalst (1985) have referred to students resorting to numbers while lacking the ability to explain their answer qualitatively. "Instruction that helps students use scientific evidence to sort out their ideas, resolve contradictions, identify overlaps and gaps in understanding and establish promising connections leads to more enduring and generative views of scientific phenomena" (Casperson and Linn, 2006, p. 317). Students can thus learn the skills to "develop and use criteria to distinguish their predictions from observations, and promote ideas that meet their criteria" (Casperson and Linn, 2006, p. 317). Chiu, Chou, and Liu (2002) specifically claim that conceptual change can be made easier if concepts are explicitly observed from an experiment. Thus, students need to be allowed to use apparatus or to assist to demonstrations which urge them to clearly 'see' the difference, if any, between the mental models used in prediction and those formed through observation. Memory work can thus be reduced and understanding enhanced.

5.3.4 Summary of results dealing with resistance of series and parallel resistors

Students found it easy to see that increasing a resistance connected in a series circuit would reduce the current. Some students could not predict an increase of current when the two resistors were connected in parallel, however, through the POE session they were motivated to find a causal reason for their observation. While some could only resort to numbers to find a solution, some could 'see' 'the 2 paths model' and reason in terms of two mono-circuits, explaining the result.

5.4 The 3rd interview - Part 1: Probing microscopic views

5.4.1 The aim of this exercise

The aim of this interview was to find out whether students' pre-instruction microscopic views of what constitutes current in the circuit had changed since they answered Qn 4 in the Physics Diagnostic Pre-test (see Figure 4.2), and whether these views had now evolved, progressing towards the scientific view. Students' answers to Qn 4 were seen as being of particular importance since much of the understanding about electric circuits depends on the ideas about what happens at a microscopic level. This is what gives the topic its abstract nature and it is also the reason for why the topic is perceived difficult.

5.4.2 Conducting the first part of the interview

Students were shown the answers they had given to Qn 4 during the pre-test, together with the question asked (shown in Figure 4.2), and they were asked to comment on the answers they had given. Each student was given time to talk about why those answers had been chosen in the test. At the same time, without having made it too obvious, the student was being allowed to talk of the mental models of circuit which seemed to have guided the pre-test answers and also to describe how these models might now have changed because of the student's learning experience.

5.4.3 The results for Qn 4 in the pre-test and the interview

5.4.3.1 Comparing students' answers

Table 5.6 shows the results of how each student answered to the parts of Qn 4 in the pre-test, and later during the interview.

The answers have been grouped to indicate pairs of questions which were related. Parts (a) and (d) refer to a model held of free charges residing only in the battery. Parts (b) and (e) probe whether students know that it is the energy which is required to make the circuit components work and not the absorption of the electrons. Parts (c) and (f) refer to charges existing everywhere in the circuit, with the battery being responsible for their movement.

The code used in the tables is as follows:

- T = True ;
- F = False.

The colour code shows how complimentary parts of the question were answered:

- both correct: GREEN;
- only one correct: ORANGE;
- both incorrect: RED.

Parts of Qn 4	a) No charges in wires. Flow is from battery	d) Before connection, charges only in battery	b) Energy from the electrons is given to the components	e) Free electrons are absorbed by bulb	c) All full of charges all the time. Battery moves all charge	f) Before connection, free charges everywhere
Correct answer	F	F	T	F	T	T
Andi(L) (PDT)			✓	✓	✓	
Andi (Interview)			✓	✓ Wrong reason: 'Not *all* the free electrons are absorbed by the bulb'	✓	
John(L) (PDT)	✓		✓	✓		✓
John (Interview)			✓	✓	✓ No reason	
James(L) (PDT)				✓	✓	
James (Interview)		✓	✓	✓ Wrong reason: 'Not the free electrons only are absorbed, but also charges from the battery, no?'		✓
Mari(L) (PDT)			✓	✓		
Mari (Interview)	✓ By 'charges' student had not understood 'electrons'	✓	✓	✓	✓	✓
Kyle(A) (PDT)			✓	✓		
Kyle (Interview)			✓	✓		
Theri(A) (PDT)	✓		✓		✓	
Theri (Interview)	✓	✓	✓	✓	✓ Reason not clear	
Chris (A) (PDT)			✓			
Chris (Interview)			✓	✓		
Mitch(H) (PDT)		✓	✓		✓	✓
(Interview)	✓	✓	✓	✓	✓	✓
Robi(H) (PDT)	✓	✓	✓	✓	✓	✓
Robi (Interview)		✓	✓	✓		✓

Table 5.6: Combining the answers to Qn 4 in the pre-test and the interview
(Note: ✓ = correct; blank box indicates incorrect answer given)

The results in Table 5.6 indicate that there was some improvement shown in students' ideas, since the pre-test (see section 4.4.2). There were now, more *correct complementary pairs* of answers, especially ones related to energy. Some students now seemed more conscious of the fact that electrons or charges are not absorbed by the components. It was rather worrying, however, to see that students like Kyle (A), for example, had not changed their alternative ideas at all. It may seem that such students were not getting all that they were meant to get from their learning experience.

Some students in the low and average ability groups, namely John (L), Andi (L), Kyle (A) and Chris (A), held very strongly to the idea of having charges flowing out of the battery to pass through the wires. This is clear in the results of Table 5.6. A look at Table 5.7, comparing students' views during the 1st and 3rd interviews, also shows that it was these same students who, upon reviewing Qn 4 still held on to this view. To give just one example, the following are John's (L) answers in the interviews:

1st interview:

I: So in the wires, are you seeing electrons?
J: Only the ones coming from the battery……….

3rd interview, reviewing Qn 4:

J: No electrons come from the wire. It is the battery that pushes them.
I: So how do you see the battery?
J: It stores charges in it and as soon as the circuit is connected, it pushes them out.

There was indeed no change in the views held by the student.

The results in this study provide striking evidence that the view of having all the charge stored in the battery, being released when the circuit is on, is very hard to change. On the other hand, for Mari (L) and Theri (A) who had previously indicated they thought about electrons residing in the wires only, it seems to have been easier to now describe charges as residing everywhere in the circuit.

Student Code	1st interview: Pictures electrons in wires	1st interview: Pictures electrons in battery	Upon Reviewing Question 4 in the 3rd interview	Evidence of evolution of ideas?
Andi (L)		✓	Charges reside only within the battery	No Change
John (L)		✓	Charges reside only within the battery	No Change
James (L)	✓ (Electrons present to offer resistance only and not to make current)	✓	Still mixed up between the 'free electrons' and the 'charges'- not clear on whether they refer to the same thing	
Mari (L)	✓		From electrons in the wires only to electrons everywhere	Change to scientific ideas
Kyle (A)		✓	Charges reside only within the battery	No Change
Theri (A)	✓		There are charges within the wires and the battery	Change to scientific ideas
Chris (A)		✓	Charges reside only within the battery	No Change
Mitch (H)	✓	✓	Charges are present everywhere	No Change but was previously correct
Robi (H)	✓ (as a start)	✓ (later on)	Finally agrees with charges being present everywhere but the idea of how the battery functions is still not clear to the student	No Change. Agrees with charges being present everywhere. Was previously correct

Table 5.7: Comparing ideas from the 1st interview to those held upon reviewing Qn 4

5.4.3.2 Problems related to meaning

Analysis of students' talk during the interview made it possible to realize, not surprisingly, that students sometimes give the wrong meanings to some words and/or phrases and thus they build unhelpful mental representations of what happens in the electric circuit.

Chris (A), for example, gave the wrong meaning to the word 'neutral'.

C: Since the wires are neutral, then there are no free charges available within them.

James (L) had shown he was rather confused when it came to dealing with the idea of free electrons and how their presence affects the circuit. He seemed not to be able to link the 'free electrons in the wires' and 'the charges coming from the battery'. The mental representation he seems to use, allowed a distinct separation between the two. The following is an extract from the interview transcript:

J: 'All the time' means even when not connected?
I: Yes.
J: There are charges in the wires. That is true – the free electrons. But I don't think that the question is referring to these…….because *otherwise the bulb would always be on*, even when the circuit is open. I don't agree with what this question says, at all.

Then, after reviewing part (e) of Qn 4:

J: It is not the free electrons only that are absorbed but also the charges from the battery, no?

The problem students have with what some terms mean emphasize the importance of the use of correct wording explained in detail. Unless students understand what a word or a phrase means, students' reasoning will not be valid. The result is then much as Niedderer and Goldberg (1996) described it, namely that student understanding can go in different directions from what was planned by the teacher. Garnett et al. (as cited in Chiu et al., 2002) claim that this is in line with what the "alternative conceptions research has established, that students develop different conceptions from those they are expected to learn, and that these conceptions can influence subsequent learning" (p. 706).

5.4.3.3 Dealing with complex situations

Analysis of the 3rd interview with Mari (L) helped to observe how this student reverted back to his earlier unscientific models of current (electrons forming the current coming only from the wires) whilst reviewing Qn 4a, before he later switched over to the scientific picture of there being free charges everywhere. This provided evidence of how students may start from their intuitive ideas, as they reason things out which appear complex and then, somewhere along the line, they come to terms with the scientific views to which they have already been exposed. Niedderer and Goldberg (1994) refer to a student's "conceptual ecology" (p. 26) to describe a picture of how the thinking processes used by a student evolve in this way, during a learning process in electric circuits. They claim that, "always in new and complex situations the student starts with the prior conception (which they refer to as) 'everyday life current'….." (p. 26) but given time or small hints, the student uses good scientific thinking to move to intermediate conceptions, as learning is in progress. While Niedderer and Goldberg (1996) continue to stress that "in a new context students typically use old cognitive tools – more accessible, confident, reliable, powerful, with more probability to be used" (p. 14), yet it does seem that often, it may be the *perception of the complexity of the task at hand* which makes the larger impact on the student's course of thought, taking the student at an intuitive level, as a starting point. In a study of the dynamics of an individual's cognitive processes Welzel (1998) also claims that "at the beginning of subsequent situations, the complexity of 'ideas' frequently returns to a lower level before regaining previously attained levels" (p. 1110).

5.4.4 Summary of results for Qn 4

These results gave evidence that the model of having all charges residing in the battery alone, is hard to change. Students who initially thought that electrons reside only in the wires, more easily conformed to the scientific view of how a current results. There was also evidence that students may not have understood some words or phrases, which then led to mistaken ideas. Moreover, it was shown how, when students perceive the question at hand as being complex, they sometimes revert to intuitive lower level ideas and use these as a starting point for their thinking.

5.5 The 3rd interview – Part 2: Meanings attributed to voltmeter readings

5.5.1 The aim of the exercise

Students often find difficulty in explaining and distinguishing between potential and potential difference (see sections 4.4.5.2 and 4.4.5.3), apart from also not distinguishing p.d. from current (see section 4.4.5.5). Having students define these terms would not have indicated understanding. It was thought, therefore, that if students could focus on the reading of the voltmeter, saying what this meant to them, probing into models of electrical potential and potential difference could be more effective. In describing an instructional approach to the teaching of electric circuits that emphasizes electrical potential and electric potential difference, Rosenthal and Henderson (2006) also stress that "an important aspect of 'their' teaching of potential difference relations in circuits is an emphasis on voltmeter readings" (p. 326).

This interview also aimed at probing what models students use to account for the fact that the sum of the potential differences across two series resistors is equal to the supply voltage. It was also deemed important to find out whether students believed that the potential difference across resistors in parallel is equal to the supply voltage in an ideal circuit, whether the resistances are equal or not.

5.5.2 Conducting the interview

This interview was once again conducted using the POE technique.

A series circuit with two equal resistors was shown to the student, together with the circuit drawing shown in Figure 5.6. A voltmeter was connected across each resistor. The following questions were asked:

- What do the voltmeters read when the resistors are equal? Why?
- What do the voltmeters read when one of the resistances is increased? Why?

The two resistances were then connected in parallel, as shown in Figure 5.7. A voltmeter was again connected across each resistor. The students were allowed to re-arrange and assemble the apparatus. The following questions were asked:

- What do the voltmeters read when the resistances are equal? Why?
- What do the voltmeters read when one of the resistances is increased? Why?

Since what students see is the reading on the voltmeter, another question which was deemed important to ask was:

- What does the voltmeter reading mean to you? Why?

The idea was that asking a question based on something concrete would enhance the possibility of students talking about their visualization of p.d., rather than just stating a definition of p.d. which may sometimes be meaningless to them.

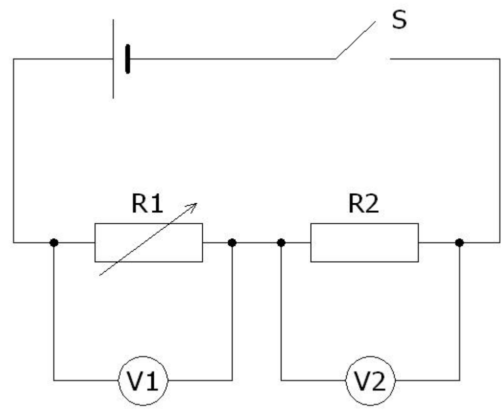


Figure 5.6: Circuit diagram showing voltmeters connected across series resistors

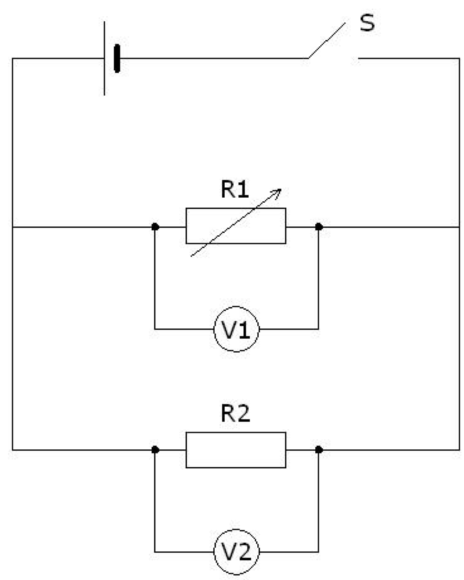


Figure 5.7: Circuit diagram showing voltmeters connected across parallel resistors

5.5.3 Students' answers for the series circuits

Table 5.8 below summarizes students' answers for the case of *resistances connected in series*, both when the resistances were equal and when they were unequal.

Note: V_{supply} =4V	2 *equal* Rs	Reason	After observation	2 *unequal* Rs	Reason	After observation
Andi (L)	Same V	'On the same circuit line'	Correct prediction	Same V but I varies	If R changes, I is affected and not the voltage. If R↑, I↓	First thinks that I is different for the two resistors then realizes that I is the same, so V α R
John (L)	Same V, 2V each	'Because they have to be the same. They are in series'	Says was recalling facts and does not know reason behind it	R↑, V↑	The bigger R has the bigger p.d.	
James (L)	'V is less than supply voltage, for each R'		V is the same since R is the same	R↑, V↑	V= IR, V α R, if I is kept constant. (Student thinks I same as for first part, even when R has changed)	Together they add up to V of supply. (Student shows mixed up ideas related to what is changing whether I and/or V)
Mari (L)	Same V	V is the same since R is the same	Correct prediction	R↑, V↑	All that could be said	Together they add up to V of supply
Kyle (A)	Same V	I same. R same. So V is the same	Correct prediction	R↑, V↑ and the other V decreases	$V_1 + V_2 = V_S$	
Theri (A)	Same V	The Rs are the same	Correct prediction	p.d. different if Rs are different, R↑and V↓		'What has increased in one, decreased in the other. Together they always add up to the same sum'
Chris (A)	Same V	Total is equal to the p.d. of the supply	Correct prediction	R↑, V↑	All that could be said	Together they add up to V_S
Mitch (H)	Same V; half Vs	$V_1 + V_2 = V_S$	Correct prediction	p.d. will be split up but the addition of V_1 and V_2 will be equal to Vs	$V_1+V_2=V_S$	
Robi (H)	Same V	'R the same. I is the same in a series circuit'	Correct prediction.	R↑, V↑ 'The sum remains the same'	$V_1+V_2=V_S$ It is the same source	Correct prediction

Table 5.8: Resistances connected in series: What do the voltmeters across the resistors read?

These results show that most students applied the rule:

$$V_1 + V_2 = V_{supply},$$

whether the resistances were *equal or unequal.* Moreover, even if the predictions were often correct, it was the reasons for them which students had problems with, implying that the rule was recalled and the probability was that students did not have a model of p.d. in mind. This goes to confirm that students answering correctly do not necessarily do so for the right reason, thus supporting the idea of having asked two-tier questions in the diagnostic tests, to probe students' understanding.

5.5.4 Students' answers for the parallel circuits

Students' answers for the case of resistances connected in parallel were analyzed in a similar manner. Results have been summarized in Table 5.9. Students predicted the same p.d. across two *equal parallel* resistances, but valid reasons were scarce. Equality of the voltmeter readings did not always imply p.d. values equal to V_{supply}. It seemed that the fact that the resistances were equal immediately prompted the necessity of having equal voltmeter readings. This could be seen as a kind of phenomenological primitive or p-prim (diSessa, 1988, 1993), or an aspect of 'common reasoning' whereby if two entities are the same, anything linked with them should also be the same.

When students referred to the current splitting up between the branches, no-one mentioned whether they saw the current in the main circuit was changing as well. Typical answers which the students gave were:

Kyle (A): The current splits. R is the same.
Chris (A): The same voltage because the resistances are equal.

Student	Equal Rs	Reason	After observation	Unequal Rs	Reason	After observation
Andi (L)	Same V	Battery V divided by 2		Same V. Later said: R↑, V↑	I↓, V↑	Says best to deal with the resistances separately
John (L)	Same V = Vs	I divides into 2, same R	V changes	Currents through the Rs are not equal. V readings are different	No reason given	'Because the current does not affect the voltage' After being urged to think further says: 'The voltage between any 2 points in the circuit will still remain the same. It is the voltage across the battery'
James (L)	V same as long as Rs are the same	I subdivides. R same. V=IR gives the same V	Both same as V_s. It did not divide like the case when in series	R↑, V↑ but Total = Vsupply (Seems to talk in the same way as for series circuits)	'Same way as usual: V=IR and so V↑ for sure. $V_s = V_1+V_2$ Attenuation ideas are expressed	Just cannot see why the voltmeter readings remain the same!
Mari (L)	Same V	The resistances are identical. 'In parallel, the current divides but the voltage, no!'		R↓, V↑	'Because some p.d. must be used up through the resistor and the smaller R, the smaller number of volts are used up'	
Kyle (A)	Same V	Same R and same I. Same V of battery. Doubts for a while whether both same as Vs, or Vs divided by 2	'I was right! Same R and same I for each'	Same V for both. Keep the same reading	R↑, I↓ and V remains the same (V=IR). If R same, I the same through that branch	
Theri (A)	Same V	Same resistances		R↑, V↑	No reason can be supplied	'I'm blanked out!'
Chris (A)	Same V	Same resistances		V changes for the R which is changed	If R changes, V should change	Resolves the problem using numbers
Mitch (H)	Same V	Told this in Form 3. 2 loops seen. V across the battery		V_{total} across battery↑ when R↑	V=IR and I leaving battery kept same , V↑ when R↑	R only affected the current. More R, more opposition. Could not explain why same V resulted
Robi (H) ready	Same when in parallel.	Same Rs and I splits exactly into 2, so same V	Same V, but mixed up on currents on further questioning. Then goes for 'same V' again	1) R↑, I↓, so V is the same. 2) For R constant, I↑ and V↑	1) R↑, I↓ 2) A larger I flows and R is the same , so V↑	Now sees the system, with I in the main circuit changing. R same has the same I. V = Vs

Table 5.9: Equal and unequal resistances connected in parallel: What do the voltmeters connected across the resistors read?

Once the resistances were made unequal, the difficulty was immediately increased, with the majority of the students now saying that the value of the p.d. across the parallel branches would **not** remain the same. Similar ideas were shown by Cohort 1 on this question in the pre-test (see 4.4.5.4). It became more complicated for students to give a reason for their prediction. Theri (A) just answered: 'I'm blank'. The question put even the high ability students in difficulty. The following is part of Robi's (H) interview transcript, showing this difficulty.

I: Now if we were to increase one resistance, what would happen to the voltmeter readings?
R: The readings would remain the same, for then the resistance increases and the current decreases and the voltage remains the same.
I: The same for the resistance which is constant, or the same for both? What about the resistance which has not been changed?

[The student takes a long time to answer.]

R: It will increase.
I: Why?
R: A larger current will flow and the resistance is the same, therefore the voltage increases.

[The student observes the results.]

R: They are reading the same! Ha!
I: And why is this, do you think?
R: Because then, even the current in the main part of the circuit, changes, because of the total resistance for the circuit.

[The student smacks himself jokingly.]

I: And so…?
R: The current coming out of the battery changes. I think it increases…. I'm calculating! So it decreases from the battery? What a mix up!

[The student goes to the circuit diagram and takes a long time thinking of what is going on.]

I: Any results?
R: The current from the battery decreases.
I: I asked you about the voltmeter readings. We saw that they remain the same. I'm asking you why this happens.
R: For the increased resistance, the current decreases. Therefore, V=IR, therefore V remains the same. For the resistance which was kept the same, while the overall current decreases, this resistance takes the same current as before, and V remains the same, since R is the same and I is the same.

The student thinks primarily in terms of current, focusing on an increase of R which decreases the current, but does not immediately consider that the current in the main circuit changes. Moreover, when the change of current was finally considered, a wrong decision was made, which negatively influenced ideas which came later.

Another interesting transcript to examine is from John's interview. John (L) also had mixed up ideas regarding the p.d. across unequal resistances connected directly to a power supply. The student was urged to think further so as to clarify his ideas.

I: What happens if we increase one of the resistances?
J: Let me do some calculations. I think that they will change.
I: Why?
J: There will be more current passing through one of them and not through the other. One will have less current and the other will have more.
I: So what about the voltmeter readings?
J: They won't be the same.

John's prediction just considered current. When John (L) changed one resistance, making it larger, and observed the results, these were not what he expected. The student seemed mixed up. I tried to motivate him to continue by repeating what he had told me, and suggest that the student looks again at the circuit and the circuit diagram.

I: Which of these do you find more helpful?
J: The circuit gives me certain answers. You know what is happening through the use of the circuit. The circuit is better.

[Later, looking at the voltmeter readings…..]

J: The voltage has not changed, I mean. Because here, in the circuit, you have the voltmeter which is giving a reading because it is connected across a resistor. It is connected between 2 points.
I: What, between 2 points?
J: The voltage between 2 points in the circuit will still remain the same. If it were 4 volts before, it is 4 volts now, for both.
I: Sure?
J: Yes, I think so.
I: So how do you explain the part about the current – that the current through one resistance was larger than the current through the other…?
J: The current was different, but the resistances are not the same. When the resistance was increased, the current decreased and at the end of it, this is not affecting the *voltage coming out at the other end*. This is in the sense that the voltmeter reads the voltage between these 2 points, which is the same as for the battery.
I: Are you sure of this?
J: Yes.

Even if the student described voltage as if it were current, referring to it as 'coming out at the other end', yet some difference between 2 points was being 'seen'. There was quite an improvement made on John's part. While this can be partly attributed to the fact that the researcher had motivated John (L) to think further and not give up, yet the power of teaching and learning using POE tasks cannot be ignored. While not all students seemed to have benefitted in the same way, yet it can confidently be said that POEs **can** help students' understanding. John (L) had shown an initial low level of performance at the start of the course. Now, given more time to think and using experimental results to support his thinking, John (L) was able to resolve uncertainties in his reasoning. Perhaps, the more students get used to the POE technique as a tool to promote understanding, the more students can get used to thinking at a deeper level, in order to come up with valid reasons backing up their ideas.

5.5.5 Mental models of voltage

The previous sections indicate that problems were being encountered by **all** interviewees, when it came to explaining predictions and observations of voltmeter readings, especially in the case of parallel circuits. In an effort to try and look further into the nature of these problems, the students were urged to talk about their mental picture of 'voltage' and 'potential difference'. The problems that had surfaced earlier were even stronger when students were asked to talk and describe what the *reading on the voltmeters meant* <u>to them</u>. Some of the students were not able to say much, if anything at all, regarding this quantity.

Theri (A) answered as follows:

T: The voltage across R.
I: What does this 'voltage' mean?
T: Hmmm! [Laughing!] I don't know!

Some students had images of 'voltage' in terms of the 'strength of the battery' (Kyle (A), John (L)) and 'the strength of the circuit' (Kyle (A)).

Chris (A) referred to 'the strength of the current', thus:

C: Voltage as the strength of the current - how that strength varies across the terminals. The current enters with some strength and leaves with a weaker strength.

[And later…]:

I: So what is this potential difference causing exactly? Is it causing anything in the circuit?
C: If you have a motor, say with 4V, it goes faster than when it is at 2V. So it's the strength of the current. It goes faster.
I: The strength of the current? What is the current doing? Are you saying the strength of the current going faster?
C: If you increase the voltage, the strength of the current is increasing and the result is, say in a motor, that it goes faster. Or a bulb will light up more brightly, if it does not burn out.

A description like the one above is not much of an extension of the basic causal model of agent-effect, indicating that linear causal reasoning is being applied at the initial stages in understanding. Chris (A) seems to link V very closely to a property of the battery. At the same time, the idea of V was not transferred to account for the voltmeter reading across a passive component.

While by this stage, some of the students had shown that they knew that a difference between current and voltage exists, they still had a problem differentiating between the two physical quantities, as was shown by a later exercise.

Kyle (A) is one example of a student who specifically referred to this difference, even if he stated that it was difficult to explain voltage.

I: What is <u>your</u> mental picture of voltage?
K: I don't know how I am going to explain it. *I don't want to mix it up with current.* As such I think it is the output of the energy of the battery.

James (L) also 'saw' the difference between current and voltage, as follows:

J: Voltage as the 'speed of the charges', you know.

[Later on…],

J: The current is the amount of electrons in the circuit. So they are not the same.

It was the high ability students who could imagine the flow of electrons as a result of the *forces of attraction* between the battery terminals. Robi (H) spoke of this attraction in the following way:

R: There will be different charges across the terminals of the battery and electrons *are attracted* to the positive terminal, and move. Others take their place. There will be something like a flow.

The other student, Mitch (H), makes a similar reference to the attractive force:

I: What does this voltmeter reading really mean to you?
M: That the potential difference in the circuit is 4.15 V.
I: What does the potential difference really mean to you?
M: *The attraction* between the positive and negative side of the battery.
I: Can you explain a bit more on this?
M: Cause there is a positive charge on the positive side of the battery and this attracts negatively charged electrons on the negative side of the battery.
I: That is how you see potential difference, then.
M: Ehe! Yes.
I: So you say that something is attracting. And if they are attracted, what happens?
M: Electrons flow through the circuit.
I: So the electron flow happens because of this attraction.
M: I think so.

Later on, the same student describes the reading on the voltmeter as a 'voltage' and as an indication of the charge passing through the resistor. Voltage and potential difference are often used interchangeably. An interesting part emerged, through further probing of ideas, when the student said that without a potential difference there would be no current.

I: What causes what?
M: *Both affect each other*. But I think that the potential difference, since it is positive and negative, and I see it as an attraction from positive to negative, it means that current, depends on that.

The student indicates his view that potential difference can be both "a cause and an effect" (Grotzer and Sudbury, 2000, p. 25), and at the same time gives evidence that he sees V as the independent variable and I as the dependent one. This puts the model of potential difference which Mitch (H) seems to hold, at a high level compared with the models which were described by other students through these interviews.

It is important to note also, that when forces and speeds were being mentioned, the underlying implication was that energy was, in some way, being provided. John (L) and Kyle (A) actually mentioned the word 'energy', during the interview. John (L) said that 'voltage generates energy', and Kyle (A) referred to the 'energy of the battery'.

On the other hand, Theri (A), who admits having done some revision after the last interview, regarding the meaning of voltage, tried to recall a definition, thus:

T: It is the electrical energy transferred to other forms of energy per Coulomb….. something like that…. in one second.
I: And you understand it?
T: Yes. It made sense.

In the case of 'voltage', putting the mental picture into words may not have proved to be an easy task. This was more so, when true understanding of 'voltage' had not been achieved, because in such cases, there was no mental image to enlighten the explanation. In such cases, therefore, a great difficulty was being encountered. The definitions for potential difference, potential and voltage and the volt which students had been exposed to, earlier in the course and in courses at secondary level, seemed to be helping students too little, if at all, in building a good mental model of voltage and potential difference.

5.5.6 Summary about how students imagine voltage

Similarly to what has been reported in other studies (e.g., Duit and von Rhoneck, 1998) voltage was mainly looked at as 'strength of the current/circuit' (Chris (A), Kyle (A), John (L)). One student referred to the 'speed of the electrons' (James (L)). Only the high ability students mentioned the force of attraction which exists on the electrons, acting towards the positive terminal of the battery (Mitch (H), Robi (H)). This indicated that the high ability students were approaching the idea of recognizing the existence of a force field between the battery terminals, but had not yet reached the highest level of understanding of electric circuits, in terms of what Borges and Gilbert (1999) refer to as "electricity as a field phenomenon" (p. 107).

5.6 The 4th interview – Differentiating between current and voltage

5.6.1 Aim of the interview

The aim of this interview was to see whether students now distinguished voltage from current. This interview was being conducted close to the end of the course in current electricity and it was expected that students would know that the ammeter is a device to measure current and that the voltmeter is a device which is used to measure potential difference. It was also quite expected that it would be common knowledge for students, that ammeters are connected in series and voltmeters are connected in parallel with resistors, so that current and potential differences, respectively, can be measured. These were issues which students had dealt with at secondary level, when these *facts and rules* are repeated many times. In fact, it can be confidently said that students easily recalled this information during the interviews, when the situation necessitated it.

Problems were met with, however, when students came to the point where recall of information alone was no longer enough. There are situations when students need to use the necessary cognitive skills to provide reasons which give evidence of deeper understanding. Such is the situation when students are required to differentiate between current and voltage, as was planned with this POE task. The POE task was based on Qn 17 in the PDT (Figure 4.17) where it was necessary to appreciate that:

- the flow of current requires a complete circuit;
- the p.d. across the terminals of an *ideal* battery is constant, whether the cell is in a complete circuit or not;
- a p.d. exists across a resistance when there is a current flowing through it but a difference in potential between two points does not always mean there is a current between them.

Students risked having problems, both in predicting the voltmeter readings and in explaining the observed results, unless they were conversant with the above ideas.

5.6.2 Conducting the interview

The circuit diagram shown in Figure 5.8 and the actual set up, were shown to the student.

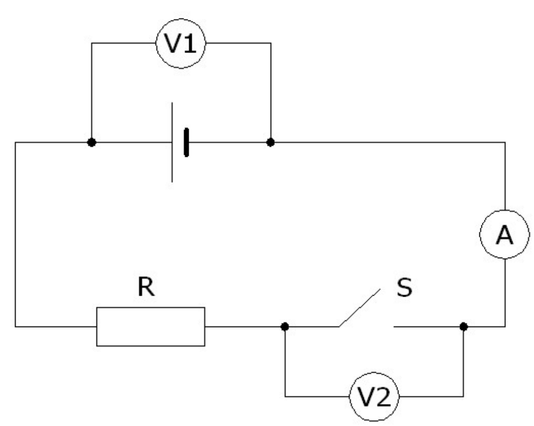


Figure 5.8: Circuit diagram showing voltmeters connected across the battery and the switch

The student was asked the following questions:

- Comment on what happens to the readings on voltmeters V1, V2 and the ammeter A, when S is switched ON? Give reasons for your answers.
- With S switched OFF, what can you say about the readings on V1, V2 and the ammeter A? Give reasons for your answers.

5.6.3 The results of the interview

5.6.3.1 The main problems

The interviews have shown that it was mainly the readings of V2 across the switch which confused students. One student, Mari (L) commented:

M: Never did I see a voltmeter across a switch!

So the situation was *new,* to that student at least, and was definitely one where students had to think deeply to clearly visualize what was happening in the circuit, possibly explaining their model in a scientific way.

Table 5.10 shows how the majority of students gave wrong predictions of what V2 would read, both when S was closed and, especially, when S was open.

Qn17 Name of student	S closed			S open		
Correct answers	Ammeter shows a reading	V1 shows a reading	V2 shows no reading	Ammeter shows no reading	V1 shows a reading	V2 shows a reading
Andi (L)	✓	✓		✓	✓	
John (L)	✓	✓		✓	✓	
James (L)	✓	✓		✓	✓	
Mari (L)	✓	✓	✓	✓	✓	
Kyle (A)	✓	✓		Sees complete circuit through V2 connection (non-ideal situation)	✓	✓(wrong reason) 'Because it passes through it and not through the switch'
Theri (A)	✓	✓	✓	✓	Sees open circuit, so no reading	There is no R at S (This answer looks at p.d. as the dependent variable)
Chris (A)	✓	✓	✓	✓	✓	✓ ('Reads the e.m.f. of the battery. Now a resistance has been created (across S)'- This answer does not convincingly distinguish between I and V)
Mitch (H)	✓	✓		✓		
Robi (H)	✓	✓	✓ (Small r at S is mentioned)	I through V2 (Situation not ideal)	✓ (Student still rather unsure of the answer)	

Table 5.10: Predictions of meter readings in the circuit of Figure 5.9, when the switch is open and closed

Since problems were being faced by students when dealing with the reading on V2, it was thought appropriate to look more closely into students' predictions and reasons offered after observation for the answers related to V2. It was important to find out why students were going wrong, trying to get to the roots of the problem.

5.6.3.2 The reading of V2 when S was closed

When S was closed, there were some students who realized that since the switch offers no resistance, then, even if a current is flowing, V2 would read zero. The following are extracts from some transcripts which indicate this, in prediction.

Mari (L): I don't think that it (V2) will give a reading. There is no difference. It is not connected to a resistor. [The student also stated that this was just recalling what was read off a text book the day before.]
Chris (A): Zero p.d. across a wire with no resistance.
Theri (A): No reading, because before and after (the switch), the voltage [meaning potential] is the same.

Looking at the answers from the other students, these were invariably showing that they could not distinguish properly between current and voltage.

Andi (L) was one example. He did not only wrongly predict that V2 should show a reading when the circuit was complete, but after observation, even the idea that charge flows through a complete circuit was contradicted in an effort to find a reason for why the reading on V2, which he had expected, was not there. For this student, the picture was that voltage was only a consequence/property of current, agreeing with Maichle's (1981) proposition that "voltage is very often conceived as part, as quality or property of the current or even as identical with the current" (p. 176). These were, indeed, similar ideas to those presented in section 5.5.4. The following transcript gives evidence of the equivalence of current and p.d. in the student's mind. After the student observed the result of the experiment, he then connected the voltmeter across the resistance which was already in the circuit, trying to make sense of the situation.

(Switch ON):

A: Through the switch, I see no charges passing, otherwise the voltmeter would give a reading, no? I see that at the same time it doesn't make much sense, but some charge must pass through it somehow.

In the case of James (L), the observation, after the switch was switched on, was not enough to instil a valid reason for why V2 was not showing a reading. The student did not show understanding of the concepts involved.

[After observation…..]

J: The voltmeters do not read the same because of the resistance?!
I: Why do you say so?

J: Because the resistance is stopping the speed of the electrons which are passing through the circuit…..That is voltage.'
I: And this way, it makes sense to you?
J: Yes.

On the other hand, in the case of Mitch (H) who also gave a wrong prediction that V2 would give a reading when the circuit is complete, the observation triggered a quick response to correct the error.

[After observation…..]

M: There is no difference between the charge or energy of the electron passing from one side to the other of the switch. [This is interpreted as meaning that the student wanted to say that the potential was the same on both sides of S.]

5.6.3.3 The reading of V2 when S was open

It was this part of the POE task which gave concrete evidence for the fact that students, even those who were categorized as able students, still found difficulty in differentiating between current and p.d. at this late stage in the course. Indeed, all the interviewees wrongly predicted zero reading on V2, when S was open. This poor performance was also observed on this question in all PDTs by Cohort 1 (see Chapter 4).

Even though students had completed a course in current electricity, they could not provide a scientific mental model of potential difference. Instead, they indicated that they could not yet separate p.d. from its current counterpart. Students' answers showed what Tiberghien (1983) reported, that "actually, for students, when current is circulating, voltage must exist, and when the current is interrupted, there cannot be any voltage" (p. 9).

Interestingly enough, in the previous interview, both Mitch (H) and Robi (H) had described potential difference as the *attraction* that exists between the negative charges and positive side of the battery. But, these students still did not 'see' a force field and thus could not provide valid reasons for why voltmeter V2 gave a reading when S was open. It was hard to see p.d. without a current.

Robi (H), *before* observation:

R: V2 reads nothing, since no current flows through the switch.

After observation, the student seemed to be in a dilemma.

R: V2 now seems to be connected in series, no, miss?....That is how it is – connected in series! What I am saying is that it cannot be that there is no current! Strictly speaking there is a closed circuit.

[And later…]

R: I am not understanding why this is happening.

Mitch (H), *before* observation:

M: Zero
I: Reason?
M: No energy transfer passing through the circuit.

In correction, *after* observation:

M: Wrong reason. No kinetic energy, but the free electrons will still be moving around in the wire.

The other students also seemed to hold the same view. The following are some examples.

James (L), *before* observation:

J: V2 will not read anything. If no electrons are passing, as I imagine it, the voltmeter will not give a reading.

After observation:

J: I just don't know what is happening!

In the case of Andi (L), what was *being observed* was baffling and unexpected for the student.

A: No reading, since it did not even read when S was closed. How is it that the circuit is OFF and V2 gives a reading, now?!'

Kyle (A) *before* observation, S open:

K: V2 is across S, the current passes like when there is an ammeter. It now passes through the voltmeter and keeps going. V2 gives a reading and the ammeter also. With S open, we still have a system and when S is ON, current passes through the shorter path.

Then, *after* observation:

K: The ammeter is not giving a reading! [The student is confused.] So since V2 gave a reading, there must be a current through V2.

This was a very explicit association of a voltmeter reading with a current.

Later Kyle said:

K: There is a value which is zero, since V = IR and I don't know whether it is V or R.
I: Where?
K: Across the ammeter.

The student was concerned because while in his mind he 'saw' a current through the voltmeter, yet, the instrument which is known to indicate current – the ammeter – was reading zero.

Difficulties like the ones indicated above, specifically based on the relation between current and p.d., seem deeply rooted. Only about half the interviewees could, after observation, recognize that V2 was connected to the terminals of the battery. These interviewees were mainly from the low and average ability groups. Even then, some still had doubts to why V2 gave zero reading with S switched ON, while giving a reading when S was switched OFF.

5.6.4 Summary of the findings from the 4th interview

During the 3rd interview, Mitch (H) and Robi (H) had demonstrated they understood what constitutes potential difference, in terms of the forces of attraction experienced by moving charges. The results of the 4th interview and related POE task have shown that the same students now gave proof that they were not in *complete* possession of a scientific model of p.d. in terms of some difference between points. The students of lower ability were not able to completely separate the concept of potential difference or voltage from that of current. For them, p.d. was still seen as an entity which was dependent on current, in most or all situations.

The outcome of this interview puts a stronger accent on the problem being encountered, when one considers that the students had just covered a course of study on electric circuits and had therefore had time to discuss, in class at least, issues related to potential and potential difference, both through qualitative and numerical approaches. This was pointing towards changes that needed to be considered in the teaching of Cohort 2, to try and help students in this line.

It is also important to note that after observing V1 and V2 both giving the same reading when S was opened (see Figure 5.8), some students from the low and average ability groups were then in a position to see that a valid explanation was that V2 was connected in parallel with the battery terminals, even if doubts in some ideas were still detected. This is again another strong point in favour of the use of POE tasks as teaching/learning tools.

5.7 Overall summary and conclusion

The semi-structured interviews described above were undertaken to try and look more deeply into students' mental models of electric circuits. Students of different ability were chosen to be interviewed with the aim of having students indicate the various ideas they may develop during the teaching. A global picture was expected to emerge, starting from students' intuitive ideas inferred at the start of the course, and possibly showing how these ideas evolve as students develop mental models which are at par with scientific views. Thus, by looking at the work done with **all** the students, it was possible to start forming a general picture of learning pathways which students' ideas seemed to follow. A diagram showing students' visualizations of what makes current has already been presented in Figure 5.2. Further reflections and conclusions about the mental models inferred as students' ideas were probed during the learning of the concepts involved are elaborated upon in Chapter 7, after the results with Cohort 2 are discussed in Chapter 6.

It must be acknowledged at the onset that the global picture indicating the mental models of circuit which emerged as a result of the interview analysis was primarily influenced by the questions which were asked through the interviews, the order in which they were asked, and also the ideas from previous work which had been reported on the topic and which permeated the work done with the students through the interviews.

At the start, when students talked of current flow, it was a sequential description that they gave. This may have been a reproduction of how some teachers describe currents in circuits, in class time. Shipstone (2002,) claims that "perhaps we unwittingly reinforce the sequence model as we talk to children" (p. 234). The author explains how, in referring to the circuit diagram shown in Figure 5.9, a teacher might say: "The current flows out of the positive terminal of the battery here, passes through the lamp L_1, then splits up at the junction with some going to lamp L_2 and the rest to the variable R…." (p. 234). A sequence of events is thus being described, and students easily give such descriptions unintended meaning.

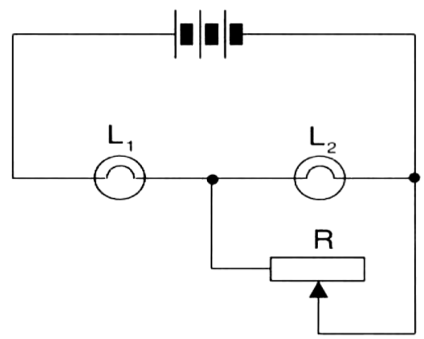


Figure 5.9: Circuit drawing (Shipstone, 2002, p. 231)

A number of students in the study conducted by Grotzer and Sudbury (2000) had also said that "simultaneous cyclic causality is difficult to talk about without resorting to a sequential explanation" (p. 24). These students had said that "they could picture it but that they found it hard to explain" (p. 24). The same thing happened with the students in this study. It may be argued that perhaps this problem is difficult to deal with, but teachers can certainly be more careful during teaching, avoiding sequential descriptions while emphasizing a system view of the electric circuit.

These interviews also pointed to some students' confusion with the microscopic ideas held of current. The impression conveyed by the interview work was that students are often left to discover, or better, to try and imagine what might be happening, without much guidance from the teacher. There were instances when students said: 'The teacher told me that, in Form 3', but none of this was said related to the microscopic views of what goes on in an electric circuit. How a battery works and how it is constructed is no longer discussed with students at secondary school level and teaching seems to highlight the macroscopic rather than the microscopic. It seems that this lack of detail causes problems with students' understanding, and can be unhelpful when students come to model the circuit as a system.

Looking at the answers to Qn 4 from the Physics Diagnostic Test (PDT) shows how few students changed their views from before the start of the course, to the review of the question some weeks later. Those students, in the 1st interview, who saw the battery as carrying all the charge inside it, allowing it to move along the wires when the circuit is complete, held strongly to this view even on the 3rd interview. It seems that unless direct reference is made to microscopic ideas in order to clarify them, one cannot easily build concrete, solid and scientific models of current.

With regard to resistors, a substantial number of the group of students believed that the total resistance in the circuit simply *depended on the number* of resistors *and not on how they were connected.* Moreover, when the fact that resistances in parallel have a reduced total resistance was emphasized using the POE technique, some students found it an almost natural explanation to talk about the *2 paths* now available for current flow. This indicates that teaching parallel circuits as a number of mono-circuits might make students' understanding of parallel circuits easier.

The use of the POE technique helped some students to grasp the ideas of why circuits worked the way they did. This pointed towards the importance of having students deal with simple experiments while being asked for predictions and reasons of what is expected to happen, allowing time for ideas to sink in and for mental pictures to develop, reinforcing deeper understanding. The POE tasks also helped to motivate students to search for a valid reason for why things may not have resulted as predicted. The idea of using these tasks in teaching, helping students to distinguish between their intuitive ideas and the scientific ones, can be an effective way of tutoring students. Students in this study started with their intuitive ideas and were given the space to work on these ideas, clarify their views and develop their mental pictures. Moreover, students' misconceptions were being addressed, there and then. This is an important aspect of teaching and learning. It is evident that making students just recall the facts is not enough to motivate them to learn and understand. Students may be externally motivated to recall facts, relying on memory work even if they find that the material has not been understood. Students may find that they still pass exams this way, but once the exam is over, all is easily forgotten. Rosenthal and Henderson (2006) likewise stress that "as usual, only telling students has limited effect; they (the students) must struggle with…. problems on their own or in small groups" (p. 324). True educators should look for ways which make learning last.

Looking globally at the interview work, it can be said that most students started with quite a number of misconceptions. Some problems seemed easily resolved, like for example, the idea of current conservation. It was the difficulty students found when dealing with potential difference that was quite pronounced. This was not unexpected since previous studies have emphasized this difficulty (see Gunstone et al., 2001; Jung, 1985a, 1985b; Liégeois et al., 2003). Potential and potential difference are difficult to describe and to imagine, not just by students but sometimes also by practitioners. The idea of potential difference in terms of forces of attraction and repulsion which cause the charges to move was described by the students of high ability. Students of lower ability did not refer to these charges and forces. The idea of the electric field between the battery terminals seems one which is ignored by students. Perhaps, not many teachers refer to it, at the same time as very few books look into and explain this detail. Students therefore, even the intrinsically motivated ones, have limited access to information about this fact which some authors, amongst them Haertel (2008a), claim is useful for the understanding of p.d.

Furthermore, the problem students had of being unable to separate potential difference from current, was also evident. Shipstone (1984, 2002) refers to this difficulty, citing the works of Maichle (1981) and von Rhöneck (1981) which also highlight this issue. The POE task which was used to probe this difference, acted as a strong indicator of this major difficulty. This task used in 'Interview 4', using the circuit diagram shown in Figure 5.8, can be used as a possible tool in the teaching of this differentiation between the two physical quantities. Students need to realise that current and potential difference differ, and that potential difference **can** exist without current. Moreover, the relationship between potential difference and current should also be discussed with students enphasising causes and their effects. The aim is to have students reach a stage proving that "the understanding is *in* performance, and not simply evidenced by it" (Millar & Beh, 1993, p. 360).

In addition, the fact that both high ability students interviewed fell short of explaining why a voltmeter such as V2 in Figure 5.8 gives a reading which is not zero when the switch is open, can be taken as a pointer towards the fact that the existence of potential difference without the presence of a current may be a *hierarchically* more difficult idea to grasp than the idea of p.d. when a current flows. This work gave evidence that students can be visualizing the attraction of electrons to the positive terminal of the battery, but need not be 'seeing' the force field between the battery terminals at the same time. Even if students described the forces of attraction between differently charged entities – a predisposition students have of thinking about mechanistic effects, making understanding easier for them (White, 1993) – it was not enough to say that they had a complete understanding of potential difference. For this understanding of p.d. to be complete, this study shows that two models must be clear to the students, namely:

- the model whereby students understand that the *forces of attraction and repulsion* exist on the moving charges when the *current is flowing* i.e. when the circuit is complete;
- the model whereby students understand further that the cause of the force of attraction is the presence of the *force field*, which exists even *when the current is not flowing* i.e. when the circuit is open.

These are two models of potential difference. One model relates to *the mechanistic view* of having *forces of attraction* between the moving negative charges and the positive battery terminal. The other *causal* model relates to the *force field* which exists between the battery terminals, even in open circuit – a model which is being shown by this study as being at a higher conceptual level than the first, since even the higher ability students found it more difficult to relate with.

All that has been said above, points towards implications for teaching which result from this work and which can be summarized thus:

- teachers need to be careful in their explanations to avoid sequential descriptions of current flow;
- teachers may find that the '2 paths model' may make it easier for students to understand parallel circuits;
- using POE tasks may help students to improve their reasoning abilities;
- helping students distinguish between current and p.d. by making students aware of the force field which exists between battery terminals, even when no current is flowing, may make it easier for students to visualize p.d.

The next chapter will now look into how the work with Cohort 1, including the above implications for teaching, influenced the teaching of Cohort 2, a year later. The analysis of the results with Cohort 2 is also discussed.

Chapter 6 Progress in Understanding of Electric Circuits in Cohort 2

6.1 Introduction

In Sections 3.9 and 3.10 of the methodology chapter, it was indicated that as part of the action research project, the plan was to administer the **same** physics diagnostic tests and the TOLT with Cohort 2, one year later, within the same time-frame of the course of study. Analysis of the results was done using similar methods as described with Cohort 1. Conducting one-to-one interviews with some of the students in Cohort 2 had also been planned. It must be emphasised that the purpose of conducting the research with Cohort 2 was not to simply repeat the work which had been done with Cohort 1, but to try and establish whether student understanding of electric circuits would improve when some changes in the additional teaching activities were made. Research with Cohort 2 was meant to help in pointing more clearly to possible reasons for poor understanding in specific areas, evident even after teaching.

This chapter first looks at the results of the pre-test with Cohort 2, checking whether students were finding the same difficulties at the start of the course, as Cohort 1. Additional teaching activities used with Cohort 2 are then described. Analysis of the post-test and delayed post-test results follows, checking whether students' progress was evident in particular areas of the topic. Moreover, the results from the interviews with students in Cohort 2 are also discussed, underlining some reasons for students' persisting difficulties.

6.2 Analysis of the pre-test results

6.2.1 Introduction

The sample in Cohort 2 consisted of 49 students in their second year of study at the college, covering the course of electric circuits with me, like the students in Cohort 1. Students' performance on the pre-test before the teaching indicated that students in Cohort 2 had similar difficulties as indicated at this stage by Cohort 1, with some problems being significantly worse for Cohort 2.

6.2.2 The facility values of questions on the pre-test

The facility values for the pre-test questions (see Table 6.1) clearly indicate that those questions which were chosen to be asked again in the post-test with Cohort 1 because of low facility value were also found difficult to answer by Cohort 2. These questions are marked in green making it easier to compare the similarity in performance of Cohort 1 and Cohort 2, prior to the teaching.

Question number	Facility Value in rank order (Cohort 2)	Facility Value (Cohort 1)
17b(i)	0.959	0.885
5	0.878	0.836
12a	0.755	0.885
12d+12e	0.755	0.738
9a(i)	0.714	0.951
10	0.694	0.672
11	0.653	0.770
15predict	0.592	0.574
1	0.571	0.656
9a(iv)+9a(v)	0.551	0.738
3	0.551	0.525
12b	0.449	0.656
15	0.449	0.459
9a(ii)+9a(iii)	0.429	0.656
4b+4e	0.408	0.410
2	0.408	0.689
16predict	0.367	0.393
9b	0.327	0.525
14	0.327	0.344
13	0.306	0.525
7	0.286	0.459
4c+4f	0.245	0.213
16	0.204	0.393
17a	0.204	0.213
6	0.163	0.262
12c+12f	0.163	0.213
17b(ii)	0.122	0.262
4a+4d	0.102	0.164
8	0.061	0.164

Table 6.1: Comparing facility values for questions on the pre-test for both cohorts

The facility value was high, for both cohorts, when questions related to scientific ideas which can be described as almost intuitive, like for example, no current when the circuit is open or less current when the resistance is larger.

6.2.3 Similarities and differences of students' answers according to concepts being probed

6.2.3.1 Microscopic views

As with Cohort 1, students in Cohort 2 did not find it easy to answer questions related to microscopic views of the electric circuit. Qn 4(a) and 4(d) probing ideas about whether charges reside only in the battery, confused many students. Table 6.2 shows that 25 students (51%) consistently saw charges flowing out of the battery and 18 students (37%) were confused.

		Qn4(d)		Total
		Correct	Incorrect	
Qn4(a)	Correct	5*	1	6
	Incorrect	18	25	43
Total		23	26	49

Table 6.2: Comparing parts (a) and (d) of Qn4 on the pre-test

Moreover, only 12 students (25%) answered correctly to both part questions 4(c) and 4(f) (see Table 6.3), probing the idea that charges exist everywhere in the circuit even before closing it.

		Qn4(f)			Total
		Correct	Incorrect	Missing	
Qn4(c)	Correct	12*	11	1	24
	Incorrect	13	12	0	25
Total		25	23	1	49

Table 6.3: Results for parts (c) and (f) of Qn 4

There is no significant difference in proportions between these results and those indicated in section 4.4.2.1, for Cohort 1 (p-value = 0.48 for (a) and (d); p-value = 0.69 for (c) and (f)). These p-values were estimated by using the chi-square test of differences between independent groups. All p-values presented in this chapter were computed by using this statistical test. The difference between groups was significant when the p-value was less than or equal to 0.05.

6.2.3.2 Models of current indicated

Students in Cohort 2, like those in Cohort 1, gave answers consistent with conservation or attenuation models. In Qn 1 and Qn 2 (Figures 4.3 and 4.4) probing current conservation in a simple circuit (see Tables 6.4 and 6.5), it was found that 18 students (37%) consistently seemed to predict ideas consistent with current attenuation (see Table 6.4). With Cohort 1, 25% seemed to be indicating the same view in both these questions (see Table 4.11). While the difference between these two percentages is not significant (p-value = 0.17), the tendency for Cohort 2 to have views consistent with attenuation was marginally higher.

		Model Qn2			Total
		CC	ACC	U	
Model Qn1	CC	19*	9	0	28
	ACC	1	13	0	14
	AEF	0	5	1	6
	U	0	1	0	1
Total		20	28	1	49

Table 6.4: Models of current in Qn 1 and Qn 2

In Qn 9a(ii) and a(iii) (Figure 4.5 and Table 6.5), asking about current conservation within a parallel branch, only 21 students (42.9%) consistently conserved the current. This was a lower percentage than the 66% of Cohort 1 who had given correct answers to both of these questions. Cohort 1 responded significantly better than Cohort 2 (p-value = 0.017) on these questions.

		Qn9a(iii)		Total
		True	False	
Qn9a(ii)	True	0	25	25
	False	21*	3	24
Total		21	28	49

Table 6.5: Results for Qn 9a(ii) and Qn 9a(iii) - 'Current conservation within a parallel branch'

6.2.3.3 How resistance controls the current

In both Qn 5, 'Use of a larger resistance' and Qn 7, 'Increasing the variable resistance' (Figures 4.6 and 4.7), the majority of students stated correctly that an increase in resistance reduces the current. Forty students (82%) answered part (a) of both questions correctly (see Table 6.6).

		Qn7(a)					Total
		i	ii	iii	iv	Missing	
Qn5(a)	i	1	0	0	0	1	2
	ii	0	3	1	0	0	4
	iii	0	2	40*	1	0	43
Total		1	5	41	1	1	49

Table 6.6: Results for Qn 5(a) and Qn 7(a)

However, only 14 students (29%) substantiated this answer with a scientific explanation in Qn 7(b) (see Table 6.7). With Cohort 1, 48% of the group chose scientific answers (see section 4.4.4.3). Cohort 1 gave significantly better answers regarding resistance (p-value = 0.04).

N=49					
Answer to Qn7(a)	Answer to Qn7(b)	Mental model consistent with answers	Mental model code	Number of students	Percentage
iii	ii	Scientific (battery cannot push as big a current through larger R)	SCI(R)	14*	29%
ii	iv	Same battery, same current	BAT	4	8%
iii	iii	A larger R 'needs' more current	R-TAKE	19	39%
Others		Unclassified	U	12	25%

Table 6.7: Mental models in Qn 7 - 'Increasing the variable resistance'

Table 6.7 shows 19 students (39%) making the iii/iii option choice: 'It gets smaller but not zero; a larger resistance **needs** more current than a smaller resistance'. These students may have possibly been showing ideas consistent with the attenuation model of current. Students may have combined the 'same battery, same current' view (the BAT model) with the fact that a bigger R allows a smaller current to flow attributing this to a higher amount of attenuation by a larger resistance and describing the situation in terms of an R-TAKE model. The number of students in this set was quite high. With Cohort 1 there were 14 students (23%) who also made this choice. This indicates similar results for both cohorts since the percentage differences were not statistically significant (p-value = 0.07).

6.2.3.4 Further indications of unhelpful models using resistances in series and in parallel

Qn 6, 'Adding an equal resistance in series' (Figure 4.8) showed how many students failed to choose the correct qualitative explanation for their otherwise correct, even if possibly recalled, answer to Qn 6(a). The results in Table 6.8 show that the R-TAKE model, the SHARE (current sharing between resistors resulting in a lower current) and the BAT models were chosen by 25%, 29% and 14% respectively. The same models that were common with Cohort 1 seemed common also with Cohort 2.

N= 49					
Answer to Qn6(a)	Answer to Qn6(b)	Mental model consistent with answers	Mental model code	Number of students	Percentage
iii	ii	Scientific (R as a control to the battery push)	SCI(R)	8*	16%
i	iv	More of A, more of B; direct proportion	More A, more B	2	4%
iii	iv	More resistors 'need' more current	R-TAKE	12	25%
iii	v	Sharing model	SHARE	14	29%
ii	iii	Same battery, same current	BAT	7	14%
Others			U	6	12%

Table 6.8: Models for Qn 6: 'Adding an equal resistance in series'

		Model Qn6						Total
		SCI(R)	R-TAKE	BAT	SHARE	More A, more B	U	
Model Qn7	SCI(R)	5*	3	3	2	1	0	14
	R-TAKE	3	4	0	7	0	5	19
	BAT	0	0	3	0	0	1	4
	U	0	5	1	5	1	0	12
Total		8	12	7	14	2	6	49

Table 6.9: Mental models for Qn 7 and Qn6

A cross-tabulation of the models in Qn7, 'Increasing the variable resistance' and Qn 6, shown in Table 6.9, indicated a very poor understanding of resistance, with only 5 students (10%) consistently confirming a scientific answer. Most of the students who gave unclassified answers to Qn 7, confirmed their confusion in Qn 6 (see numbers encircled in Table 6.9), choosing answers consistent with either the R-TAKE or SHARE model. The BAT model was consistently used by 3 students (6%) in both these questions.

In Qn 8, ‘Adding an equal resistance in parallel’ (Figure 4.9), while it was evident that many could not answer scientifically for lack of knowledge about parallel resistors at this stage of the course, yet the answers still helped to indicate intuitive ideas about the effect of resistances connected in parallel. Answers consistent with the BAT model appealed to 9 students (18%). Five students (10%) chose option iii/i, indicating that they just considered the number of resistors and not how they were connected (see Table 6.10). On the other hand, (15+14) students (59%; see numbers encircled) who were incorrect about what happens to the current, were conscious of the two paths introduced because of the parallel branches. With Cohort 1 (see section 4.4.4.5), 44% of the students showed the same views. This difference, however, was not significant (p-value = 0.12).

		Qn8(b)			Total
		i	ii	iii	
Qn8(a)	i	0	3*	0	3
	ii	1	15	9(BAT)	25
	iii	5(I↓, R↑)	14	2	21
Total		6	32	11	49

Table 6.10: Results for Qn8

6.2.3.5 Problems with the conceptualization of p.d.

In Qn 10 and Qn 11 (Figures 4.10 and 4.11) only 24 students (49%) from Cohort 2 (see Table 6.11), as compared to 59% of Cohort 1(see section 4.4.5.2), answered correctly to both questions probing whether students visualized p.d. as some sort of push, increasing with increased battery voltage. While this difference between cohorts was not significant (p-value = 0.48), yet Cohort 1 performed marginally better than Cohort 2.

		Model Qn11				Total
		SCI(p.d.)	R-TAKE	V↑,R↑,I↓	U	
Model Qn10	SCI(p.d.)	24*	2	3	1	30
	R-TAKE	2	3	0	1	6
	V↑,R↑,I↓	2	0	4	0	6
	U	2	2	0	3	7
Total		30	7	7	5	49

Table 6.11: Comparing models for Qn 10 and Qn 11

Thirty seven students (76%) predicted the correct voltmeter reading in Qn 12 (a) (Figure 4.12) where the voltmeter was directly connected across the two points in question. However, only 21 students (43%) transferred the idea to having the same voltmeter reading across equivalent points in Qn 12(b) (see Table 6.12). With Cohort 1, the percentage answering correctly to Qn 12(a) was 89% – the difference between cohorts was not significant (p–value = 0.07). However, 66% of Cohort 1 had answered correctly to Qn 12(b). Here Cohort 1 had answered significantly better than Cohort 2 (p-value = 0.02).

In these part questions, the problem of students seeing a loss of p.d. across connecting wires reappeared with Cohort 2. A substantial number of 14 students (29%), encircled, saw this loss of p.d. and thus did not recognise equivalent points in an ideal circuit. The difference between this and the 20% of Cohort 1 who gave the same answer to this question is not statistically significant (p-value = 0.27). Thus, students in both cohorts may have been linking p.d. with current or energy. Students may believe that p.d. is ‘attenuated’ in the same way that they think current is, or ‘lost’ like energy, when current flows.

		Qn 12(b)					Total
		>6V	6V	<6V	Zero	Missing	
Qn12(a)	>6V	1	1	0	0	0	2
	6V	1	21*	14	1	0	37
	<6V	0	0	2	0	0	2
	Zero	0	0	2	4	0	6
	Missing	0	0	1	0	1	2
Total		2	22	19	5	1	49

Table 6.12: Results for Qn 12(a) and Qn 12(b)

Answers to Qn 12(c) and 12(f) showed the problem many students found, like the students in Cohort 1, of acknowledging zero p.d. across connecting wires (see Table 6.13). There was no significant difference between the percentages of students giving the correct answer in both cohorts (see also section 4.4.5.3).

		Qn 12(f)					Total
		>6V	6V	<6V	Zero	Missing	
Qn12(c)	>6V	1	1	0	0	0	2
	6V	0	17	6	1	1	25
	<6V	0	2	7	1	1	11
	Zero	0	0	0	8*	1	9
	Missing	0	0	0	1	1	2
Total		1	20	13	11	4	49

Table 6.13: Results for Qn 12(c) and 12(f)

6.2.3.6 P.d. across series and parallel resistors

Qn 13 and Qn 14 (Figures 4.13 and 4.14) asked about voltmeter readings across equal and unequal series resistors respectively. A lower percentage (see Table 6.14) than in Cohort 1 correctly predicted and explained the answers, even if the difference was not statistically significant (p-value = 0.23). A significantly higher proportion (p-value = 0.01) – 14 students (29%) in Cohort 2 compared to 10% of Cohort 1– gave unclassified answers to both questions.

		Qn14					Total
		Correct, complete	Correct, incomplete	Repeats part (a)	Alternative ideas	Unclassified	
Qn13	Correct, complete	2*	3*	0	2	0	7
	Correct, incomplete	0	6*	0	2	0	8
	Repeats part (a)	0	1	0	0	0	1
	Alternative ideas	0	0	1	9	1	11
	Unclassified	0	4	0	4	14	22
Total		2	14	1	17	15	49

Table 6.14: Results for Qn 13 and Qn 14

Some students' answers were consistent with attenuation and at times the reasons provided mentioned only current. These students' viewed p.d. as something similar to current. One answer for the p.d. across the larger of two resistances connected in series with a 6V supply as asked in Qn 14 was as follows:

> *'Between 6V and 3V'; 'Some current is used by the resistance. Since the resistance is bigger, more current is used up.'*

This answer shows that the student is thinking in terms of current and seeing this as being attenuated. It also suggests that the student seems to look at the resistor in question only, rather than treating the whole circuit as a system. Answers like this one can be taken to indicate the complexity of the problem which students demonstrate in understanding electric circuits. Schwedes and Dudeck (1996) also acknowledge this when they refer to alternative ideas which "do not exist separately and independently from each other but normally are part of an inner conceptual relationship and are interrelated to each other" (p. 51).

In the case of parallel resistors, once again as with Cohort 1, the splitting of p.d. was indicated by many students as they answered Qn 15, 'p.d. across equal parallel resistors' and Qn 16, 'p.d. across unequal parallel resistors' (Figures 4.15 and 4.16; Tables 6.15 and 6.16). Some students split the p.d. equally whether the resistances were equal or not. Others used unequal splitting in Qn 16, with more students thinking that it was 4V which would result across the smaller resistance of 2Ω. This was further evidence of students considering p.d. as current, using general rules like, 'less resistance, more current', as they reason about p.d. There was no significant difference between the answers from both groups.

Answer to Qn15	Number giving this answer in Cohort 2	Percentage Cohort 2 (N=49)	Percentage Cohort 1 (N=61)
(8V , 8V)	30	61%	57%
(4V , 4V)	14	29%	38%
Other	4	8%	3%
Missing	1	2%	2%

Table 6.15: Voltmeter predictions to Qn 15 - 'equal parallel resistors'

Answer to Qn16	Number giving this answer in Cohort 2	Percentage Cohort 2 (N=49)	Percentage Cohort 1 (N=61)
(6V , 6V)	23	47%	39%
(3V , 3V)	5	10%	8%
(4V , 2V)	11	23%	15%
(2V , 4V)	4	8%	16%
Other	5	10%	15%
Missing	1	2%	7%

Table 6.16: Voltmeter predictions to Qn 16 - 'unequal parallel resistors'

Moreover, like Cohort 1, most students saw p.d. either as some kind of difference between points, or as some kind of flow (see Table 6.17).

Model Qn15	Model Qn16			
	Difference model	Flow model	Other	Total
Difference model	10	4	8	22
Flow model	0	9	6	15
Other	0	4	8	12
Total	10	17	22	49

Table 6.17: Comparing models of voltage in Qn15 and Qn16 - 'resistors in parallel'

In Qn 17: 'p.d. across an open and closed switch' (Figure 4.17), students' answers gave further evidence that p.d. was treated like current. Only 6 students (12%)

saw that the p.d. across the switch in open circuit was 3V, equal to the battery voltage (see Table 6.18). With Cohort 1, 26% had answered correctly - a difference which while not significant (p-value = 0.07) still shows Cohort 2 being more confused than Cohort 1. A majority of students in both cohorts expected a p.d. when a current was flowing, but no p.d. when the current was zero.

Prediction	Frequency	Percentage
0	43	88%
3V	6	12%
Total	49	100.0%

Table 6.18: Frequency of answers to Qn 17b(ii)

6.2.4 Summary of the results in the pre-test

The performance of Cohort 2 on the pre-test was very similar to that shown by Cohort 1. There was evidence that questions which were difficult to answer by Cohort 1, were also found difficult by Cohort 2. Moreover, when the results were examined in detail, similarities between cohorts were seen in the following aspects:

- Cohort 2 showed similar confused views as Cohort 1 regarding whether charges are present only within the battery, coming out when the circuit is complete, or whether charges reside everywhere in the circuit even before closing it;
- students in both cohorts had views consistent with either conservation or attenuation of current. There was a marginal difference noted between cohorts, with more of Cohort 2 tending to use attenuation;
- in dealing with resistance, models common with Cohort 1 were also common with Cohort 2. Students had views consistent with the R-TAKE, SHARE and BAT models;
- a similar proportion of students in both cohorts had problems with attributing the same p.d. to equivalent points. Similar problems were shown when students did not acknowledge zero p.d. across ideal connecting wires;
- a similar percentage of both cohorts treated p.d. like current, splitting it at junctions;
- similarity was also shown in the percentage of students expecting no p.d. when no current was flowing, with the performance of Cohort 2 being marginally worse.

Significant differences, with Cohort 2 resulting as the weaker group, were observed in:

- the percentage of students conserving current within a parallel branch (p-value = 0.02);
- the percentage of students answering to ‘increasing R , reduces the current’ in Qn5 and Qn7 (p-value = 0.04);
- the percentage of students giving unclassified explanations to questions related to the p.d. across equal and unequal series resistors.

The evidence shows that Cohort 2 performed slightly worse than Cohort 1 at the pre-test stage. Much work was evidently needed through the course to help students understand key concepts. Revised, as well as new teaching activities were thus used as tools to promote learning. This is further discussed in the next sub-section.

6.3 Additional teaching activities used with Cohort 2

6.3.1 Introduction

While the additional teaching activities used with Cohort 1 were deemed beneficial for student understanding, yet responses in tests and interviews, as well as in class discussions with Cohort 1 had shown that more could be done. Reflections on results with Cohort 1 helped in deciding what activities to use with Cohort 2. Some activities used in the previous year were kept, others were slightly revised and new ones were introduced. The aim was of helping students to become more meta-cognitively aware of their doubts, improving their understanding through deeper reflection.

6.3.2 Revising the static electricity course

It was important to give students in Cohort 2, like Cohort 1, the opportunity of making the macro-micro link (Eylon & Ganiel, 1990; Licht, 1991; Viennot & Rainson, 1992) by revising the static electricity course. This had been covered by students in their first year at the college. Lessons were conducted once a week during tutorials (see section 3.8.8) running in parallel with 2 other lesson periods per week covering course work.

6.3.3 Circuit diagram representation

During all lessons, especially at the start of the teaching unit, I was careful not to introduce an arrow next to the battery, on any circuit diagram. Students in Cohort 1 had made it evident that an arrow drawn near the battery gave them the impression that current comes out of the battery, like water from a tap. To indicate electron flow, the circuit was drawn as shown in Figure 6.1. Conventional current was drawn with the arrow reversed.

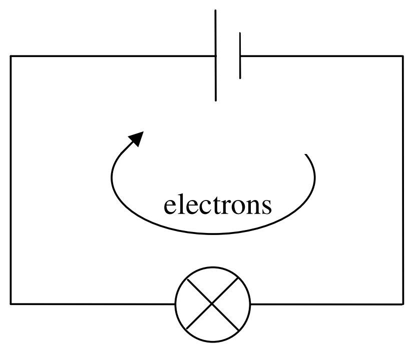


Figure 6.1: Electron flow in an electric circuit

This measure was taken to encourage students not to think along the very common idea of having the electrons only in the battery at the start, moving out of it when the circuit is switched on. I was careful to reduce the chance of having teaching become a source of unhelpful models. (Niedderer, 1994, 1996; Duit et al., 1985).

6.3.4 The 'electron experience' task

6.3.4.1 Setting the task

Chronologically, this task was set for students to tackle, early through the course, about two weeks after the pre-test had been administered and just before the idea of current conservation was introduced. Students were shown a diagram of a simple electric circuit and asked to "describe the way a circuit works in terms of the experience of a specific electron" (Taber et al., 2006, p. 158). The aim of this exercise was to make students "reflect on their own thinking in more depth" (Prain & Hand, 1999, p.156), as they put their ideas in writing, before they could be influenced and possibly just accept without thinking, any ideas presented by others.

After collecting students' written material, some of the writing was read out to the class, emphasizing the different ideas which had been exposed. A class discussion then followed, so that students' mental models of the electric circuit at work could be reflected upon, creating the possibility for students who did not hold the scientific view, to hear it from their peers. This discussion also made it possible for students to become aware of the existence of models of the electric circuit other than their own (Coll et al., 2005).

6.3.4.2 The results of the task

Table 6.19 shows details which students used or referred to in their writing which, together with the pre-test results, indicate how students viewed the mechanism of the electric circuit at work.

Details / expressions used in explanations	**Number of students**
Used an *arrow* to indicate electron movement correctly	4
Used an *arrow* to indicate a current from negative to positive	3
Used an *arrow* on the diagram to show the conventional current	28
'The electron *moves/ leaves/ comes from* the negative to the positive terminal'	25
'The electron *leaves the battery'*	5
'There is an electron *flow from positive to negative'*	10
'The electron *opposes the current'*	2
'The electron needs *energy to leave the battery'*	4
'The closed *circuit charges the electron'*	3
'The *battery provides a push'*	3
'Arriving *near R,* the electron *velocity is reduced/slows down'*	14
'The electron *flow decreases because of R*, and the current is less'	5
'The flow *stops if R is too big'*	3
'The electron *loses charge in passing through R'*	3
'The electron *loses energy in passing through R'*	16
'R reduces the power of the electron'	1
'The electron moves *from a point at one potential to one at a different potential*'	4
'The electron *moves due to the p.d. experienced*'	2
'The electron *is repelled from the negative terminal and attracted to the positive terminal*' (a description in terms of an electric field with the possibility of students not necessarily 'seeing' the field)	5

Table 6.19: Students' ways of explaining the 'electron experience'

The results show that there was a strong tendency for students to look at the electron as starting at the battery. Only 3 students mentioned the battery push experienced by the electron. There was also a tendency to describe a decrease in electron flow after the current passes through R, indicating sequential reasoning (Licht, 1991; McDermott & Shaffer, 1992; McDermott & van Zee, 1985; Millar & King, 1993; Shipstone, 1984, 1985b). Three students said that the electron loses charge, perhaps implying electron absorption by the resistor. A good number of 16 students referred to the energy lost by the electron in passing through R. Only 6 students mentioned potential and p.d. in their explanations, and 5 students mentioned the repulsive and attractive forces experienced by the electron. This description implies the presence of an electric field guiding electron flow, but as has been explained in section 5.7, one cannot be sure of whether the students were 'seeing' this field or just recalling a reason which they had heard of or used before, for the electron movement. Much of students' views described in this task had also been indicated during the interviews with Cohort 1.

6.3.4.3 Reflections after class discussion

Students' discussions and the written descriptions made it clear that at secondary level students had been indoctrinated with the phrase: '*the current is the same everywhere in a simple circuit*'. Some students recalled and used this phrase, but still imagined that either a smaller number of electrons come out of the resistor, or that charge is absorbed or lost within the resistor. Students' recall was not equivalent to students' understanding.

On the other hand there were some students who not only spoke of current conservation, but who gave reasons for it, describing it using analogies. One student compared current flow to traffic flow, thus:

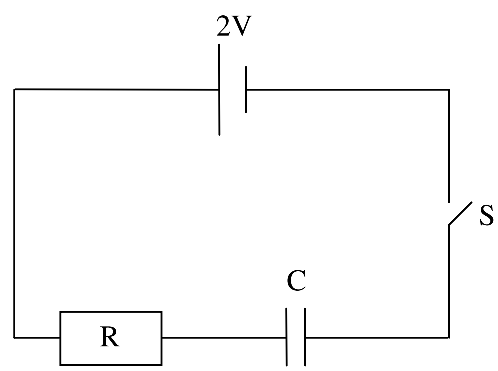
> 'If you have electrons flowing, it is just like traffic. If you stop at the front, all the traffic is affected, not just the part at one end. The velocity of the electrons is reduced, but not because it is reduced within the resistor. It is reduced at switch on, at the start, choosing any electron at any point.'

The discussion was guided by the teacher/researcher. Conflicts arose, urging further discussion. Students were given a chance to realize that their ideas were not always compatible with the scientific view.

This exercise was not expected to immediately change students' views towards what is scientific. However, some common unhelpful ideas had been exposed and students were thus given a possibility of becoming meta-cognitively aware of their understanding, or the lack of it. Students may have been encouraged to think in terms of current conservation. Moreover, the exercise may have been instrumental in helping to counteract the common use of the BAT model (same battery, same current), shown to be popular with both cohorts.

6.3.5 Differentiating between current and p.d.

The data collected in the previous year had supported findings from other studies in the literature that many students think that p.d. cannot exist without current flow. This was also supported by the results of the pre-test with Cohort 2. An example relating to current flow and the establishment of a p.d. across components in an R-C circuit was thus worked out with the student sample (see Figure 6.2). Students were directed to ponder on how the p.d. across the resistor and the capacitor change, as the capacitor is being charged. The example was clear in pointing out that p.d. exists across the fully charged capacitor, even though no current flows through the circuit at that time. It was thought that this might help students to differentiate p.d. from current.



(i) Calculate the value of the current within the circuit when S is **just** switched ON.
(ii) Explain how the p.d. across the resistor and the capacitor change as the capacitor is being charged.
(iii) **After a very long time**, what will be the value of the current within the circuit?

Figure 6.2: R-C circuit question used to help differentiate p.d. from current

6.3.6 The DVD and the PowerPoint presentation

The DVD material (see section 3.6.4.1) referring to static and current electricity used with Cohort 1 was also used with Cohort 2. The PowerPoint presentation was also shown to the students in a slightly revised form with more slides added (see Appendix 7 for the final revised version of the PowerPoint presentation). The aim of this presentation was to help the students link concepts in current electricity to other topics in physics, through the use of analogies. More models and analogies were introduced to help students' understanding and class discussion was encouraged.

The DVD and PowerPoint presentation were now used mid-way through the course, rather than at the end of it as had been done with Cohort 1, thus allowing more time till the end of the course, for students to reflect on what they had seen and discussed as the teaching was in progress.

6.3.7 PhET simulations

Simulations from the website of the PhET project (Physics Education Technology, 2008) of the University of Colorado were used in class, throughout the course, to help clarify students' ideas. The Circuit Construction Kit (CCK) was used to provide an animated view of the electrons flowing through different closed circuits. Such representations are seen as useful (Urban-Woldron, 2008) in trying to reduce students' misconceptions due to abstract concepts. These simulations are freely available and the students were encouraged to use them further during their study, as they reflected about their work and to help solve their qualitative reasoning doubts, if and when these arose.

6.4 The post-test results

6.4.1 Introduction

After the teaching of current electricity with Cohort 2, including the additional teaching activities, it was hoped that an improvement would be shown in students' performance on the post-test. Students' mental models were expected to have improved since the pre-test stage. In general, Cohort 2 was expected to perform at least at a similar level compared to Cohort 1 at this stage, even if with the help from the new teaching activities used, more was expected of this group.

More specifically, more students were expected to have a clearer idea of the electric circuit working as a system, comparing current flow to a bicycle chain effect. Moreover, students were expected to have moved on from their intuitive view of 'same battery, same current' model (the BAT model). A better visualization was expected from students of how resistance controls the battery push, and of the meaning of p.d. This should have been helped by the analogies that were introduced and discussed during the PowerPoint presentation.

The following sections focus on providing evidence which shows that while Cohort 2 improved in some aspects, yet more had been expected.

6.4.2 Persistent difficulties with microscopic views

The results in Table 6.20 were compared with those of Cohort 1 (see Table 4.49). The difference was insignificant (p-value = 0.64), between the 19 students (39%) of Cohort 2, and the 34% of Cohort 1,who still incorrectly but consistently saw electrons in the battery only, before the circuit is connected.

		Qn4(d)		Total
		Correct	Incorrect	
Qn4(a)	Correct	15*	5	20
	Incorrect	9	19	28
	missing	0	1	1
Total		24	25	49

Table 6.20: Results of Qn 4(a) and Qn 4(d) on the post-test

The difference was again not significant (p-value = 0.62) in Qns 4(c) and 4(f) (see Table 6.21), between the 21 students (43%) in Cohort 2 and the 48% in Cohort 1 (see Table 4.50) who 'saw' the circuit as one system with charges moving everywhere and together in the post-test.

		Qn4(f)		Total
		Correct	Incorrect	
Qn4(c)	Correct	21*	16	37
	Incorrect	2	10	12
Total		23	26	49

Table 6.21: Results for Qn 4(c) and Qn 4(f) on the post-test

However, the results also indicated that while difficulties with microscopic views persisted, yet Cohort 2 made better progress since the pre-test, compared to Cohort 1. Fifteen students (31%) of Cohort 2 now gave correct answers to both part questions 4(a) and 4(d) compared to the 5 students (10%) who had answered correctly in the pre-test (see Table 6.2). The number thus tripled. With Cohort 1, the number had approximately doubled from 16% in the pre-test to 34% in the post-test.

6.4.3 Improvement on current conservation views

The results in Table 6.22 for Qn 1, 'Current at points (a) and (b)', show that many students now had ideas consistent with current conservation (CC). Few students showed consistency with attenuation views (ACC).

		Qn1(b)		Total
		i	ii	
Qn1(a)	i	0	7(ACC)	7
	iii	42*(CC)	0	42
Total		42	7	49

Table 6.22: Results for Qn 1(a) and Qn 1(b) on the post-test

When comparing students' views of current used in Qn 1 and Qn 9'(a), 'Current conservation within a parallel branch' (Table 6.23), 39 students (80%) chose answers consistent with current conservation in both questions. This was similar to the 82% of Cohort 1.

However, in Qn 1 and Qn 2, 'Current using two ammeters' of the pre-test, results showed that only 38% of Cohort 2 had been consistent with current conservation. The percentage showing these consistent views on these same questions in the pre-test with Cohort 1 had been much higher at 59% (see Table 4.11; p-value = 0.03).This means that, in fact, Cohort 2 showed a more substantial improvement in conserving the current. It was possible that the '*electron experience*' task may have been effective in guiding students' views in the context of these questions. This does not, of course, rule out that other elements in the students' learning experience may have helped as well.

		Qn9'a			Total
		CC	ACC	AEF	
Model Qn1	CC	39*	1	2	42
	ACC	0	7	0	7
Total		39	8	2	49

Table 6.23: Comparing models in Qn 1 and Qn 9'(a)

6.4.4 Understanding resistance

6.4.4.1 Popular models used in describing resistance

		Qn6(b)					Total
		i	ii	iii	iv	v	
Qn6(a)	i	1	0	0	0	0	1
	ii	0	0	14(BAT)	0	1	15
	iii	0	11*	0	15(R-TAKE)	7(SHARE)	33
Total		1	11	14	15	8	49

Table 6.24: Results for Qn 6

Answers to Qn 6, 'Adding an equal resistance in series' (Table 6.24), indicated that ideas consistent with the SHARE and the BAT models were used by 14% and 29% of the sample, respectively. With Cohort 1 a year earlier, these values were not significantly different at 20% and 36% respectively (p-values equal to 0.46 and 0.40 respectively). Fifteen students (31%) in Cohort 2 (it was only 3 students (4%) with Cohort 1 - see Table 4.57) chose the iii/iv option in this question, acknowledging a smaller current when the resistance is increased because '2 resistors "need" more current than one on its own'– ideas consistent with the R-TAKE model. In the pre-test, 12 students (25%) had also made this choice. Students may have been pointing to an attenuation view combined with the BAT model as explained in section 6.2.3.3. It seems that while students may have moved away from attenuation in questions like Qn 1, asking directly about current, yet, intuitively the influence of the attenuation model may remain, and students still use it in trying to solve problems related to other concepts. This idea may be linked with the fact that understanding does not develop linearly in all areas in a topic like this, where some concepts are hierarchically more difficult than others. Sometimes students start from a lower base-line again before they can accommodate a new concept (Welzel, 1997, 1998).

6.4.4.2 Confirming the popular use of the BAT model

In the post-test with Cohort 1, the BAT model had been proposed as one of the possibilities which may hinder students' learning about resistance. With Cohort 1, 22 students (36%; see Table 4.61) had ideas consistent with the BAT model on the post-test in Qn 8, 'Adding an equal resistance in parallel'. With Cohort 2, 14 students (29%) had the same ideas (Table 6.25).This difference between cohorts was not significant (p-value = 0.40) indicating that, in spite of having dealt with the 'electron experience' task which also touched ideas related to this unhelpful model, the BAT model remained popular with students of Cohort 2.

		Qn8(b)			Total
		i	ii	iii	
Qn8(a)	i	0	17*	1	18
	ii	0	8	14 (BAT)	22
	iii	2	6	1	9
Total		2	31	16	49

Table 6.25: Results for Qn 8 in the post-test

Moreover, 13 students (27%) used views which were consistent with the BAT model in both Qn 6, 'Adding an equal resistance in series' and Qn8, 'Adding a resistance in parallel'. This confirms the popular use of this model by students, manifesting the difficulty students find to move away from it (see Table 6.26).

		Model Qn8 (post-test)				Total
		SCI(R)	BAT	I↓ the more resistive components	U	
Model Qn6 (post-test)	SCI(R)	6*	0	1	4	11
	ACC	6	4	0	5	15
	SHARE	5	1	1	0	7
	BAT	0	13	0	1	14
	U	0	2	0	0	2
Total		17	20	2	10	49

Table 6.26: Models for Qn 6 and Qn 8 in the post-test

6.4.5 Effect of the additional teaching activities on the understanding of p.d.

As has been explained earlier in this chapter, teaching activities especially geared to help students understand p.d. had been conducted with Cohort 2 during the course (see section 6.3). After making the extra effort, students did not show the expected progress in all questions probing this concept.

6.4.5.1 P.d. across resistors connected in parallel

When students dealt with equal or unequal resistances connected in parallel with the battery, in Qns 15 and 16, slightly more than half the sample, 53%, (see Table 6.27), answered correctly to both questions. With Cohort 1, 44% of the sample (see Table 4.69) had done the same at this stage. These percentages only show a marginal difference between cohorts (p-value = 0.34), with Cohort 2 performing slightly better. However, with only 10 students (20%; see Table 6.28) in Cohort 2 having answered both questions correctly in the pre-test, compared to 21 students (34%) from Cohort 1 (see Table 4.42), the progress of Cohort 2 was evidently better.

		Model Qn16 (post-test)					Total
		SCI(C)	SCI(D)	p.d.FLOW(I)	Missing explanation	U	
Model Qn15 (post-test)	SCI(C) (scientific: causal)	3*	3*	1	0	0	7
	SCI(D) (scientific: difference)	1*	19*	2	1	1	24
	p.d.FLOW(I) p.d. viewed as current	0	2	9	1	3	15
	Missing explanation	0	0	0	1	1	2
	U	0	0	0	0	1	1
Total		4	24	12	3	6	49

Table 6.27: Models for Qn 15 and Qn 16 in the post-test

		Model Qn16 (pre-test)		Total
		Correct	Incorrect	
Model Qn15 (pre-test)	Correct	10*	12	22
	Incorrect	0	27	27
Total		10	39	49

Table 6.28: Models for Qn 15 and Qn 16 on the pre-test

It must be emphasised that both these questions did not suggest any change to the circuit presented. Students had to just 'see' equivalent points with the same p.d. across them. Indeed, as soon as the question suggested a change being made to the original circuit, the change acted as a distractor and the performance dropped.

6.4.5.2 P.d. when changes were made to the circuit

In Qn 18, 'p.d. across a resistor, adding another resistor in parallel' (Figure 4.23), the change distracted the students. Many focussed mainly on the change and not on the constant p.d. across equivalent points. Ten students (20%) seemed to treat p.d. like current, choosing options related to sharing of p.d. between parallel branches (Table 6.29). Cohort 1 results were similar – 12% of the cohort indicated the same idea. The difference in percentages was not significant (p-value = 0.20), with Cohort 2 performing marginally worse than Cohort 1.

		Qn18(b)			Total
		i	ii	iii	
Qn18(a)	i	2	0	2	4
	ii	1	32*	2	35
	iii	10	0	0	10
Total		13	32	4	49

Table 6.29: Answers to Qn 18

6.4.5.3 Common unhelpful views of p.d.

In spite of the teaching, the problems which Cohort 2 had with understanding p.d. were made evident at the post-test stage when a surprising level of confusion was shown in Qn 12' (Figure 4.21). Only 14 students (29%) answered correctly to zero p.d. across connecting wires (see Table 6.30). Moreover, in part (a), predicting p.d. across equivalent points to voltmeter terminals, only 37% gave correct answers. This was significantly different (p-value < 0.0002) from the 82% correct answers with Cohort 1 (see section 4.5.6.2). Furthermore, Cohort 2 showed a slight regression on the pre-test performance, when 43% had answered correctly at that time. It seems that the p.d. concept was still not understood by the majority of students in Cohort 2. It is always tough covering the course work in a limited time and students may have shown that they needed more time to reflect on the work done.

		Qn12’(c)			Total
		6V	<6V	Zero	
Qn12’(b)	>6V	0	1	0	1
	6V	20	6	1	27
	<6V	0	6	0	6
	Zero	1	0	14*	15
Total		21	13	15	49

Table 6.30: Answers to Qn 12’(b) and (c) relating to p.d. across connecting wires

More unhelpful views were evidenced in Qn 17’(b), ‘p.d. across an open switch’. 86% of the cohort expected ‘no p.d. for no current’ (Table 6.31). About half of Cohort 1 had expected the same.

Prediction	Frequency (N=49)	Percentage
>3V	1	2%
0	42	86%
3V	6*	12%
Total	49	100%

Table 6.31: Frequency of answers to Qn 17’b

Table 6.32 shows that 39 students (80%) who in the pre-test expected no p.d. when no current was flowing still had the same view in the post-test. Moreover, comparing the percentage of students answering ‘zero volts across an open switch, for zero current in the circuit’ in both cohorts shows that the difference is insignificant (p-value = 0.25). The implication is that the additional capacitor question activity done with Cohort 2, which was meant to directly make students reflect about the idea that a p.d. **can** exist when no current flows, did not have the desired effect.

		Qn17b(ii) (pre-test)		Total
		0	3V*	
Qn17'(b) (post-test)	>3V	0	1	1
	0	39	3	42
	3V*	4	2	6
Total		43	6	49

Table 6.32: Performance on part Qn 17: 'p.d. across an open switch'

6.4.6 Summary of the post-test results

In dealing with microscopic views, while better progress since the pre-test was detected with Cohort 2 when compared to Cohort 1, yet only less than half of Cohort 2 consistently saw the current as the movement of charges present in all parts of the circuit.

No significant difference was found in the number of students in both cohorts using ideas consistent with current conservation at the post-test stage. However, comparing results to the pre-test showed a more substantial improvement by Cohort 2, in the shift students made towards current conservation.

In questions about resistance, there were no significant differences between cohorts, in students' use of ideas consistent with the SHARE, BAT and R-TAKE models. This was in spite of the additional teaching activities conducted with Cohort 2. It was interesting to observe that some students, who had moved to conservation from the attenuation view in questions asking directly about current, still seemed to apply attenuation within the R-TAKE model when answering questions about resistance.

Students did not show the expected progress in all questions probing p.d. While progress was noted in answers directly predicting p.d. across parallel resistors, when no changes were made to the circuit in question, yet, some students still split the p.d. between branches, applying ideas about current at junctions, to p.d.

In Qn 18, for 20% of the students, the changes within a parallel branch took priority over the idea of p.d. remaining the same across equivalent points. A regression in performance was noted in Qn12'(a), predicting the voltmeter reading across equivalent points, thus showing students confusion with the concept of p.d. even after teaching.

Only 12% of Cohort 2 saw p.d. without the presence of a current in Qn 17'(b). Many students in both cohorts kept the mistaken idea of 'no current, no p.d.', with no significant difference in performance between cohorts. Moreover, no progress was shown on this question by Cohort 2 since the pre-test. Even when the capacitor question task had been used specifically to try and correct this difficulty, it seems that using the activity once was not enough to provide the desired effect.

These results indicated that students' ideas had neither advanced at the same pace in all areas, nor within the same area in different contexts. This is somewhat what is expected while learning is taking place.

6.5 Analysis of the delayed post-test results

6.5.1 Introduction

The delayed post-test was answered by students a month after the post-test, as with Cohort 1. Cohort 2 not only indicated good knowledge retention since the post-test stage, but also showed progress in understanding related to ideas about current and resistance. There was also some improvement related to p.d. but this was not linear in all questions. The sub-sections below refer to details which show changes in students' progress since the post-test. Like the result with Cohort 1, students seemed to show more progress in understanding now, rather than at the post-test stage. Students were close to sitting for a national exam in physics and were thus more conscious of the need for them to study.

6.5.2 Where do charges reside?

Dealing with microscopic views, while more students answered correctly in Qn 4 at this stage (see Tables 6.33 and 6.34 and Tables 6.20 and 6.21 to compare), there was evidence of confusion shown from a good number of students. These students did not move away from the model of charge flowing out of the battery on connecting the circuit.

		Qn4(d)		Total
		Correct	Incorrect	
Qn4(a)	Correct	25*	3	28
	Incorrect	16	5	21
Total		41	8	49

Table 6.33: Answers to Qns 4(a) and 4(d) on the delayed post-test

		Qn4(f)		Total
		Correct	incorrect	
Qn4(c)	Correct	32*	8	40
	Incorrect	5	4	9
Total		37	12	49

Table 6.34: Answers to Qns 4(c) and 4(f) on the delayed post-test

The data shows more problems with answering Qn 4(a) and 4(f). The results of these parts were compared to the post-test results, (see Tables 6.35 and 6.36), to check for knowledge retention. The results indicate that 15 students (31%) in Qn 4(a) and 21 students (43%) in Qn 4(f) kept their scientific views, while shifts away and towards these views occurred. While overall progress resulted in students' microscopic views, it must also be acknowledged that concept understanding did not occur linearly. Time is needed for reflection, as students' ideas might regress, before the leap is made towards meaningful learning.

		Qn4(a) (delayed post-test)		Total
		Correct	Incorrect	
Qn4(a) (post-test)	Correct	15*	5	20
	Incorrect	12	16	28
	missing	1	0	1
Total		28	21	49

Table 6.35: Comparing answers to Qn 4(a) on the post-test and delayed post-test

		Qn4(f) (delayed post-test)		Total
		Correct	Incorrect	
Qn4(f) (post-test)	Correct	21*	2	23
	Incorrect	16	10	26
Total		37	12	49

Table 6.36: Comparing answers to Qn 4(f) on the post-test and delayed post-test

6.5.3 Current conservation and attenuation models

More students than in the post-test now conserved the current in a simple circuit (see Table 6.37).

		Qn1 (delayed post-test)		Total
		CC	ACC	
Qn1 (post-test)	CC	42*	0	42
	ACC	3	4	7
Total		45	4	49

Table 6.37: Comparing Qn 1 - 'Current at points a and b' on the post- and delayed post-test

However, conservation within a parallel branch was still problematic. Table 6.38 shows that only 34 students (69%) were consistent in using current conservation also within a parallel branch. In the post-test, 39 students (80%) had used current conservation consistently in these questions. (See also Table 6.23). This points once again to movements in some students' answers, away from the correct view, when concepts are not yet clear. At the same time the indication is that parallel circuits pose a problem for understanding.

		Qn9'(a) (delayed post-test)		Total
		CC	ACC	
Qn1 (delayed post-test)	CC	34*	11	45
	ACC	0	4	4
Total		34	15	49

Table 6.38: Qn 1 and Qn 9'a on the delayed post-test

6.5.4 Answers about resistance

Results for Qn 6, 'Adding an equal resistance in series' indicated that the understanding of resistance was still also posing problems. Only 20 students (41%) answered scientifically (see Table 6.39). Even so, there was progress shown since the post-test, when only 11 students (22%) had answered correctly.

Answers consistent with the BAT, SHARE and R-TAKE models still persisted.

		Qn 6(b) (delayed post-test)				Total
		ii	iii	iv	v	
Qn 6(a) (delayed post-test)	i	0	1	0	0	1
	ii	0	12(BAT)	0	1	13
	iii	20*	0	8(R-TAKE)	7(SHARE)	35
Total		20	13	8	8	49

Table 6.39: Qn 6(a) and 6(b) on the delayed post-test

When the models consistent with students' answer choice in the post- and delayed post-test were compared (see Table 6.40), one could see that only 7 students had kept both the resistance and the battery in mind, working together (the SCI(R) model), as they answered:

'The battery cannot push as big a current through two resistors.'

There was a bigger shift towards the scientific model than away from it. Of the 20 students who now answered correctly, 13 had changed from their previous alternative views of R-TAKE, SHARE and BAT. The BAT model was held on to by 7 students (14%), who confirmed the difficulty some students find in moving away from this model, having a strong conviction of the 'same battery, same current' view.

		Model Qn6 (delayed post-test)					Total
		SCI(R)	R-TAKE	SHARE	BAT	U	
Model Qn6 (post-test)	SCI(R)	7*	1	0	2	1	11
	R-TAKE	6	2	5	1	1	15
	SHARE	4	2	1	0	0	7
	BAT	3	3	1	7	0	14
	U	0	0	0	2	0	2
Total		20	8	7	12	2	49

Table 6.40: Comparing models in Qn 6 on the post- and delayed post-test

Further proof of this was Qn 8, 'Connecting an equal R in parallel'. Approximately $^{1}/_{3}$ of the sample (13 students; 27%) gave answers consistent with the BAT model (Table 6.41).

		Qn8(b) (delayed post-test)				Total
		i	ii	iii	missing	
Qn8(a) (delayed post-test)	i	0	23*	0	0	23
	ii	0	7	13(BAT)	0	20
	iii	4	0	1	1	6
Total		4	30	14	1	49

Table 6.41: Answers to Qn 8 on the delayed post-test

Moreover, comparing Qn 6 and Qn 8, the BAT model was consistently inferred from the answers of 8 students (16%; see Table 6.42). Similarly, with Cohort 1 at this stage, 16% had answered in the same manner (see Table 4.79). This difference was not significant (p-value = 0.99).

		Model Qn8 (delayed post-test)				Total
		SCI(R)	BAT	R↑, I↓	U	
Model Qn6 (delayed post-test)	SCI(R)	11*	1	4	4	20
	R-TAKE	6	1	0	1	8
	SHARE	4	2	0	1	7
	BAT	1	8	0	3	12
	U	1	1	0	0	2
Total		23	13	4	9	49

Table 6.42: Models in Qn 6 and Qn 8 on the delayed post-test

6.5.5 Difficulties with understanding p.d.

The issue that p.d. was difficult to master had been given priority since the start of this study. With a number of teaching activities aimed at directing students towards reflection on, and visualization of this concept, there was the hope of progress in students' performance in questions related to p.d.

In Qn 12'(a) of the post-test students' regression in attributing equal p.d. to equivalent points had been pointed out. Only 37% of the sample had recognized equivalent points in this part question. In the delayed post-test it was 90% of the sample choosing the correct answer (see Table 6.43). The facility value for this part question had certainly increased. The majority of students now seemed to recognise equivalent points within the circuit. This was confirmed by a larger number of students who now also correctly recognised zero p.d. across connecting wires (see Table 6.44).

Prediction	Frequency	Percentage
6V	44*	90%
<6V	5	10%
Total	49	100%

Table 6.43: Frequency of answers to Qn 12'(a) on the delayed post-test

		Qn12' (c) (delayed post-test)			Total
		6V	<6V	0	
Qn12'(c) (post-test)	6V	11	3	7	21
	<6V	5	2	6	13
	0	2	1	12*	15
Total		18	6	25	49

Table 6.44: Comparing answers for Qn 12'(c) on the post- and delayed post-test

Even so, one cannot ignore the 18 students (37%) who still saw 6V across the connecting wire, thus showing their lack of understanding.

Students' performance was also found to slightly improve in questions dealing with p.d. across parallel resistors connected directly across the battery. The results for question Qn 16, which was more demanding than Qn15, are evidence of this (see Table 6.45).

		Model Qn16 (delayed post-test)					Total
		Correct, complete	Correct, incomplete	Restating answer	Alternative ideas	Unclassified	
Model Qn16 (post-test)	Correct, complete	1*	2*	0	0	1	4
	Correct, incomplete	3*	14*	1	3	3	24
	Alternative ideas	0	8	0	3	1	12
	Unclassified	1	1	1	1	2	6
	Missing	0	3	0	0	0	3
Total		5	28	2	7	7	49

Table 6.45: Comparing models in Qn 16 on the post-test and delayed post-test

Moreover, Tables 6.46 and 6.47 both indicate a majority of students correctly predicting the same p.d. across equal and unequal resistors in parallel in Qn 15 and Qn 16.

Prediction	Frequency	Percentage
(4, 4)	6	12%
(8, 8)	42*	86%
others	1	2%
Total	49	100%

Table 6.46: Frequency of predicted voltages for equal parallel resistances in Qn 15

Prediction	Frequency	Percentage
(4, 2)	4	8%
(2, 4)	5	10%
(6,6)	34*	70%
others	6	12%
Total	49	100%

Table 6.47: Frequency of predicted voltages for unequal parallel resistances in Qn 12

These results also indicate that some students still held on to the view of voltage/p.d. being split, like current. This unhelpful view of treating p.d. like current became more evident when students answered Qn17'(b), 'p.d. across a closed switch'. Many students (80%) still expected a p.d. only when a current flows. Many of these students had held the same view at the post-test stage (Table 6.48). Students' performance dropped drastically in this question implying major problems related to p.d. in this context.

		Qn17' (b) (delayed post-test)		Total
		0	3V*	
Qn17'(b) (post-test)	>3V	0	1	1
	0	36	6	42
	3V*	3	3	6
Total		39	10	49

Table 6.48: Comparing answers for Qn 17'(b) on the post- and delayed post-test

6.5.6 Summary of the delayed post-test results

Most students retained the knowledge they had gained regarding microscopic views. Moreover, more students now saw charges moving everywhere and together.

Most students conserved the current in Qn 1, but regression was evidenced for current conservation within a parallel branch.

When the effect of increasing a resistance in series was probed in Qn 6, more students (41%) than in the post-test (22%) now answered correctly. Ideas consistent with the BAT, SHARE and R-TAKE models were still used, with the BAT model being predominantly inferred from the answers. Only 7 students had consistently held on to the scientific meaning of resistance, since the post-test.

A majority of students (90%) now gave correct predictions of the voltmeter reading across equivalent points. Progress was shown on p.d. predictions across connecting wires.

Improvement was shown also when dealing with p.d. across parallel resistors, but about ¼ of the sample still split the p.d. There was proof that a majority of students expected p.d. only in the presence of the current. This seemed a major stumbling block in students' understanding of p.d.

6.6 An overview of the performance of Cohort 2 in the diagnostic tests

6.6.1 Deductions from the diagnostic tests results

The analysis of the answers to the pre-test with Cohort 2 showed that much of what had been indicated by Cohort 1 was indeed being replicated by Cohort 2. At the same time, more students from Cohort 2 showed evidence of misconceptions at this stage. A significantly larger proportion of students in Cohort 2 appeared to hold ideas consistent with unhelpful models in questions dealing with conservation of current within a parallel branch, the effect of the resistance in the circuit, and the p.d. across series resistors.

Looking globally at the post-test results it was noted that while the additional teaching activities used through the course may have helped students' learning in some areas, problems still persisted in others. Students progressed more noticeably in questions probing current. With questions probing resistance, the BAT model (same battery, same current) remained consistently used by a good number of Cohort 2. Moreover, even if students had been expected to show progress with problems probing p.d., the failure to differentiate p.d. from current remained.

The results of the delayed post-test, once again as with Cohort 1, indicated the improvement made by the students in all areas being probed in their effort to prepare themselves for the forthcoming fast approaching national exams. However, the problem of using the same rules that apply to current when thinking of p.d. remained. The problem of expecting p.d. to be present only when current is present was still very pronounced. The indication was that p.d. is a harder concept to deal with and understand, especially when a p.d. exists without current flow, as in Qn 17(b) - the open switch question. Students did not show awareness of the idea of a field within the circuit. Had they visualised the field, something which had been brought to students' attention in the PowerPoint presentation, the problems experienced with the open switch question may have been overcome.

6.6.2 Analysis and comparison of the test scores for the two cohorts

Table 6.49 shows details of test scores results for Cohort 2, including the results for Cohort 1 as a comparison. The post-test and the delayed post-test were identical. The pre-test and the post-test had some common questions.

Diagnostic Test	Total score	Mean score	Standard Deviation	Mean score as a percentage of the total score	Standard deviation for the percentage scores
(N=61) Cohort 1					
Pre-test	29	15.2	5.3	52.5%	18.3
Post-test	27	13.5	4.8	50.0%	17.7
Delayed post-test	27	14.2	4.9	52.5%	18.0
(N=49) Cohort 2					
Pre-test	29	12.5	3.6	43.1%	12.3
Post-test	27	12.5	4.8	46.3%	17.9
Delayed post-test	27	14.8	4.6	54.9%	17.1

Table 6.49: Mean scores and standard deviations for all Physics Diagnostic Tests (PDTs) (all questions asked)

Cohort 2 has a mean pre-test score which is lower than that for Cohort 1 on the same test. Comparing the percentage marks on each test for the two cohorts using independent t-tests, it was found that there was a significant difference between the scores of the 2 cohorts in the pre-tests (p-value < 0.05) but not in the post-tests (p-value = 0.29) and the delayed post-tests (p-value = 0.48). The performance of the Cohort 2 was thus significantly weaker at the pre-test stage than that of Cohort 1, becoming slightly better on the delayed post-test.

(N=49) Cohort 2				
Diagnostic Test	Mean score out of a total of 19	Standard deviation	Mean score as a percentage of the total score	Standard deviation for percentage scores
Pre-test	5.9	2.5	31.0%	13.3
Post-test	9.7	4.1	51.0%	21.7
Delayed post-test	11.7	3.9	61.6%	20.3

Table 6.50: Mean scores and standard deviations of PDTs (common questions only)

Considering only the common questions on the tests (see Table 6.50 and Table 4.90), there was once again a significant difference between the percentage marks for the two cohorts in the pre-test (p-value = 0.02), but no significant difference in the post-test and delayed post-test marks (p-values equal to 0.32 and 0.23 respectively).

Difference between tests	Mean difference between percentage scores	Standard deviation of the difference between percentage scores
(N=61) Cohort 1		
Post-test score – Pre-test score (*All questions asked*)	-2.6	14.7
Delayed post-test – Post-test score (*All questions asked*)	2.5	12.0
Post-test score – Pre-test score (*Common questions asked*)	16.0	17.0
Delayed post-test – Post-test score (*Common questions asked*)	1.8	14.7
(N=49) Cohort 2		
Post-test score – Pre-test score (*All questions asked*)	3.3	15.5
Delayed post-test – Post-test score (*All questions asked*)	8.5	15.1
Post-test score – Pre-test score (*Common questions asked*)	20.0	17.5
Delayed post-test – Post-test score (*Common questions asked*)	10.5	17.4

Table 6.51: Comparing the differences in pairs of test scores between the two cohorts

Table 6.51 shows that there were significant differences between cohorts, considering the difference between the post-test and pre-test percentage marks (p-value < 0.05), the difference between the delayed post-test and the post-test percentage marks (p-value = 0.02), all questions considered. When the common questions only were analysed the difference was significant between the delayed post-test and the post-test percentage scores (p-value = 0.01), but not significant between the post and the pre-test scores (p-value = 0.23). Students in Cohort 2 showed more progress going from start to finish. This supports the analyses of the diagnostic tests results presented earlier in this chapter.

The scores in Table 6.52 show changes in the mean scores within each group of questions in the diagnostic tests (compare the results for Cohort 1 in Table 4.93).

(N=49) Cohort 2								
Diagnostic test	Group A (Microscopic views)		Group B (Models of current)		Group C (How resistances control current)		Group D (conceptualization of p.d.)	
	Mean %	Standard Deviation	Mean %	Standard Deviation	Mean %	Standard Deviation	Mean %	Standard Deviation
Pre-test	25.2	27.7	53.7	31.0	32.7	21.1	45.9	16.0
Post-test	40.8	34.9	70.8	29.4	42.9	31.0	43.8	20.5
Delayed post-test	57.1	34.7	78.2	29.3	46.9	34.9	52.2	18.2

Table 6.52: Means as a percentage for the question groups in all tests

The following are some observations on these results:

- the mean became consistently larger for Group questions A, B and C, going from pre- to post- to delayed post-test, but it dropped from pre- to post-test in Group D. There was a similar trend with Cohort 1 for questions in Group D. This may be a result of having asked more questions probing p.d. in the post-test, making problems with understanding p.d. more visible;
- questions probing models of current have the largest mean values, possibly implying that current is the easiest concept to understand;
- surprisingly, the means for questions about resistance are always less than for p.d. related questions - also evidenced with the Cohort 1. This may be a consequence of the questions asked probing resistance;
- there was a sharp increase in the mean marks for all groups of questions going from post- to delayed post-tests. This indicates knowledge retention for Cohort 2 as well as progress with learning and understanding. It is important to note that this increase was larger for Cohort 2 partly because Cohort 2 started from a lower baseline, indicating that Cohort 2 made a more substantial improvement than Cohort 1.

6.7 The interviews with Cohort 2

6.7.1 Type of interviews conducted

As explained in section 3.10, interviews with a sample of students in Cohort 2 were planned and conducted after students had answered the post-test questions. These interviews were planned with a different aim than those conducted with Cohort 1. It was now important to see why students still found some ideas difficult to grasp, even after having revised the additional teaching activities. Semi-structured interviews were again used at a one-to-one level. Each student was presented with circuit drawings and asked to explain how the circuits would work, in terms of the students' visualizations of how the circuit components function. The interview schedule is shown in Appendix 9, but through the following sections, relevant circuit diagrams are presented for ease of communication.

6.7.2 The sample

Nine students of different ability were interviewed. They were chosen in a similar manner as described for Cohort 1, considering performance on the TOLT and diagnostic tests. Each interview lasted approximately one hour, and was conducted during school hours during a 'free lesson' for both student and researcher. All students showed enthusiasm for having been chosen to participate and were curious about what questions they would be asked.

6.7.3 Deciding on the questions to ask

The electricity course had been conducted in such a way as to introduce ideas to students, in ways which would help students to discuss, reflect upon and visualise complex concepts. The revised PowerPoint presentation (Appendix 7) referred to different models and analogies, trying to improve students' understanding of circuits through various diagrammatic representations. Class discussions about the representations were encouraged amongst the group, to allow space for students' different mental models to surface (Coll et al., 2005).

The interview questions were meant to probe by how far students were using the ideas which had been introduced through the course. Since many of the problems indicated by Cohort 2 had also been indicated by Cohort 1, the decision was made to use the questions which had been used in interviews with Cohort 1, to guide interview questions with Cohort 2. In fact, the same circuit diagrams were now used, without including ammeters and voltmeters, and considering equal resistances only, trying to keep diagrams and ideas presented as simple as possible, avoiding distractors.

Through the study, the underlying hypothesis had been that if students hold a scientific model of the electric circuit rather than just remembering what they had learned by rote, then they would perform well in tests and more importantly, understand and give better qualitative explanations of how circuits work. A number of researchers have claimed the usefulness of analogy in model generation or modification (Clement, 2011; Duit, 1991; Duit & Glynn, 1996; Gentner & Gentner, 1983; Wong, 1993a, 1993b). So it was decided to present the circuit diagrams mentioned above to the students, asking questions probing students' visualizations of how each circuit works. Students were urged to explain what they thought was happening, focussing on comparisons/analogies.

Students were first shown a simple circuit diagram and asked to describe qualitatively what goes on in the wires and components. They were then asked to describe changes, if any, when a second identical resistor is connected, first in series and then in parallel with the first.

Whether students had proposed any analogy or not in the previous answers, when it came to explain about resistors connected in parallel - an area where problems are usually experienced as supported by evidence from the tests - students were prompted to compare the situation to a similarly connected water circuit. The water analogy is one of the most commonly used by authors/researchers, in relation to electricity (Gentner & Gentner, 1983; Hewitt, 2002; Paatz et al., 2004; Schwedes & Dudeck, 1996). In this interview, the prompt used suggested water flow rate as an analogy for current in the first resistor. Ideas were then probed for what current/water flow rate one expects through the second resistor connected in parallel (see Figure 6.5). Students' ideas were then further probed regarding p.d. across the resistors, asking for their views on what happens to the flow rate through each branch, in an analogical water circuit. In this part, expressing the view of an increased water flow rate supplied by the source was crucial to show students' understanding of the concepts.

While some previous research work had made use of analogue feeding target (see Gentner & Gentner, 1983; Gick & Holyoak, 1980; Gick & Holyoak, 1983; Harrison & Treagust, 1993; Treagust, Harrison, Venville & Dagher, 1996), in this study, the situation was reversed. Students had not been coached on the water analogy in depth, so it was hypothesised that if they could explain the water circuit to fit with the electrical ideas, this would be proof of meaningful learning, through the students' ability to construct mental models.

6.7.4 Examining the results of the interviews with Cohort 2

6.7.4.1 Introduction

Analysis of interview transcripts was conducted in the same way as for Cohort 1. The following sections describe results which led to conclusions about students' ways of learning, as well as possible reasons for difficulties encountered.

6.7.4.2 Students' mental visualization of current

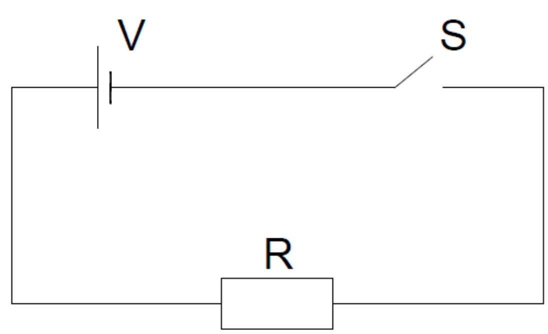


Figure 6.3: The simple circuit diagram shown to students

When students were asked for their mental picture of how a simple circuit works almost all mentioned the movement of electrons from the negative to positive side of the battery. When the conventional current was referred to, students knew that this is indicated opposite to the electron flow. However, in explaining current, a few students seemed confused as they dealt with the two opposite directions used. The following is an extract from an interview transcript. Names in all the following extracts are pseudonyms.

> Phil: For the electrons to move there is repulsion from the negative terminal, but ultimately, for current to flow there is the movement of the conventional current.

This statement seems to suggest that it was two separate 'movements' that were being imagined and that even if electrons flow in the circuit, it is the conventional current which has the final responsibility for the flow. Such ideas can be instrumental in giving rise to unhelpful models of current, like the clashing currents model, for example. This is not to say that this student actually referred to this model, but to point at the possibility of having it induced by teaching, if we are not careful.

6.7.4.3 Some comparisons that students used

Through the interview students were urged to make comparisons between the electric circuit at hand, and something else which helped them visualise what was happening in the circuit. Some students said they did not use comparisons, but just used the equations to guide them. Other students made comparisons as they explained their views.

Kev and Phil explained resistance as follows:

Kev: I imagine the electrons moving. Yes, they move and then in R, **like when we face the wind**, there is a resistance here, but the electrons still manage to pass through it and go back to the battery. In the same way as we manage to pass through the wind.

Phil: The resistance is **like a barrier** that reduces the current flowing. Obviously, this is reduced in the whole circuit, not just before the resistance. So, from the positive terminal less current will come out, such that there is the same current in the whole circuit.

Both students referred to resistance as an object. It is important to note that both students made it clear that current is conserved. This may have been a positive effect resulting from the teaching.

Some students compared voltage to gravitational p.d. This may have been a result of having seen this in the PowerPoint presentation during the course.

Mentioning parallel branches, Phil used the following idea to describe the currents through the branches:

Phil: At school (secondary school) they used to tell us to compare with postmen. I see a number of postmen. The postmen reach the junction and the number of postmen divides between the branches. Some postmen pass through the first R in the first branch, others through the other R. It depends on how large the resistance is. Every postman has the same number of letters for the resistance and the letters are like the voltage.

In this analogy, Phil indicated the postmen which seem to be analogous to electrons within the circuit. In fact, Phil saw that the number of postmen through each branch depending on the resistance. Phil seems to introduce a misconception when referring to voltage. The letters which are delivered should be seen as ‘energy’ delivered to the resistor while current flows. Phil seems to have equated energy to voltage in his example – a common misconception (Engelhardt & Beichner, 2004; Gunstone et al., 2001).

6.7.4.4 Adding an equal resistance in series

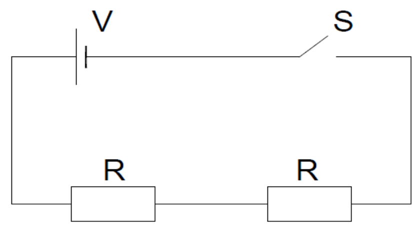


Figure 6.4: The circuit diagram shown to students adding a resistance in series

When students described what happens when an equal R is added in series with the first, all students seemed confident in what they said, acknowledging that R_{total} was now larger and that as a result, the current would decrease.

6.7.4.5 Adding equal resistances in parallel

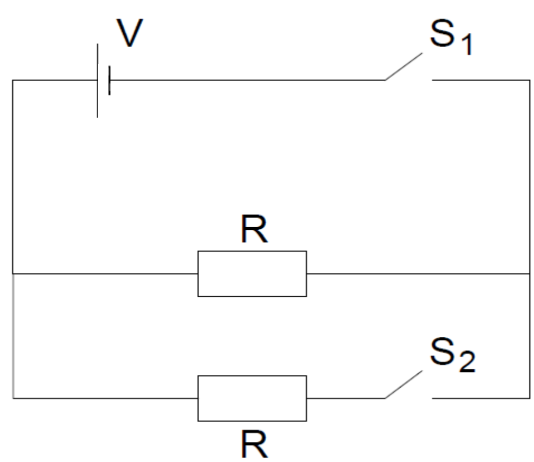


Figure 6.5: The circuit diagram for an added resistance in parallel

While it cannot be said that through the other parts of the interview the students did not fall back on some alternative ideas which they still seemed to hold, it was mainly when it came to dealing with the addition of a parallel resistor, that common problems became more evident.

The first 5 students in a row being interviewed all described their view that when the second resistance is added in a parallel branch, the original current in the circuit with one resistor would be divided into two halves, each half passing through each resistor. As has been already indicated, if students did not come up with a comparison on their own, they were prompted to compare the situation with the water analogy, considering water flow rate. These 5 students said the same thing as what they had described in the electrical situation. Students were assuming the BAT model in electricity (same battery, same current) whilst confirming the claims of Schwedes, Schwedes and Dudeck, and Schwedes and Schilling (as cited in Schwedes & Dudeck, 1996) that similar alternative ideas as in electricity exist when using the water analogy, including the BAT model. These students had all referred to the battery as the pump, pushing the same amount of water into any circuit. Similar responses were also offered by some other students who were interviewed later.

One other student, Stef, had the correct answer for the p.d. across parallel resistances remaining the same but went wrong when it came to using the water analogy. Stef could not offer any causal reasoning to back up the correct answers in electricity. This suggested lack of understanding and probably, rote learning. It may have been that Stef did not have a mental model in mind when answering the question. Stef compared the battery to a motor and used ideas consistent with the BAT model in the water analogy. This did not help the student resolve the confusion in the comparisons made.

6.7.4.6 Conflicts between teacher–researcher

After having interviewed the first 5 students, I started reflecting deeply and questioning myself about what was happening. Students' answers, at least from those interviewed up till now were incorrect with reference to parallel resistors. In my capacity as the teacher I had expected some incorrect results but not for *all* 5 students interviewed till now to be confused about how the circuit works, adding another resistor in parallel with the first. But, when I put on the researcher's hat, I realised that these interviews were indeed being conducted in the spirit of finding reasons for why students in Cohort 2 were still finding problems in the topic, sometimes similar to those which Cohort 1 had shown, even if Cohort 2 had been presented with teaching activities to guide students' understanding. Moreover, this study was geared at answering the research questions outlined in section 3.2. It was possible that these interviews could provide evidence of specific approaches to the learning of the subject, as highlighted by the third research question.

6.7.4.7 An interview with a difference

Once the aims of conducting these interviews were again put in focus, more students were interviewed according to previous appointments which had been made. By coincidence, the next on the list to be interviewed was one of the high ability students in the group - Dan. Dan's interview was labelled 'the interview with a difference' because it made a direct link to one of the research aims of the study. It explained at least one way of how the water analogy can be used successfully helping in providing a specific approach to understand key concepts regarding circuits. Moreover, it provided an answer to why the previously interviewed students had gone wrong in using this analogy. Parts from an extract of Dan's interview shown in Appendix 10 are used below to highlight important points indicated by this student.

Dan was one of the few students who started using the water analogy without being prompted to do so. When a parallel branch was introduced on the circuit drawing, ***Dan easily recognised the extra path now available for current. He immediately saw a lower resistance resulting in a bigger current.***

I: So can you try and visualize the situation in terms of some comparison within another context?
Dan: Now there are 2 paths for the electrons and these have a better chance to pass… They pass more easily. More of them pass.
I: More of them move?
Dan: In fact, the battery gets drained more easily. In fact, when the resistance is less, more electrons flow……. Here there is a lower resistance, the battery is used up quicker and the electrons move and separate out more easily.

Dan used the water analogy together with the gravitational field concept to understand voltage and p.d. He linked water height to pressure and imagined potential and p.d. as some kind of electrical pressure. Other students had also linked p.d. with gravitational potential difference, perhaps recalling slides in the PowerPoint presentation they had seen through the course. The difference lay in that these students all then compared the battery to a pump. Dan used the idea of a tank with different pipes connected to it, representing different branches.

Dan: You can consider the battery as a tank which is placed high up so that you can create the p.d. You put the tank high up and a pipe lower down. In this case you are using 2 pipes since there are 2 resistances in parallel. The 2 pipes are in parallel. The water comes out of the tank more quickly from 2 pipes instead of 1. More water comes out, because if there is just 1 pipe, a certain amount of water is released, but if you open another outlet there will be two pipes. The pipes have to be the same width if the resistances are the same and more water comes out.

The problem which other students had was that using the pump idea, they did not see a variable supply of water from it. Using a tank and a variable amount of pipes, Dan did not have this problem.

Moreover, through the interview, Dan interchanged ideas about analogue and target with ease, showing deep understanding.

I: And if you were to imagine a certain amount of water flowing, say 100 cm^3/s, flowing when you only had one resistor?

Dan: **This is the 'current' in terms of water flow**. Now with electrons the current is electrons per second. In fact current is charge transfer per unit time.

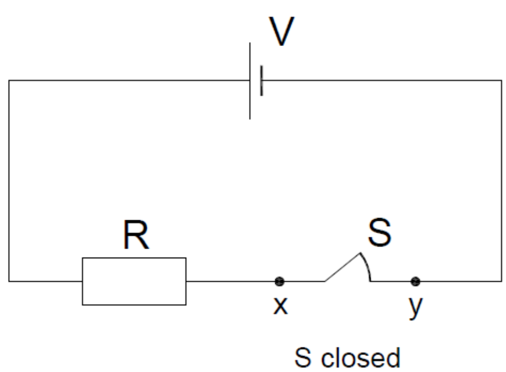
I: So now, how would you imagine the situation when switch 2 is switched on?

Dan: Now the rate will be increased. It will be doubled. Double what it was before, since a new path has been introduced. **They both have the same pressure, these pipes, since the voltage remains the same.** The two pipes will have the same pressure of water through them, because the pressure is the same and you've opened a larger flow of water. So now you have an extra 100 cm^3/s. Now you have 200 cm^3/s.

Dan thus showed his ability to think, reflect, compare and refine his thoughts. The student used a cyclic refinement of thought, going from analogue to target and vice versa, appreciating that each example can be used creatively to help understand the other (Gick & Holyoak, 1980, 1983). Bauer and Richter, and Steiner (as cited in Duit, 1991) refer to this as "a 'two way' process involving developing both analogue and target" (p. 653). The student admitted that through the use of the analogy he could 'see' and solve a complicated system more easily.

Dan: You can imagine new pathways, extra pipes for water to pass through. You have a complicated system and you can see it better with this comparison. It depends though. If you have four or five resistors, then you have to imagine different widths, lengths…. But in terms of the concept, it is always the same.

These extracts reveal how Dan explained the concepts involved elegantly and correctly. The student also explained what helped in making him reach the stage where ideas were more meaningful and clearer to him. Interestingly, he had met the right people at school who had used analogies which were appealing to him e.g. his teacher of 'Electrostatics', and myself when I presented the PowerPoint presentation to the class. One cannot but note the motivation and curiosity with which the student confronted learning, his need to discover what was happening in the electric circuit, since a young age, never giving up and using different instances in his student life to improve his knowledge, nurturing his imagination and clarifying his doubts. The student had already been noticed to be one of the more able students and had since a long time learnt to exercise his 'intellectual wings' (see Freeman, 1995; Span, 1995).



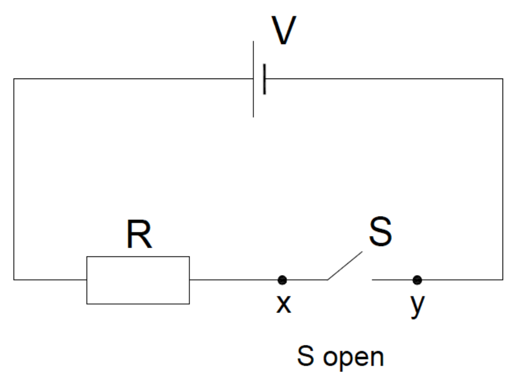


Figure 6.6: Circuit with switch closed **Figure 6.7: Circuit with switch open**

Moving on to another part of the interview when the circuit diagrams in Figures 6.6 and 6.7 were shown to Dan, he used his analogy further giving a correct answer backed with causal reasoning. All the other students interviewed had opted to predict zero p.d. across an open switch in a simple circuit with no current. Dan answered as follows:

> Dan: The voltmeter reads V. There isn't the same pressure here. The pipe is split. On one side there is more pressure than on the other side. At the negative plate (the negative end of the battery) there are more electrons, and at the other end there is less and you see a potential difference.

Dan's interview was one out of the nine interviews conducted with Cohort 2. It can be argued that basing conclusions on what just one student said, may not necessarily help our teaching and learning methods. Yet, previous work by Niedderer (1994, 1996) and Clement and Steinberg (2002) also present important research with one student. Furthermore, Dan's answers during the interview cannot be ignored. The evidence of Dan's understanding of the topic was very convincing. Admittedly, more research is needed in this area, looking into the effectiveness of the teaching approach using the water analogy as explained by Dan. For now, this analogy using a water tank and pipes, can still be considered as a tool to help understanding of the topic, especially p.d., thus offering an answer to the third research question of this study.

6.7.5 Conclusion from the results of the interviews

These interviews helped to show that problems in student learning could be a result of students not being able to link their ideas to useful visualizations of what goes on in the electric circuit. Alternative ideas also offer mental visualisations, but these mislead the learner and thus understanding does not progress. In this case, comparing the battery to a high level water tank and pipes leading to a lower level made it easier to understand *the system* with resistances connected in parallel. When students compared the battery to a pump, alternative views were at the forefront in both analogue and target and this impeded the possibility of getting at a correct interpretation of the facts. Using analogies in teaching may help if the correct ones are used or indicated to the students. Some students may find their own way and their own solutions, as has been shown above, while others need clear guidance from the teacher. This links well with results from a study by Sutala and Krajcik (as cited in Duit, 1991) when it was found “that students with high cognitive abilities benefited more from creating their own analogical connections, whereas students with low abilities benefitted more from having the teacher help them make the analogical connection” (p. 657).

Glynn et al. (as cited in Duit, 1991) describe analogies as “double edged swords” (p. 666). This was evident from these interviews. Reference has been made to how the water analogy was used by interviewees who focussed on the misconceptions of it, supporting misconceptions related to the electric circuit (like the BAT model: same battery same current). Dan, on the other hand, used the analogy fruitfully in a different way, benefitting from understanding and meaningful learning. The implication is that care is required in the choice of which analogy to use and how to use it as a useful tool helping learning to progress.

The interviews also showed how important it is to motivate and instil curiosity in our students. “Curiosity, at its core, is all about noticing and being drawn to things we find interesting. It’s about recognizing and seizing the pleasures that novel experiences offer us, and finding novelty and meaning even in experiences that are familiar” (Kashdan, 2010).

There was evidence shown that when the motivation to learn exists, then there is room and time for reflection, for comparisons, and for refinement of thought, even if scientific ideas do not develop immediately.

6.8 Conclusion from the 2nd cycle of the research

The performance of students in Cohort 2 was significantly weaker at the pre-test stage, when compared to that of Cohort 1, however, the analysis of the results gave evidence that students' performance improved in the post-test. Not only did students show retention of knowledge gained but they showed further overall improvement in the delayed post-test. Compared with Cohort 1, Cohort 2 made better progress.

The teaching activities used with the Cohort 2 were shown to have helped some students' understanding but this did not happen in all areas and to the same extent. Current conservation became more noticeable, as was the idea of how resistances work, even if persistent reference to ideas consistent with the BAT model remained. Problems were still evident with parallel circuits, especially with p.d. across branches carrying unequal resistances. Problems with p.d. in the context of no current flow were also found difficult to deal with. Learning did not progress at the same pace, in all directions. Areas which students found easier to deal with were distinguished from other areas which proved more demanding or hierarchically more difficult.

The interviews with the Cohort 2 helped in supporting the researcher's hypothesis that when students have useful visualizations of how a circuit works, then causal reasoning can be managed and used fruitfully to develop knowledge with understanding. The indication was that possible use of analogies and analogical reasoning in teaching may help guide students away from rote learning, through the formulation of meaningful ideas because of increased curiosity and motivation. Using analogy as a two-way process, analogue feeding target, and vice versa, can help refine ideas related to complex concepts, as well as developing scientific ones.

Having analysed the results of the research with Cohort 2, linking it with that from Cohort 1, the next step was to reflect on the results while looking back at the research questions to decide how this study helped in answering them. This is dealt with in the next chapter.

Chapter 7 Reflections and Conclusions

7.1 Introduction

This chapter reflects on the results from the diagnostic tests, interviews, teaching activities and class discussions with both cohorts. The aim is not to repeat what has been discussed in detail in the previous chapters but to explore how far the research questions have been answered, and at the same time help to elaborate and highlight innovative material which results from this work. Strengths and weaknesses of the study, as well as suggestions for future work are also indicated.

7.2 Reflections on the first research question

The research questions which guided this study were stated in section 3.2. The reader is reminded of each question in respective sections of this chapter, at the same time as answers to the questions, as revealed by this study, are outlined.

The first question was aimed at probing which *mental models post-secondary students appear to useas they learn about electric circuits*. It can be said that the detailed analyses of the results of the tests, interviews and discussions with both cohorts described in Chapters 4, 5 and 6 amply indicated students' ideas consistent with different models of current, resistance and p.d. With regard to current, there was evidence that students at this level and in this context seemed to use either conservation or attenuation models. Progress from attenuation to current conservation, in questions probing current models, seemed easily managed by the majority of students. This did not necessarily imply that students did not use attenuation in problems probing the meaning of resistance.

The model depicting the battery as the source of charges which move into the circuit when this is closed was also widely evidenced. With both cohorts, about one half of the sample held on to this view, even after teaching.

Some students put a focus on the battery once again when they used ideas consistent with the BAT model (same battery, same current) in questions probing the meaning of resistance. Views consistent with the R-TAKE model (a larger resistance 'needs' more current than a smaller one) and the SHARE model (current is shared between resistances) appeared as well. The BAT model seemed to become more popular with students after teaching.

Moreover, apart from the scientific view of p.d. as some difference between points, with a few students acknowledging movement of charge due to attractive and repulsive forces from battery terminals, the view of p.d. as a property of current or as equivalent to current was also observed. Many split p.d. at junctions and could only see p.d. in the presence of a current. The modelling of p.d. as some kind of flow was quite pronounced.

Links between these mental models shall be further elaborated upon as reflections about this research and its analysis are outlined in the next sections.

7.3 Reflections on the second research question

7.3.1 Learning pathways in terms of mental models

The second question related to *whether learning pathways can be shown to exist, in terms of the mental models students seem to develop as they learn the topic*. It must be admitted that this question was not easy to answer because ideas change as they are developing and probing for what can sometimes be a momentary best account of an idea is difficult. Norman (as cited inBorges &Gilbert, 1999) claims that mental models are "unstable, naturally evolving and incomplete" (p. 96). However, the study design helped in getting information about students' ideas using different research instruments at different stages during the teaching, as has been described in previous chapters. Moreover, persistence on the part of the researcher in probing students' ideas during interviews and discussions, trying not to miss opportunities to get to the bottom of students' difficulties whenever possible, also helped. Students' talk was guided by careful questioning, making students' ideas clearer to both students themselves, as well as to the researcher. This made it possible for students to become more meta-cognitively aware of their views and mental visualisations, helping their understanding to develop. At the same time, the researcher had the possibility of depicting a global picture of how ideas from different students seemed to evolve along learning pathways.

Earlier research studies (e.g., Clement & Steinberg, 2002; Niedderer & Goldberg, 1994, 1996; Scott, 1992) exposed learning pathways as tools to help develop learning and understanding. In this study, the researcher followed the development of students' ideas by carefully examining:

- how ideas consistent with specific mental models changed through the course of study by analysing the results of the PDTs;
- the similarities and differences between ideas of students of different ability by analysing interview transcripts.

To give an example, when interviewees were asked to describe their mental picture of what happens when a circuit is switched on, each response was examined and students' ideas were followed until some meaning was expressed which described current flow and what causes it. Students' views were then put together constructing the global picture shown in Figure 5.2. Thus learning pathways were identified.

Learning pathways inevitably put ideas and concepts in a hierarchy, providing possible intermediate steps progressing from intuitive ideas to scientific ones. A list of ideas/models which were inferred during this research was drawn up based on the level of difficulty students indicated while explaining their answers in questionnaires and interviews. Moreover, careful analysis of mental models related to electric circuits, as proposed by earlier works, were also put in a hierarchical list which logically explains the progression of ideas. It was reasonable to expect that cognitive development affects students' understanding. Thus, in this study with students at post-secondary level, it was not necessarily expected that all students would start by using ideas at the very bottom end of any hierarchical list of mental models proposed. On the other hand, similar to what happens in the classroom situation, not all students were expected to necessarily manage a complete scientific understanding of all concepts introduced through the course.

Comparing the mental models inferred bystudents in the present study with models from previous works, some differences became evident. By linking the results from this research with that proposed in earlier works, a learning model in terms of mental model pathways was designed, showing how students' ideas seem to evolve during the study of electric circuits.

The following section describes the details of reflections which guided the design of this learning model in terms of mental model pathways leading to the understanding of current, resistance and p.d.

7.3.2 Reflections on researchers' efforts to map students' learning of electric circuits in terms of mental model pathways

7.3.2.1 Studies which took a central role during reflections

The early works of Shipstone (1984, 1985b) presenting possible mental models of current, were of particular importance in these reflections. More recent work by Grotzer and Sudbury (2000) and also by Borges and Gilbert (1999) also played an important role and had a big influence on the conclusions from the reflections. The latter works go further than just looking at models of ***how*** current flows, but look for causal models to explain ***why*** a circuit functions the way it does, as a system.

7.3.2.2 Shipstone's work proposing models of current

Shipstone's work (1984, 1985b) already indicated a learning pathway for models of current. This pathway starts at young students' intuition of the unipolar model. Students may use other models as ideas develop depending on age and experience (Shipstone, 1985b), leading the way to current conservation. This progression of ideas is shown in Figure 7.1 indicating how Shipstone's models of current (see also Figure 2.2) can be presented as a logical hierarchy of models, starting at an intuitive level held at an early age, progressing towards the scientific view.

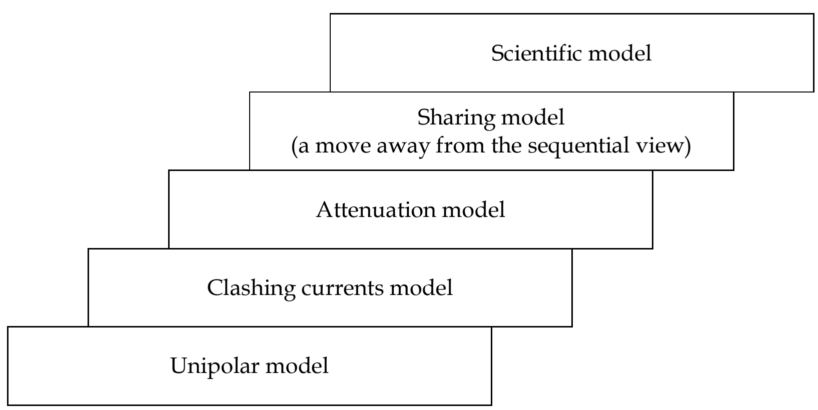


Figure 7.1: Shipstone's models of current in a hierarchy

The unipolar model stands at the lowest end of the hierarchy since individuals holding this model do not yet visualize a complete loop for current to flow. The clashing currents view takes us a step up along the hierarchy because it exists when intuitions require the presence of a closed loop. The attenuation model is the first model which considers flow of current in one direction, but it is the sharing model which moves away from a sequential view of what goes on in the circuit (Grotzer & Sudbury, 2000). The scientific view of current conservation stands at the highest level.

As has been explained above, an individual's view may not necessarily start at the lowest level in the hierarchy. It can start at any level depending on age, personal experience and cognitive ability. Students in this study at post-secondary level indicated ideas which were consistent with the attenuation and scientific models. When the sharing option was presented, many indicated a tendency to use this idea.

7.3.2.3 Causal models of electric circuits suggested by Grotzer and Sudbury

The causal models suggested by Grotzer and Sudbury (2000) follow a logical evolution similar to Shipstone's models, but move on further to models explaining the reason for current flow in terms of p.d. as some kind of difference between points. These models have also been put in a hierarchy, shown in Figure 7.2. The latter summarises the explanation and diagrams included in section 2.7.3.

The 'simple linear causal model' is at the lowest level in the hierarchy, leading on to models at a higher conceptual level, finally reaching the scientific view providing reasons for ***why*** there is a current in a closed circuit, viewing a system at work.

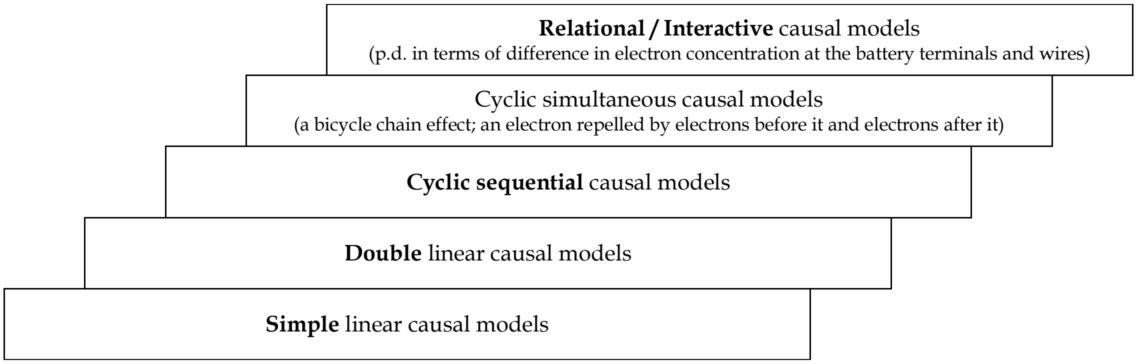


Figure 7.2: Causal models of electric circuits suggested by Grotzer and Sudbury (2000)

7.3.2.4 Models of electric circuits reported by Borges and Gilbert

Borges and Gilbert (1999), on the other hand, report four levels in the development of models of electric circuits (see Figure 7.3). These levels can once again be seen as indicating a natural progression from a simple view of current as some kind of moving fluid, to models which explain the reason for the presence of p.d. These authors use the general term ‘electricity’ to describe views held by individuals they interviewed, explaining how a simple circuit works and why it works in this way.

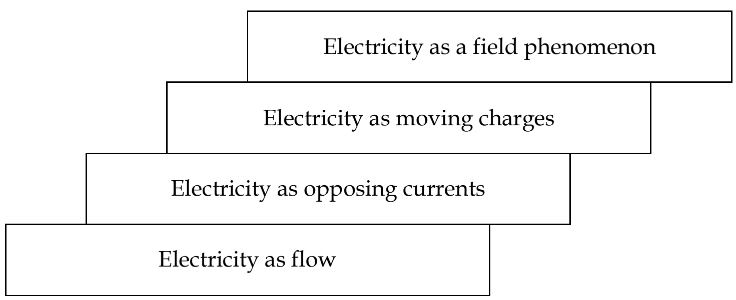


Figure 7.3: A progression of models of electric circuits reported by Borges and Gilbert (1999)

The two lower levels refer to non-scientific models of current which are similar to those described by Shipstone’s work. It is the upper two levels in this group of models which are more interesting to follow in relation to the findings from the present research project, given the problems experienced with understanding p.d. by both cohorts in this study. These two levels are thus explained in more detail below.

When Borges and Gilbert (1999) refer to 'Electricity as moving charges', they claim that the visualization is of electric charges moving through a conductor in a closed circuit. Descriptions of what happens follow a time-dependent sequence of events, with emphasis made on individual components. The circuit is thus not seen as a system.

In describing the circuit in terms of 'Electricity as a field phenomenon', they claim that the individual can explain how charges move under the action of a p.d., with current being conserved. The battery is seen as maintaining a difference in potential between its terminals, creating an electric field. The circuit is here seen as an interacting system.

7.3.2.5 An intermediate model proposed by the present study

The details explained in section 7.3.2.4 were of particular interest to this work because when compared to students' answers in the present study, not one student in either cohort mentioned the presence of an electric field and its effects within the electric circuit. The best a few students did was to 'see' the flow of charge in terms of forces resulting because of the attraction of electrons towards the positive terminal of the battery and their repulsion away from the negative end (see White, 1993). Mitch was amongst these few students. He was a high (H) ability student from Cohort 1. The following are short extracts from responses during successive interviews that Mitch had with the researcher.

M (H): All the current coming out of the battery must enter the other side. As in Kirchhoff's law, it is the same amount leaving the battery, equal to the amount entering it. It is not the same exact electrons, but the same amount.

I: What does the potential difference really mean to you?
M (H): The attraction between the positive and negative side of the battery.
I: Can you explain a bit more on this?
M (H): Because there is a positive charge on the positive side of the battery and this attracts negatively charged electrons on the negative side of the battery.

I: Is there a p.d. across the open switch
M (H): Zero.
I: What is your reason for saying this?
M (H): No energy transfer is passing through the circuit.

These extracts show that Mitch had ideas consistent with current conservation (first extract) and saw p.d. as the attraction between charges at the two battery terminals (second extract). This student, however, gave no evidence that he saw the presence of an electric field in a closed circuit, even if the circuit was seen as an interacting system. This inability to see the field created problems when Mitch dealt with the p.d. across an open switch (third extract) - the existence of p.d. without a current was not acknowledged.

Indeed, this study provided evidence that a *few students, like Mitch, saw the interacting circuit as a system without acknowledging the presence of the electric field* (see also section 5.7). This helped to identify an intermediate model which can be added between the last two levels in the list proposed by Borges and Gilbert (1999), since some students' answers seem to imply that they hold a view which is somewhere between these levels. I shall refer to this intermediate model as the '***The symptoms of field phenomenon***' (see figure 7.4), since it bridges a gap between the 'Electricity as moving charges' and the 'Electricity as a field phenomenon' level.

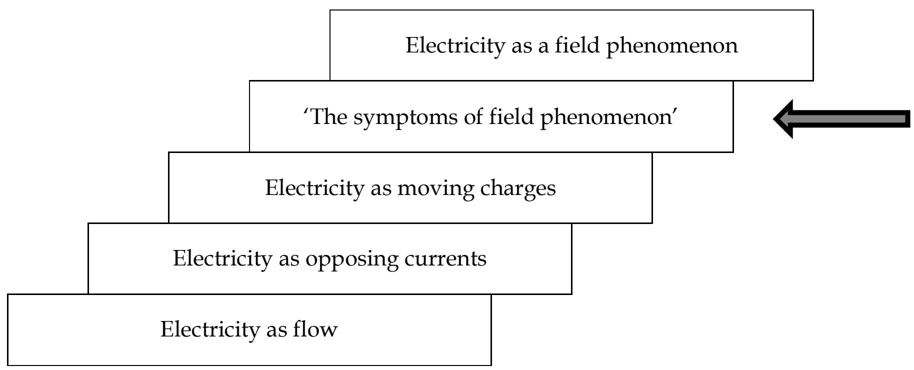


Figure 7.4: Introducing an intermediate model – 'The symptoms of field phenomenon'

7.3.2.6 Splitting a mental model level into two

Another interesting point to note is that the 'Electricity as a field phenomenon', as described by Borges and Gilbert (1999), does not elaborate on the fact that the electric field within the circuit exists because of the presence of the battery, **both** when a current is flowing and when the flow is interrupted. The present study provided evidence that students from both cohorts found it more difficult to see a p.d. when no current was flowing (see sections 4.4.5.6 and 6.5.5 and the interviews with Cohort 1 and Cohort 2). The present study suggests that the 'Electricity as a field phenomenon' level proposed by Borges and Gilbert (1999), be split into two levels. Individuals who can explain the presence of a p.d. across an open switch can be said to have moved towards a more ‘complete’ understanding of p.d. than those who can model p.d. and acknowledge its presence only when a current flows. This finding helped the researcher to see more clearly how models of p.d. which students seemed to use in this study can be linked with those suggested by previous works.

7.3.2.7 Models of p.d. proposed in a hierarchy

The reflections elaborated upon in the previous sections, together with students’ responses during this study, made it possible to put models of p.d. together in a hierarchy indicating logical progress towards the scientific view. This is shown in Figure 7.5.

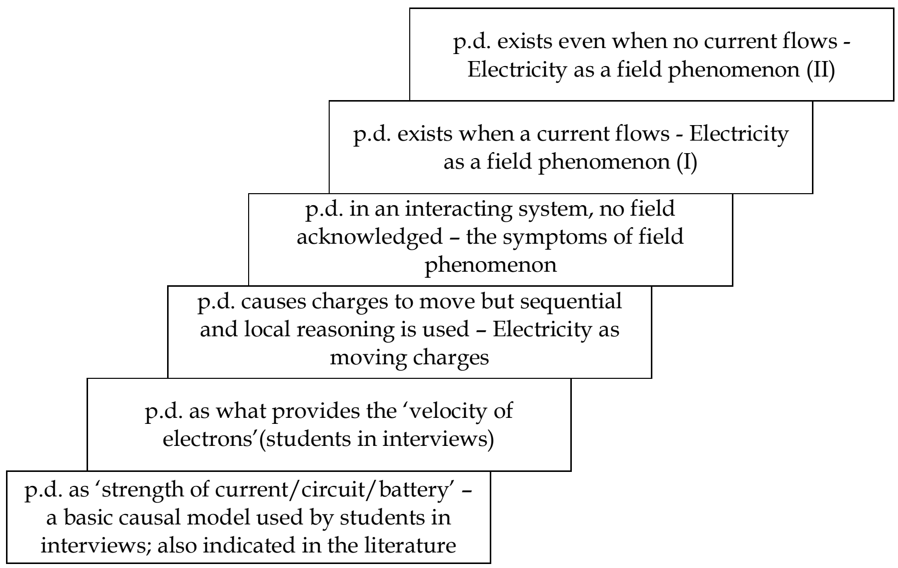


Figure 7.5: A hierarchy of mental models of p.d.

At the lowest level, p.d. is viewed as ‘strength of the current’. Chris (A), an average student from Cohort 1, for example, saw ‘voltage as the strength of the current – how that strength varies across the terminals’. This is a basic causal model referred to by some students during interviews, as well as one referred to in the literature (see Duit & von Rhöneck, 1998).

In the interviews students also referred to p.d. as what provides ‘velocity to the electrons’. The indication of something moving as a result of p.d. puts this model at a slightly higher level than the previous. The four other levels use Borges and Gilbert’s (1999) models with the adjustments/additions suggested in the previous sections, leading to levels where p.d. is understood in terms of the presence of the field, even when no current flows.

7.3.2.8 A unified view of models of electric circuit

Once a view of possible mental models of current and p.d. in a hierarchy was clear, reflection turned on how these models could be linked.

Students had indicated their microscopic mental models of current, especially Cohort 1, who were not just questioned about these ideas in the Physics Diagnostic Tests but also interviewed (see Chapter 5 and also section 7.3.1). Some had seen charges in the battery only, or in connecting wires only, or in both, before the circuit was connected. Some students visualised the battery push when the circuit was switched on, while others had not. These visualizations led to an understanding of how something was flowing. Only when these microscopic models of current could be linked with models of how resistance affects the current in the circuit could the models of current suggested by Shipstone (1984, 1985b) start having any significance within a unified learning model for electric circuits.

When students viewed resistance as 'a blockage'/'a gate'/'a crowd of people', described resistance as 'taking energy from the current' and had ideas consistent with sequential reasoning and attenuation, students saw more current before the resistance than after it. Resistance was seen as 'absorbing' something flowing through it, which was coming from the battery, or the connecting wires or both. When students' microscopic views were linked with answers in the PDTs like 'the current is shared between the two resistors, so each gets half', the SHARE model of current (see section 4.4.4.4) was inferred. Thus, ideas about what makes current, linked to how resistance affects current lead to mental models of current. Shipstone's (1984, 1985b) models of current can then be seen to result from this link.

Furthermore, models of current must be also linked in some way with those proposed for p.d. in Figure 7.5. This is suggested by the fact that p.d. is treated like current by many individuals, as this study has shown clearly. When one student said: 'If you have a motor, say with 4V, it goes faster than when it is at 2V. So it is the strength of the current. It goes faster', a clear distinction between p.d. and current was not provided. When students applied the rule $V_1 + V_2 = V_{supply}$ (see section 5.5.3) without providing valid reasons for why this was so, they seemed to have had a mental model of p.d. equating it with current.

Moreover, many students only saw p.d. in the presence of a current. One student said: ‘I see no charges passing through the switch, otherwise the voltmeter would give a reading’. Another student said: ‘V2 will not read anything. If no electrons are passing, as I imagine it, the voltmeter will not give a reading’. And yet another said: ‘V2 gave a reading. There must be a current through V2’, thus explicitly associating the voltmeter reading with current.

Furthermore, until ideas move on from the treatment of p.d. as current, individuals cannot understand how the circuit works and provide valid reasons for their views. This level of reasoning can only be said to be complete when p.d. is linked to the presence of the electric field within the circuit, the circuit being treated as an interacting system. Reasoning and understanding can only be assumed complete and scientific when p.d. is seen as “a relationship of imbalance” (Grotzer & Sudbury, 2000, p.10) which exists even in an open circuit.

This learning model for electric circuits in terms of an evolving sequence of mental models is shown in Figure 7.6. It is a unifying model which helps to give a holistic picture of how individuals’ views of how a simple circuit works may develop along learning pathways, as understanding progresses.

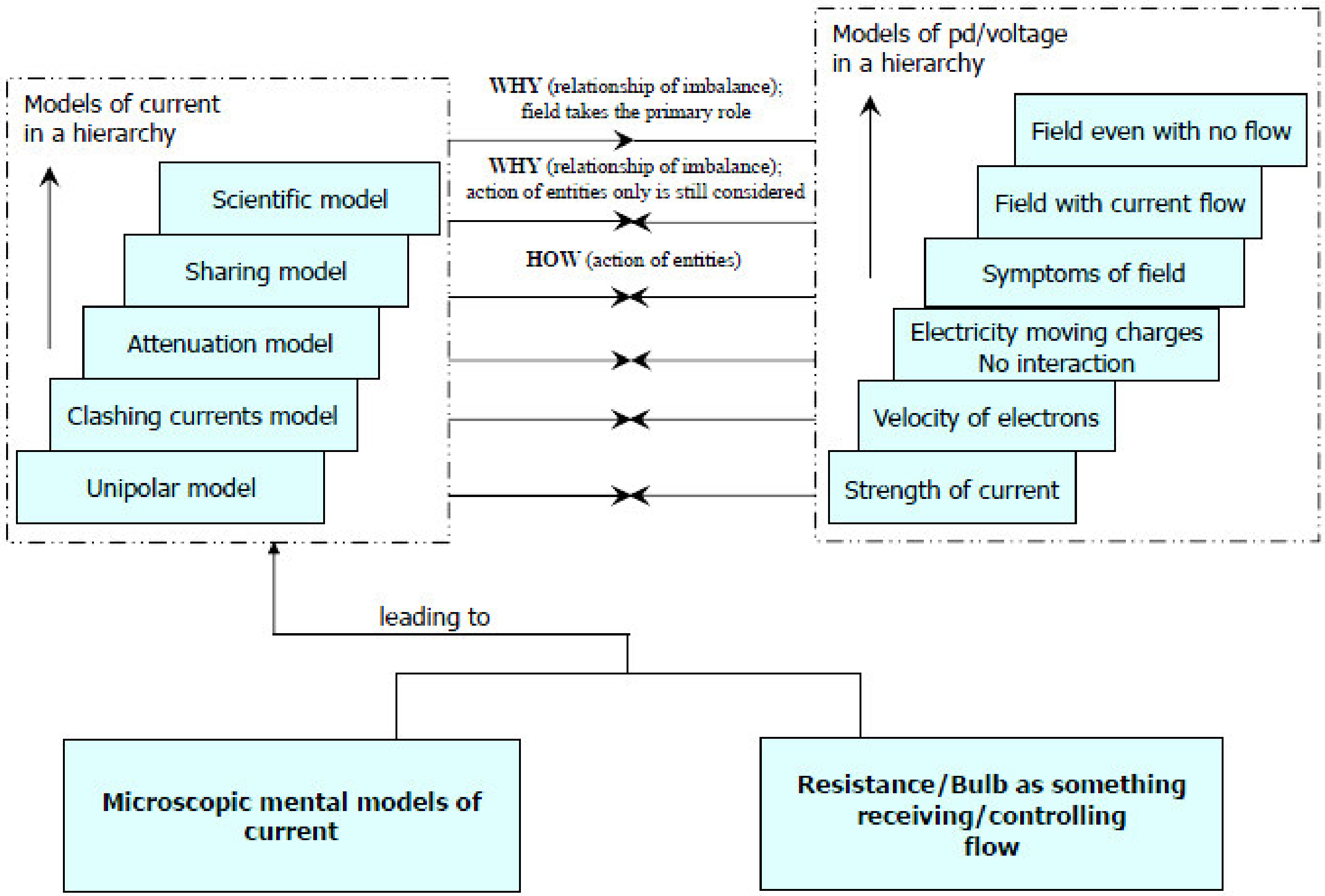


Figure 7.6: A learning model for electric circuits in terms of mental models placed in a hierarchical structure

Looking closely at this learning model and at p.d. in particular, it can be seen that what is being proposed is that, before one can completely understand p.d., one has to know about and be able to visualize the electric field. This is quite acceptable, even if it must be acknowledged that both p.d. and the electric field concepts are difficult to grasp. P.d. seems, however, the more abstract of the two concepts since visualizing the field can be made more concrete using experiments like the ones suggested by Jefimenko (1962) (see section 2.7.5).

7.4 Reflections on the third research question

The third research question asked for *evidence of whether particular approaches used during the teaching process can influence students' thinking, guiding them towards the use of scientific mental models of the electric circuit*. Through this action research project a number of teaching activities were used with the aim of improving students' understanding. Not all activities helped to the same extent.

A teaching activity which had helped to improve students' understanding of current included the use of the PhET (Physics Education Technology, 2008) simulations. These were used with Cohort 2 after some students from Cohort 1 had remarked that by seeing the charges move round the circuit while viewing sections of the DVD, they could mentally visualize the charge flow occurring simultaneously in all parts of the circuit (see section 3.8.5). The PhET simulations helped students 'see' the abstract. With Cohort 2, these simulations were not used alone. They were complemented by the 'electron experience task' (see section 6.3.4) with students being asked to write in their own words how they visualized the movement of an electron within a circuit. Students were thus made to concentrate on what happens to charges within the circuit. Writing about their ideas and discussing them with their peers and the teacher, students became aware of their alternative views. Similarly to what is claimed by Duschl, Schweingruber and Shouse (2006), this introduced students to views, other than their own, and directed students to evaluate their ideas. When this was done, results indicated progress. In fact, Cohort 2 made noticeable improvement as regards ideas about current conservation, as has been documented in Chapter 6.

The PowerPoint presentation shown to students (see Appendix 7) and discussed with them was also helpful. The presentation exposed students to different analogies related to current, resistances connected in series and in parallel, and p.d. Thus students could ponder upon the meaning of important concepts, comparing ideas from other contexts with what goes on in the electric circuit. While some studies claim that analogies can confuse students (see for example, Duit, 1991; Glynn, 1991; Harrison, 2001), authors like Else, Clement and Rea-Ramirez (2008) refer to articles by Brown and Clement, Clement, and Spiro, Coulson and Anderson claiming "that using multiple analogies was helpful in overcoming the shortcomings of individual analogies" (p. 216). Moreover, a student may benefit from being allowed to choose the analogy which appeals most to him/her, as long as it suits the understanding of the target in question.

When Cohort 1 had seen this presentation at the end of the course, students said that the ideas had clarified their doubts. The following was the reaction from a Cohort 1 student, at the end of the PowerPoint presentation:

'These slides answered those questions which I have been asking myself and struggling with through the course. To have seen this presentation early would have been beneficial'.

Since this was not the only student who reacted this way, it was decided that the presentation would be used with Cohort 2 earlier in the course. The results of this study did not show that students' understanding progressed immediately with regard to current, resistance and p.d. However, Cohort 2 made a significantly larger improvement than Cohort 1 between the pre-test stage and the delayed post-test stage (see section 6.6.2). Evidence has also been presented in Chapter 6 pointing to how analogies used during the PowerPoint presentation could help. When Dan, a high ability student, linked his views of electric circuits to the water analogy using tanks and pipes (see section 6.7.4.7), meaningful learning was an outcome. The student easily 'saw' how the p.d. across parallel resistors could be explained. This was an important piece of evidence even if it came from one student only because this student had reflected deeply about his mental visualization of the circuit and had outlined a way of comparing the behavior of water to the flow of current in circuits in an easy way which can be effective if used with other students. Other students did not interact with knowledge in the same way. Clement (2009) acknowledges that 'it is difficult to capture multiple instances of unusually creative behavior' (p. 505).

As a general comment, from a teacher's perspective, the PowerPoint presentation was seen as a means of engaging the students, guiding them to a minds-on activity, as they could analyze their thoughts.

With reference to the Predict-Observe-Explain (POE) tasks, these proved "strikingly effective" as Millar (2004, p. 10) has described them. Students were motivated because they got immediate feedback for their answers – correct or incorrect. When incorrect answers were predicted, conflicts arose between students' unhelpful visualizations/mental representations and the results obtained, urging students to try and resolve their difficulties, if that could be helped. Reference to this was made in Chapter 4 using extracts from students' transcripts. The POEs helped students become accustomed to asking a very important question in science: 'Why?'. During this study, having noticed how students can be urged to give more meaning to knowledge acquired by complimenting their answer with reasons for it, I started to ask this question to students more frequently throughout my teaching. Students thus realized the importance of supporting their answers with causal reasoning.

While this study gave evidence of students' progress, yet it also pointed towards the need of helping students more in their understanding of parallel circuits, in overcoming the strong inclination of using ideas consistent with the BAT model and in not treating p.d. like current. Teaching activities directed at improving these areas of study, had not been very effective.

On the other hand evidence was provided showing that when students were given an opportunity, through various activities, to interact with their teacher/researcher and their peers, this was translated into learning with understanding. To summarise, the activities that made a difference included:

- having students talk about their writings in teacher guided class discussions;
- 'seeing'the abstract and being guided to discover mental pictures and to speak about them, using simulations like the PhET;
- discussing the PowerPoint presentation introducing different analogies, improving mental pictures to aid learning;
- using POE tasks, complementing predictions/answers with reasons for them.

7.5 The contribution to knowledge made by this study

The reflections on each research question in the previous sections of this chapter indicate key elements of the contribution to knowledge made by this study.

It was found that while the course work helped students make considerable improvement in moving on from alternative ideas of current like attenuation, some students still used these ideas when other concepts were involved like, for example, when dealing with resistance.

This study also showed that the BAT model (same battery, same current) could be reinforced by teaching. This has not been referred to by any previous work and it happened in spite of the researcher's attention to avoid descriptions of the electric circuit which may reinforce misconceptions, as well as the introduction of teaching activities to promote scientific reasoning.

Interpretations of students' answers during interviews made it possible to augment Borges and Gilbert's (1999) models of electricity. An intermediate model of p.d. ('the symptoms of field model' in Figure 7.4) was included and the 'Electricity as field phenomenon' was split into two levels (see Figure 7.5). These adjustments made it possible to better understand how students' ideas may develop as understanding of p.d. develops.

The main contribution to knowledge which this study makes, however, is the development of a more integrated model that links the ideas students have of current, resistance and p.d. (see Figure 7.6). Such links have not been elaborated upon by previous work. Figure 7.6 was constructed by putting together ideas from previous literature and adding the results and interpretations from this study. The mental models of electric circuits are shown as an evolving sequence of ideas put in a logical hierarchical order. Students' development of ideas cannot be expected to necessarily start at the lowest level of any hierarchy, moving step by step to higher levels until ideas become scientific. Much depends on students' cognitive development, their experience prior to the course of study and students' interest in meaningful learning, as opposed to just recalling material needed to pass an exam. It should also be made clear that students' ideas of current, as shown in Figure 7.6, are not necessarily expected to develop in line with those of p.d., as shown in the same diagram. Indeed, this study showed that most students first managed to relate to the scientific view of current, before they grasped the meaning of p.d. Moreover, depending on students' retention of ideas or the lack of it, the possibility exists of having ideas either developing or regressing along the levels shown in the hierarchy. The ideas proposed in Figure 7.6 can indeed be used by teachers as a guide to help decide students' level of understanding of the concepts related to electric circuits. Thus lesson preparation can be better focused on helping students develop their understanding, moving towards the scientific view.

7.6 Strengths and weaknesses of the study

7.6.1 A general note onteaching and learning

Duschl et al. (2006) claim that "the power of schooling is its potential to make available other people, including adults and peers, to learn with; thought-provoking tasks; tools that both boost and shape thinking; and activity structures that encapsulate learning-supportive norms and processes" (p.2.13). A strength of this study was that this power of schooling was made use of in this action research study, using research techniques which probed students' ideas, while at the same time making students think. Students' participation in the research gave them an incentive to improve their understanding of the topic, the latter being part of a course leading to an important examination which would decide the students' future academically. This contrasts with research studies of students' ideas, involving subjects who may have a low commitment to understanding.

Students' views were exposed as the learning of how the electric circuit works was in progress, using tools which challenged and engaged the students, as students became meta-cognitively aware of their understanding or their problems with it. This research has provided substantial evidence of how students' learning evolved during instruction of the topic. It showed ideas which students easily understood, as opposed to those which students found difficulty to relate with. It showed the difference which exists between students of low, average and high ability in the way they use ideas to promote their understanding of this topic. Putting mental models in hierarchical order showing how individuals can move to ideas which are still abstract but more complex, like p.d. for example, is one of the strengths of this work. Indicating levels of complexity linking abstract concepts can help learners as they make sense of what more needs to be learnt. It can also help teachers during lesson preparation and lesson delivery. This is much in line with what advocates of formative assessment propose (see for example, Boston, 2002; Bell & Cowie, 2001).

On the other hand, the research methods used offer guidance for other researchers who wish to follow up similar work in this particular area. The study emphasizes the importance of knowing what students' ideas are and the reasons behind these ideas, at the same time as indicating instruments and methods which can help in gaining this knowledge. This can form a base for future research. Moreover, adopting similar research methods that emphasize causal reasoning may also be useful in helping to understand how learning progresses in other areas in physics, dealing with complex and abstract ideas.

7.6.2 The diagnostic tests

Students' mental models were probed using pre- and post-tests, together with a delayed post-test. These tests indicated ideas that students were using more frequently. The quality of the questions used in these tests is a strength of this study. While the two-tier questions used in these tests are not themselves new, they may well be used as assessment tools designed to identify students' misconceptions, thus answering DeBoer's (2011) call for the need of a new approach to science assessment. This approach emphasizes tests as sharp tools to improve teaching and learning, rather than to check learning by rote.

7.6.3 Proposing a unified learning model for electric circuits

The results from the diagnostic tests were analysed quantitatively. Moreover, qualitative analyses were also used with intervening data gathered during class discussions and interviews. Using quantitative and qualitative analyses in this way has been described by Clement (2000) as having "the potential to generate new insights about learning mechanisms" (p.1047). This was indeed a main feature and a strength of this study. Insights gained from the analyses of the data were used to generate ideas about a learning model of circuits in terms of mental models, as described in section 7.3.2.8. This learning model for electric circuits can be said to be an important result from this work. Previous research studies had probed mental models of current (e.g., Psillos et al., 1987; Shipstone, 1985b), resistance (e.g., Johnstone & Mughol, 1978) and p.d. (e.g., Gunstone et al., 2001) separately, even if they also stressed the idea of the circuit as a system. This study gives a unified picture of the mental models of current, resistance and p.d., as they evolve and affect each other, putting the models in a hierarchy. If used well, this unified picture can offer a powerful means by which teachers and students use their transformation potential (Sassi & Feiner-Valkier, 2010) to change teaching methods and learning practices respectively, bringing about meaningful learning.

7.6.4 Validity and reliability of the research findings

In section 3.12, reference was made to how validity of the methods used in data collecting and its interpretation was addressed in this action research study. It was explained how, due to the specific nature of action research, efforts were concentrated towards improving the *trustworthiness* of the study. Methods used to answer the research questions were described in detail. Moreover, collaborative participation was encouraged throughout the research study period, between researcher and students in both cohorts, and between researcher and the thesis advisory group. This helped in making careful decisions about how to take the study further, providing the necessary means to answer the research questions in detail.

Indeed, measures were taken, at various stages of the research, to ensure the validity of the research findings as recommended by Cohen et al. (2001).

At the design stage, plans were made to use tests and interviews to help probe deeper into students' ideas as these evolved through the course. Both tests and interviews were used to bring out reasons behind students' ideas, and questions asked were always based on items which had been covered in class. Moreover, a time-frame was set for the administration of the tests and interviews. Setting a test before the start of the course was important to show where students were. Having a test at the end of the course was important to see whether students had progressed. The delayed test, a month later, helped to check the retention of ideas.

At the data gathering stage, students were encouraged to participate and make an effort to answer questions carefully and completely. It was emphasized with them that the research would help them in *their* understanding, apart from being useful to the researcher. As students were sitting for a high stakes exam in a few months' time, understanding was a priority for them and thus students participated in the project wholeheartedly with motivation.

Data reporting was done carefully and in detail, with claims made being backed up by relevant data. The need to use the data to answer the research questions was always kept in mind. Moreover, at the data analysis stage, all data was processed and subjective interpretation of it was avoided. As much as possible, coding of the answers and their interpretation was previously prepared and abided by.

At the same time as considering the validity of this study, it was important to ensure that the method adopted for the research, the instruments used, as well as the interpretation of the results were reliable. "Reliability is essentially a synonym for consistency and replicability over time, over instruments and over groups of respondents" (Cohen et al., 2001, p. 117). While reliability is considered as a pre-condition for validity (Cohen et al., 2001; Lincoln & Guba, 1985), yet it is stronger, in principle, to deal with reliability separately (Lincoln & Guba, 1985). In flexible research, like the action research undertaken in this work, Lincoln and Guba (1985) interpret reliability as *dependability*. This results from the fact that in action research replication as proof of reliability is not always possible.

Considering the present study, different teaching activities were being conducted with different cohorts, so students' overall performance throughout the course was expected to be somewhat different. Replication was expected, however, in the pre-test results with the two cohorts when students were still starting the course and had not yet been instructed differently. Indeed, even if the facility values of the questions asked were different, evidence was provided showing that questions which were chosen to be asked again in the post-test with Cohort 1 because of low facility value were also found difficult to answer by Cohort 2 (see section 6.2.2). Thus the pre-test can be taken to be a reliable/dependable instrument which can be used to show students' knowledge before they start a course about electric circuits at advanced level.

At the same time it must be added that for this work to be trustworthy and dependable, measures that make research instruments and methods of data collection, as well as research findings, dependable in any study, were adopted as much as possible in this research. Reliability of test answers and their interpretation was controlled by asking clear questions probing one idea only, using consistent wording and consistent circuit diagrams. For each idea tested, two questions were set, asking the same question in a slightly different way. Thus students' consistency in answering could be checked, increasing reliability of the data collected.

In order to understand the depth of students' knowledge and understanding, probing into student difficulties as well as the reasons behind answers provided had to be done (McDermott & Redish, 1999). Semi-structured interviews were an effective way in helping to understand students' talk. Space was allowed for the interviewer to ask the required questions such that students' answers could be understood, improving reliability of data interpretation. During interviews, the researcher controlled the wording used, avoiding leading questions. The interviewer was also empathic, steering and observant, linking and relating what was said throughout the interview while trying to make the best of the interview session. Moreover, pilot studies had been conducted prior to the start of the actual data collection phase for this project, with the aim of getting some training on how to best conduct interviews (Oppenheim, 1992).

It can also be said that analysis of all data was done in a systematic manner, with procedures used being described in detail, safeguarding the reliability/dependability of the results.

7.6.5 Gender issues

A possible weakness of this study is that gender issues have not been addressed. It would have been interesting to compare responses to physics diagnostic tests questions and interviews with girls and boys. This was not done because the existence of strong gender differences was not expected and also because it would have made the study too long.

7.6.6 The problem of interpretation of responses

In this study, emphasis was made throughout on students' voice, through class discussions, the answering of questions in diagnostic tests, one-to-one interviews, predict-observe-explain tasks and expressions of individual ideas in writing. The analyses of the data from such research necessitated the sound interpretation of responses. This was certainly not an easy chore. Klaassen and Lijnse (1996) claim that "it is often difficult to interpret classroom discourse, let alone interpret it unambiguously" (p.115). They explain how the language which students use is meaningful to the students, yet often may be different from that used by teachers. Viennot (1985) and Klaassen (1995) emphasise the same view.

Efforts were thus put into trying, as much as possible, to avoid communication breakdown between student and researcher. Being a teacher-researcher helped in this matter since I am used to students' everyday classroom talk. Also, whenever there were students' ideas which were not clearly explained, I rephrased the question, pushing for a clearer answer. However, admittedly, there were limits to having the problem of interpretation completely eliminated. Addressing this issue using peer-validation of a sample of the data collected would have helped. Unfortunately this was not possible, given the demands of the teaching timetable.

7.7 Implications for practice

7.7.1 Model based teaching and learning

This study has highlighted data collection of students' ideas based on mental models. It also made use of additional teaching activities which were directed at making students meta-cognitively aware of what and how mental models can help understanding. The implication for practice is to promote the use of mental models in teaching and learning current electricity, to help improve understanding of this abstract topic. This study has exposed how students' understanding of circuits progresses in terms of mental models students seem to use as their ideas evolve towards the scientific view. Teachers can thus centre their teaching around these mental models, using discussions to help students become aware of their intuitive/alternative ideas and to build upon them. Teaching centred around mental models of current, resistance and p.d., as shown in Figure 7.6, empowers the teacher with the potential for forward thinking, helping teachers to recognize what comes next in lesson preparation, and in searching for ideas which need to be discussed with students, to support learning in progress.

The use of teaching activities like the ones used in this research is thus suggested. While students are guided by the teacher in their knowledge construction, teachers learn more about students' ideas as the teaching progresses. The traditional lecture presentation needs to be adjusted to start to involve class time which is more student-centred. Clement (2008b) refers to class environments where "the knowledge developed is largely student generated but at the same time the agenda is largely teacher directed" (p.15). Thus learning can become more meaningful. The following sections describe how teaching activities which can complement model based learning can be used with students during class time, promoting guided inquiry techniques.

7.7.2 The Predict-Observe-Explain (POE) technique

This work has put POEs in a very prominent position as a teaching and learning aid. The POE technique was instrumental in bringing students' ideas and related mental models to the forefront. This is not something which just helps the teacher to know where students are. It also helps to indicate to the learner his/her level of understanding. In other words, POEs are powerful tools during instruction. Klaassen and Lijnse (1996) claim that "in general students do not have much to subtract from what they already believe" (p. 128). Even if students have more incorrect ideas than these authors seem to claim, subtracting these incorrect ideas just for the sake of memorising new material, is not as important as having students recognize through first-hand experiences (by, for example, doing an experiment or seeing a demonstration and discussing results) that what they are suggesting or predicting does not work. When students have proof of wrong predictions, they may become internally motivated to think more deeply, constructing new knowledge, and moving forward. Moreover, making students give reasons behind predictions made and behind changes in answers suggested after observation, helps to emphasize to the learner the importance of causal reasoning, which is fundamental for understanding. After students in both cohorts, especially the ones who had been interviewed, became used to the fact that they had to answer to the question 'Why?' they started to ask this question automatically by themselves. Using POEs can help students make a qualitative leap in the understanding of electric circuits through predictions made, careful observation of the results and reflections on them.

7.7.3 Teacher guided discussions

This study has also highlighted the importance of class discussions. Hammer (1995) claims that "as students listen and respond to each other's propositions, they become more aware of alternative perspectives and the need to support their views with reasons and evidence" (p. 424). This helps understanding.

Studies by Prain and Hand (1999) and Constantinou and Papadouris (2004) also support the idea that discussion can help to improve development and understanding. These authors refer to how discussions bring about 'conceptual negotiation' between participants as they interact with each other, making it "probable for meaning evolution to become a gradual and explicit process, in the sense of new knowledge emerging" (Constantinou & Papadouris, 2004, p. 24).

The teacher's role during discussions becomes fundamental. As an expert, she/he needs to involve all students in what makes them responsible for their learning. Students need to be encouraged to speak about their ideas when required, and also to *actively* listen to their peers and learn from the views of others. Moreover, teachers need to see the importance of drilling students in asking the question'Why?'. This question is key to promoting higher level discussion based on abstract thinking (Rabow, Charness, Kipperman & Radcliffe-Vasile, 1994).

7.7.4 Analogies and analogical reasoning

The use of analogies has also been explored in this research, by using a PowerPoint presentation providing a visual as well as a verbal communication channel fostering discussion about abstract ideas, linking them to previous experiences. This helped students improve their mental representation of how a circuit works, by comparing concepts of electric circuits to ideas in other contexts (see also section 7.4). Teaching activities including analogies compliment model based learning. Using analogies to guide mental model evolution is suggested, emphasizing those parts of the analogue which are helpful in understanding the target. The use of the water analogy using the gravitational model with tanks and pipes is specifically suggested, since this has been shown in this study to help depict a clearer picture of p.d. – an otherwise difficult concept to grasp (see section 6.7.4.7).

7.8 The role of teachers

7.8.1 Didactic versus student centred methods

While student centred environments offer ideal situations, yet some teachers may find a traditional didactic environment easier to handle. Valanides (1997) has criticized educational institutions which use didactic methods of knowledge transmission, saying that reasoning development "seems to be hindered by intellectually restrictive educational environments and teaching approaches which demand coverage of the curriculum and put emphasis on extensive factual knowledge" (p. 182).

For learning to be student centred, the role of the teacher becomes of particular importance. In their professional role, teachers have to look for strategies like the teaching activities referred to in this work, which can enable students to do what is so difficult for them – **THINK**. When students were asked to write down what they thought an electron does when the circuit is switched on, they were being made to think about their mental model of current. Some students said they didn't have a model of current, but still managed to write about their mental picture after giving it some thought. When students were urged to discuss their views with their peers – defending or changing their ideas – they were being given the opportunity to think, clear their doubts, and understand. Guiding students' thinking can help their understanding, as opposed to the training some students get for memory recall of pieces of information.

7.8.2 Addressing teachers' conflicts

With teachers' claim that they cannot keep adding more to what they have to do in class, over and above an already overloaded curriculum (see Hammer,1995; Clement,2008a, amongst others), teachers may perhaps oppose the idea of introducing additional teaching activities like the ones indicated in the previous sections, as aids to learning. Such activities may at first appear as an extra burden to carry. Yet, conducted with the spirit of making learning enjoyable, these teaching activities only pose a *small* change to a usual lesson plan. Even so, sometimes, as Viennot (1999) claims, the "so-called 'small' changes can do more than commonly expected" (p. 15).

7.9 Suggestions for future work

In view of the results of this study, the following suggestions are made for future work:

- It is suggested that a 3rdcycle of research be carried out to try and resolve problems which Cohort 2 still experienced, even after teaching.

  Those teaching activities which helped Cohort 2 would obviously be repeated. The static electricity course would again be revised with students. The electron experience task accompanied byclass discussions would again be conducted to help with current conservation views. PhET simulations shall also be used with the same aim. Moreover, the use of the PowerPoint presentation used with Cohort 2 is suggested, promoting analogical reasoning for understanding.

  Cohort 2 still experienced difficulty with parallel circuits, especially when using unequal resistances. It is suggested therefore, that the teaching of parallel circuits be explained in terms of mono-circuits. Some students had seen parallel circuits in this way, so perhaps this may have some impact on students' understanding.

Moreover, to help with understanding p.d., the use of the POE technique during whole class teaching is suggested. PhET simulations, used as class demonstrations accompanied by discussions, can promote students' active participation. Emphasis would be made on circuits carrying parallel resistors, R-C circuits, and simple circuits carrying a closed/open switch, with a voltmeter connected across it. Thus students would be guided to see that p.d. can exist without a current. Students would be asked to write their predictions and explanations, as well as discuss their writing with their peers, bringing their ideas to the forefront, before observations and related discussions are further undertaken.

Experiments like the ones suggested by Borghi et al. (2007) can be demonstrated (see section 2.7.5) in an effort to better link current electricity concepts to those used in electrostatics.

Explanations regarding surface charge cannot be dealt with very deeply with students at post-secondary level, but emphasizing the presence of field lines between the battery terminals and along connecting wires and circuit components would be beneficial.

The impact of these whole class activities would then be evaluated to see whether Cohort 3 would have benefitted significantly from them, when compared with progress shown by Cohort 2.

- This study has indicated the popular use of the BAT model (same battery, same current), regardless of changes made to the electric circuit. Moreover, evidence was provided showing that more students from both cohorts seemed to use the BAT model after instruction (see sections 6.4.4.2 and 4.5.5.2). Reasons for why this was happening were not addressed by this work. Other researchers had not mentioned this problem and it was thought necessary to first check whether the result would be confirmed by Cohort 2. In view of the confirmation, future work is suggested to try and find reasons for this problem.
- Gender issues have also not been addressed by the present work, mainly due to time constraints. It is suggested, therefore, that future work may probe differences, if any, which may exist in the way boys and girls reason about electric circuits.

7.10 Conclusion

The teaching activities promoting discussion and analogical reasoning which have been suggested by this work and further highlighted in this chapter are not difficult to adopt. No problems were encountered during the course with my students, because of these added activities. On the contrary, students were more engaged and motivated to understand rather than just recall pieces of information. By involving students in relevant discussions and analogical reasoning, teachers can give a slight *twist* to their teaching, making it more effective. Students are thus directedtowards taking "active steps to manage their learning processes to facilitate knowledge acquisition and comprehension" (Weinstein &Underwood, 1985, p. 243). This is, indeed, when true learning takes place.

I would like to end by saying that this study has dealt with the important issue of learning for understanding. It has focused on model based learning – an area described by Clement (2000) as a key research area in science education. Teaching activities which offer the key to a powerful and qualitatively enriched learning experience have been highlighted. Moreover, the study has contributed to knowledge by identifying a unified set of learning pathways, guiding us as to how understanding progresses in the area of electric circuits. As Scott (1992) puts it, "once we begin to better understand how children's ideas are likely to progress in a particular science domain, then we shall be better placed to develop teaching approaches to support that progression" (p. 223).

This study has looked at ways of how students' ideas develop during the teaching of this topic. It is augured that this work be used and built upon, in the future, by students, teachers and researchers, with the aim of making the study of electric circuits appear less complex and abstract.

Appendix 1 The Secondary Education Certificate (SEC) Physics Syllabus

The Physics syllabus at SEC level can be retrieved from
https://www.um.edu.mt/__data/assets/pdf_file/0016/66400/SEC24.pdf

Only theme 5 dealing with electric circuits is shown here.

Theme 5: Electricity in the Home

Describing the unit

Our homes provide comforts that frequently we take for granted. At home you can turn on the light or a heater at the flick of a switch. You may easily take a snack from the fridge and cook it in the microwave as you watch your favourite TV serial. Without electricity most of these appliances would not work and our lives would be completely different.

In this topic we shall explore how electricity was discovered when the effect of rubbing materials together was noticed. An understanding of the static electricity formed in these instances may give students a better insight about certain phenomena that take place around our homes but also enable them to consider particular applications.

This topic provides the opportunity to discuss what electricity is and how it can be measured through different circuits. It gives students the opportunity to explore different sources of electricity and investigate the relationship between voltage and current in resistors and filament lamps. Students shall also be given the opportunity to investigate components that are influenced by changes in light and temperature. This topic enables the students to appreciate how electrical energy is generated, how this is used in our houses and how its cost can be calculated. The topic also considers why electricity can be dangerous and ways to use it in a safe way.

Have you ever thought about the following?

1. Why do television screens and computer monitors become so dusty?
2. Why when after combing your hair, placing the plastic comb near a very thin stream of water will make the stream bend to the side?
3. How is a spark produced?

4. Which is the safest place to seek shelter in a thunderstorm?

5. Why is it better to use a vacuum cleaner rather than a broom to clean a carpet?

6. Why do you get an electric shock when you touch the body of a car when you come out of the car?

7. Why are many contacts in high quality electronic systems gold-plated?

8. Why does an electrician have to wear shoes with thick rubber soles at work?

9. How do the lights in street lighting remain on when one bulb is broken?

10. How do you wire up a three pin plug?

11. What happens when you blow a fuse?

12. How much does it cost to charge a mobile phone in one year?

Learning Programme:

- Measuring charge.
- There are forces acting between charged objects.
- Difference between conductors and insulators.
- Measuring and describing current and potential difference.
- Ways of producing electricity.
- The resistance of materials depends on particular factors.
- The change of resistance of electrical devices is used in a variety of applications.
- The potential difference, current and resistance in a circuit are related.
- The behaviour of potential difference, current and resistance differs through different circuits.
- House wiring.
- Risks and hazards associated with electricity. Safety measures.

Internet Links

Balloons and static electricity - Charging by rubbing and forces between charges.
http://phet-web.colorado.edu/web-pages/simulations-base.html

Current construction kit- Constructing series and parallel circuits
http://phet-web.colorado.edu/web-pages/simulations-base.html

Ohm's Law
http://www.walter-fendt.de/ph14e/ohmslaw.htm

Series and parallel circuit simulations
http://www.walter-fendt.de/ph14e/combres.htm

A.C. circuit
http://www.walter-fendt.de/ph14e/accircuit.htm

Appendix 2 The Matriculation and Secondary Education Certificate (MATSEC) Board Physics Syllabus at Advanced Level

The Physics syllabus at advanced level was retrieved from

https://www.um.edu.mt/__data/assets/pdf_file/0013/101821/AM26.pdf

Only section 5 dealing with electric circuits is shown below.

5 ELECTRIC CURRENTS

5.1 Charge and current:

Current as the rate of flow of charge.	Current = slope of charge-time graph = dQ/dt.
Current model.	Derivation of $I = nAve$ is expected. Distinction between conductors, semiconductors and insulators using the equation.
Intrinsic and extrinsic semiconductors.	Crystal structure of silicon. Effect of impurities and temperature on conduction.
Simple band theory.	To explain differences between conductors, intrinsic and extrinsic semiconductors, and insulators.
Electrical potential difference.	Potential difference = work done/charge.
E.m.f. of a cell.	Definition of e.m.f.
Kirchoff's laws.	Simple circuit calculations.
	Emphasis on conservation of charge and energy.

5.2 Resistance:

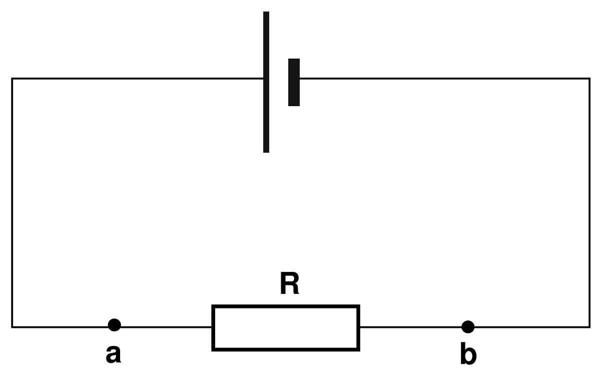
Current-voltage characteristics for a metal wire at constant temperature, filament lamp and diode.	Experimental investigations are expected.
Resistivity and conductivity.	
Temperature dependence of resistance of metals and thermistors.	Experimental investigation included. Determination of the temperature coefficient of resistance.
Internal resistance of a cell and its	Practical importance of internal resistance in

measurement.	car battery and extra high-tension supplies.
Resistors in series and in parallel.	Simple circuit problems, including the use of Kirchoff's laws.
The potential divider.	The potential divider equation. Use of light-dependent resistor or thermistor to control voltage.
Balance of potentials and the principle of null methods.	Circuit principles are expected. Only simple numerical problems based on simple circuits can be set. Reference to terms such as 'potentiometer', 'Wheatstone Bridge', etc., are to be avoided.
Energy and power in d.c. circuits.	Including the kilowatt-hour.
Use of ammeters, voltmeters and multimeters.	Extension of range of electrical meters. Internal structure of meters is not included.

Appendix 3 Diagnostic Test Questions in the Question Bank

Qn 1

In this circuit, a battery is connected to a resistor, R.



(a) What can you say about the electric current at points **a** and **b**?

Choose one answer.

i	The electric current at **a** is bigger than at **b**.
ii	The electric current at **b** is bigger than at **a**.
iii	The electric current is the same size at **a** and **b**.

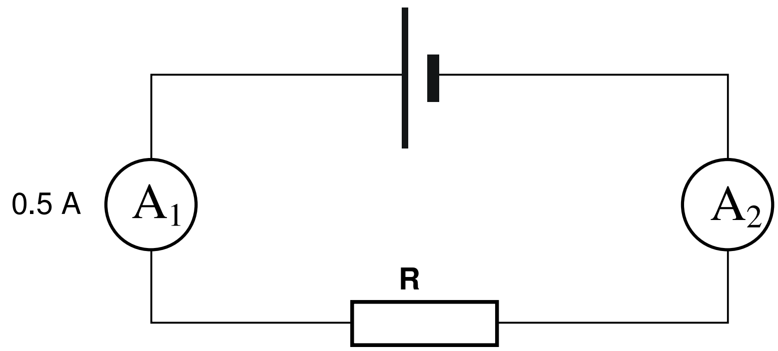
(b) How would you explain this?

Choose one answer.

i	The current is the same all round the circuit.
ii	**Some** of the current is used up by the resistor.
iii	**All** of the current is used up by the resistor.

Qn2

The figure shows a battery connected to a resistor. Two ammeters measure the electric current at different points in the circuit. The reading on ammeter A_1 is 0.5 A.



(a) What will the reading on ammeter A_2 be?

Choose one answer.

i	More than 0.5 A.
ii	Exactly 0.5 A.
iii	Less than 0.5 A, but not zero.
iv	Zero.

(b) How would you explain this?

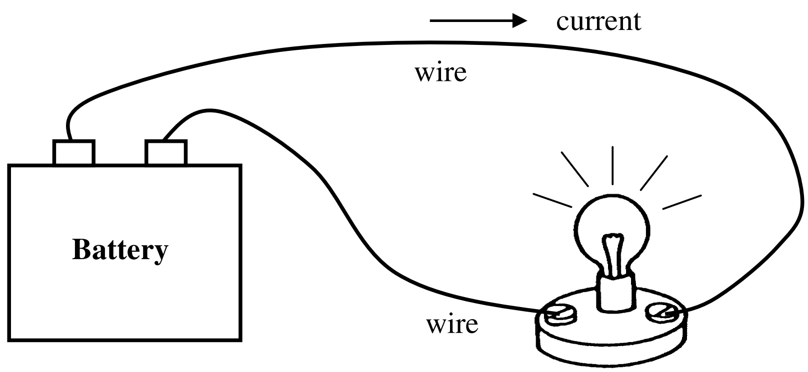
Choose one answer.

i	**Some** of the current is used up by the resistor.
ii	**All** of the current is used up by the resistor.
iii	The current is the same all round the circuit.

Qn3

A battery is connected to a bulb. The bulb is lit.

There is an electric current in wire A **from the battery to the bulb**.



(a) What can you say about the **electric current** in wire B?

Choose one answer.

i	There is an electric current in wire B **from the battery to the bulb**.
ii	There is an electric current in wire B **from the bulb to the battery**.
iii	There is **no** electric current in wire B.

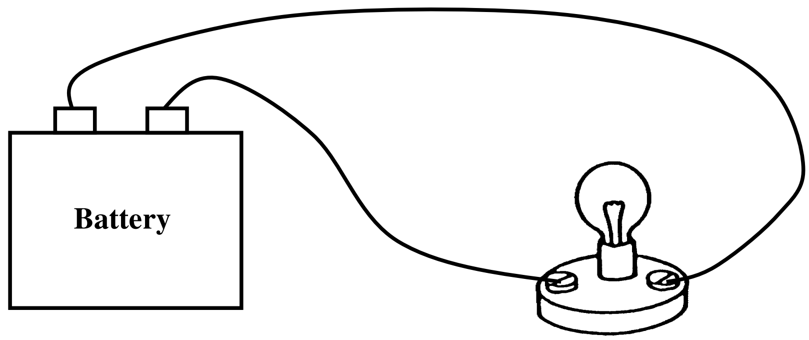
(b) How can you explain this?

Choose one answer.

i	There is an electric current through one wire to the bulb. It is **all** used up in the bulb, so there is **no current** in the other wire.
ii	There are **two** electric currents from the battery to the bulb. They **meet** at the bulb and this is what makes it light.
iii	There is an electric current through one wire to the bulb. **Some** of it is used up in the bulb, so there is a **smaller current** going from the bulb to
iv	There is an electric current through one wire to the bulb. It **all** passes through the bulb and back to the battery through the other wire.

Qn 4

In this circuit, the bulb is lit.



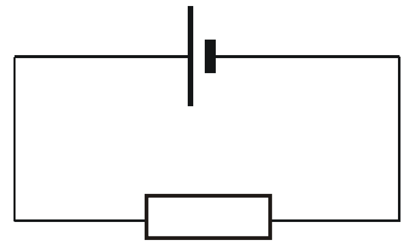
Read each of the statements below.

Decide whether each statement is 'True' ***or*** *'False' and mark your answer on the answer sheet.*

	Statement	True	False
(a)	Before the battery is connected, there are no electric charges in the wire. When the battery is connected, electric charges flow out of it into the wire.		
(b)	When the circuit is connected, the free electrons gain kinetic energy. As they move round, the free electrons give this energy to the components they pass through.		
(c)	The battery, the wire and the bulb filament are all full of charges, all the time. When there is a closed circuit, the battery makes all these charges move round together.		
(d)	Before the circuit is connected up, there are free charges in the battery only. There are no free charges in the wires or the bulb filament.		
(e)	When the circuit is connected, the free electrons which are moving are absorbed by the bulb, to produce light.		
(f)	Before the circuit is connected up, there are free charges in the battery, the wires and the bulb filament.		

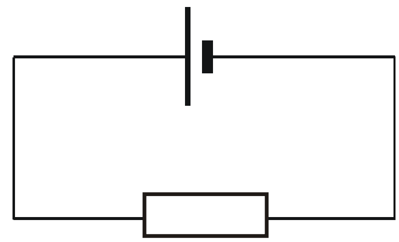
Qn 5

The resistor in this circuit, R_1, has a small resistance.



R_1 - small resistance

It is replaced by R_2, which has a large resistance.



R_2 - large resistance

(a) What happens to the current in the circuit?

Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller, but not zero.
iv	It drops to zero.

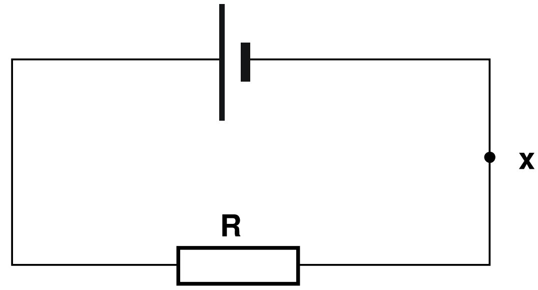
(b) How would you explain this?

Choose one answer.

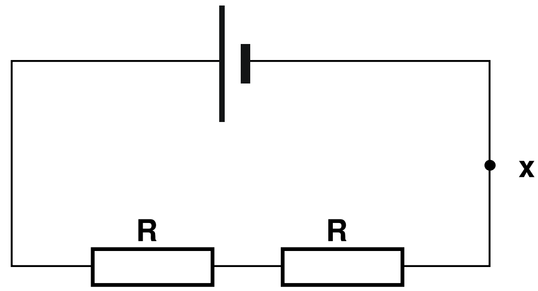
i	The battery is not strong enough to push any current through a larger resistor.
ii	The resistor controls the size of the current that the battery can push around the circuit. The bigger the resistance, the smaller the current.
iii	A large resistance needs more current than a small resistance. The bigger the resistance, the bigger the current.
iv	It is the same battery, so it always supplies the same current.

Qn 6

Sam makes this circuit.



He then adds a second identical resistor.



(a) What happens to the current in the circuit at point x?

Choose one answer. Use the answer sheet.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller, but not zero.
iv	It drops to zero.

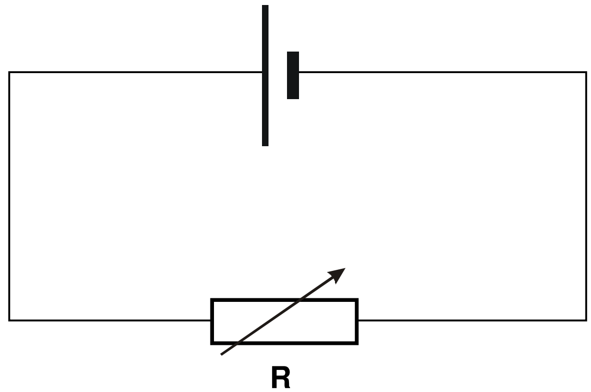
(b) How would you explain this?

Choose one answer. Use the answer sheet.

i	The battery is not strong enough to push any current through two resistors.
ii	The battery cannot push as big a current through two resistors.
iii	It is the same battery, so it supplies the same current.
iv	Two resistors need more current than one on its own.
v	The current is shared between the two resistors, so each gets half.

Qn 7

Peter makes this circuit, with a battery and a variable resistor, R.



He then **increases** the resistance of R.

(a) What happens to the current in the circuit?

Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller, but not zero.
iv	It drops to zero.

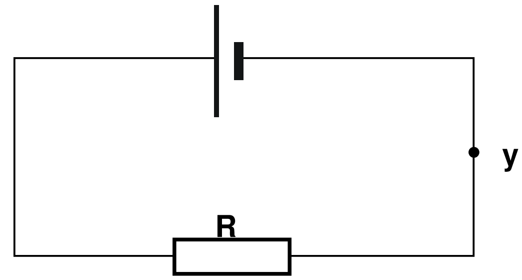
(b) How would you explain this?

Choose one answer.

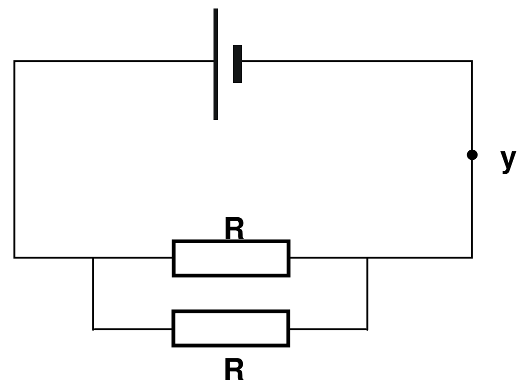
i	The battery is not strong enough to push any current through a larger resistor.
ii	The battery cannot push as big a current through a larger resistor.
iii	A larger resistance needs more current than a smaller resistance.
iv	It is the same battery, so it supplies the same current.

Qn 8

Sam connects this circuit. A current flows.



He then adds a second identical resistor, like this.



(a) What happens to the current at y?

Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller.

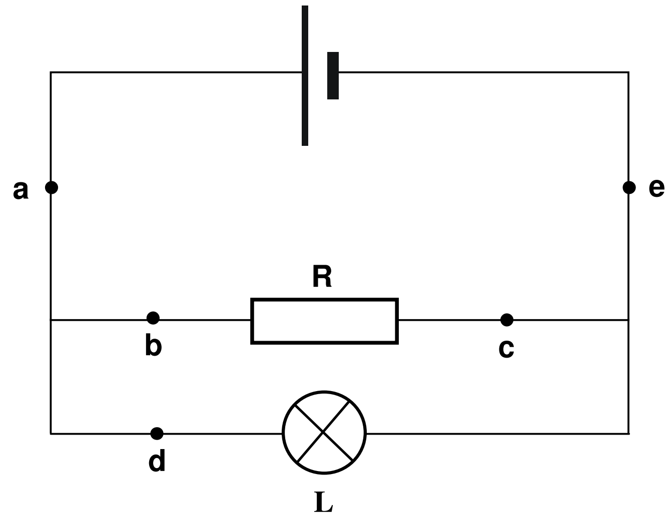
(b) How would you explain this?

Choose one answer.

i	The battery cannot push as big a current round the circuit.
ii	The second resistor provides an extra path for current to flow.
iii	It is the same battery, so it always supplies the same current.

Qn 9

In this circuit a battery is connected to a resistor R and a bulb L, as shown.



(a) What can you say about the following statements related to the currents at the various points in the circuit?

*Choose True **or** False for each statement. Mark the answer sheet.*

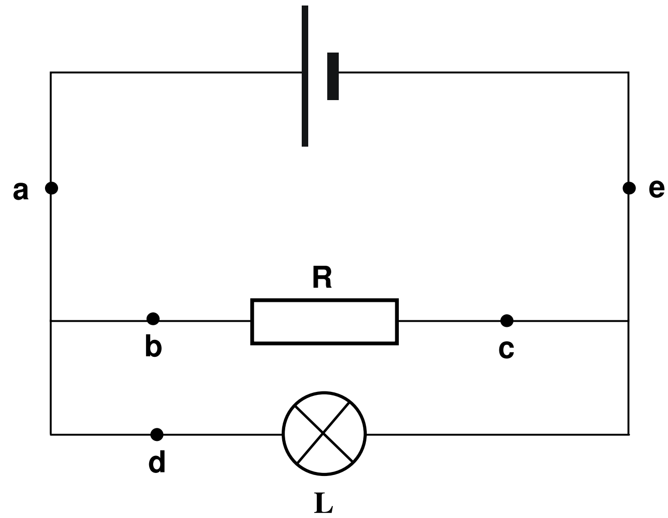
	Statement	True	False
i	d + b = a		
ii	b is larger than c		
iii	b equals c		
iv	a is larger than e		
v	a = e		

(b) Is b equal to d? Yes / No

How would you explain this?

Qn 9'

In this circuit a battery is connected to a resistor R and a bulb L, as shown.



(a) What can you say about the electric current at points **b** and **c**?

Choose one answer.

i	The electric current at **b** is bigger than at **c**.
ii	The electric current at **c** is bigger than at **b**.
iii	The electric current is the same size at **b** and **c**.

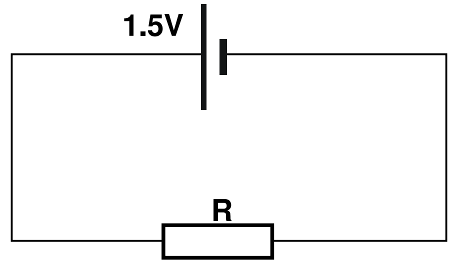
How would you explain this? *Use the answer sheet.*

(b) Is b equal to d? Yes / No

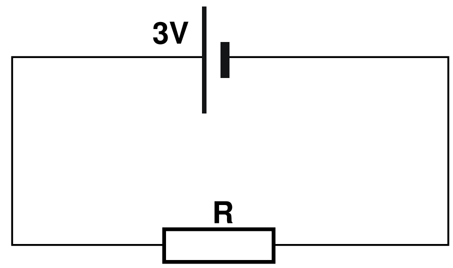
How would you explain this? *Use the answer sheet.*

Qn 10

This circuit consists of a 1.5V battery and a resistor, R.



A 3V battery is now connected to the same resistor, instead of the 1.5V battery.



(a) What happens to the current through the resistor?

Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller, but not zero.

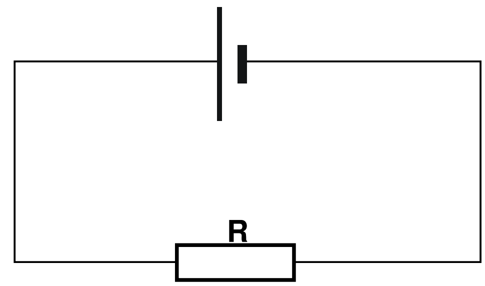
(b) Which of the following is the best explanation for this?

Choose one answer.

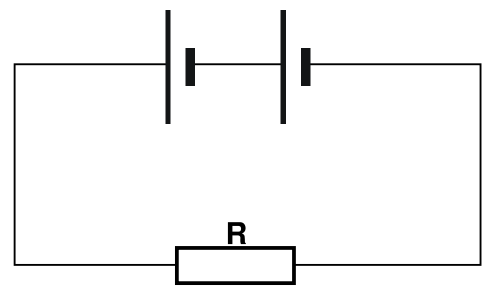
i	It is the same resistor so it needs the same current.
ii	The potential difference increases, the resistance then has a larger effect, therefore the current is less.
iii	The 3V battery exerts a bigger 'push' on the electric charges.

Qn 11

This circuit consists of a battery and a resistor, R.



A second identical battery is added.



(a) What happens to the current through the resistor?

Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller, but not zero.
iv	It drops to zero.

(b) Which of the following is the best explanation for this?

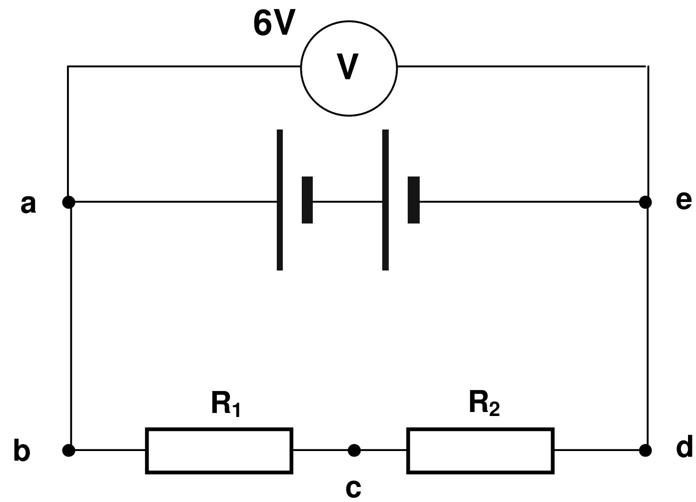
Choose one answer.

i	Two batteries exert a bigger 'push' on the electric charges.
ii	It is the same resistor so it needs the same current.
iii	The potential difference increases, the resistance then has a larger effect, therefore the current is less.
iv	The two batteries push in opposite directions and cancel each other out.

Qn 12

The circuit consists of some batteries connected to two resistors R_1 and R_2.

A voltmeter connected across a and e reads 6V.



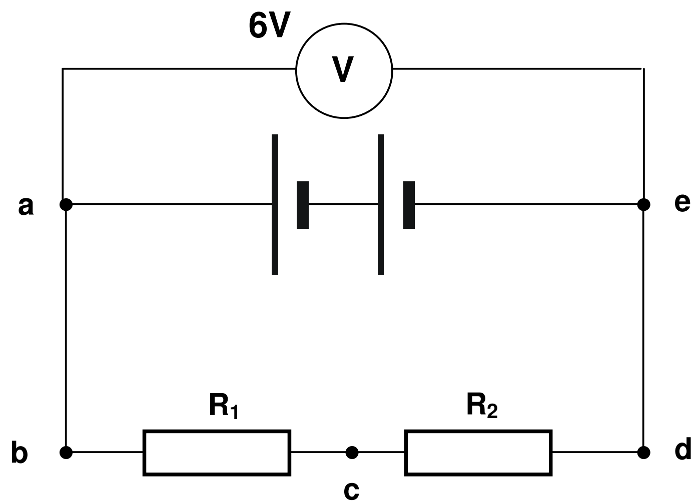
For each question, choose one answer. Mark your answer on the answer sheet.

		More than 6V	6V	Less than 6V	Zero
(a)	What is the potential difference (p.d.) between points a and e?				
(b)	What is the potential difference (p.d.) between points b and d?				
(c)	What is the p.d. between points a and b?				
(d)	What is the p.d. between points b and c?				
(e)	What is the p.d. between points c and d?				
(f)	What is the p.d. between points d and e?				

Qn 12'

The circuit consists of some batteries connected to two resistors R_1 and R_2.

A voltmeter connected across a and e reads 6V.

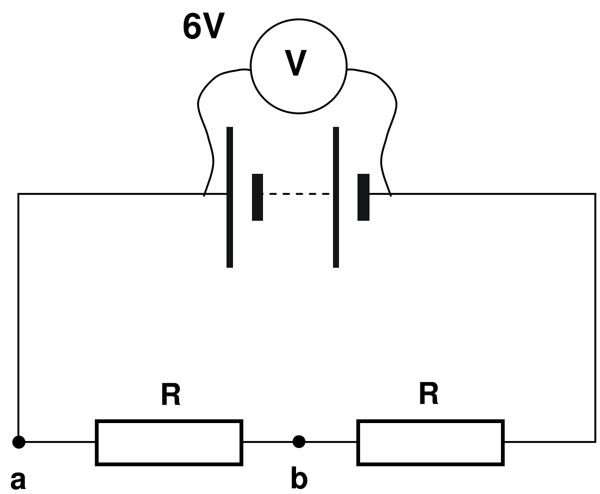


For each question, choose one answer. Mark your answer on the answer sheet.

		More than 6V	6V	Less than 6V	Zero
(a)	What is the potential difference (p.d.) between points b and d?				
(b)	What is the p.d. between points a and b?				
(c)	What is the p.d. between points d and e?				

Qn 13

In this circuit, a 6V battery is connected to two identical resistors in series.



(a) What is the potential difference (p.d.) between the points a and b?

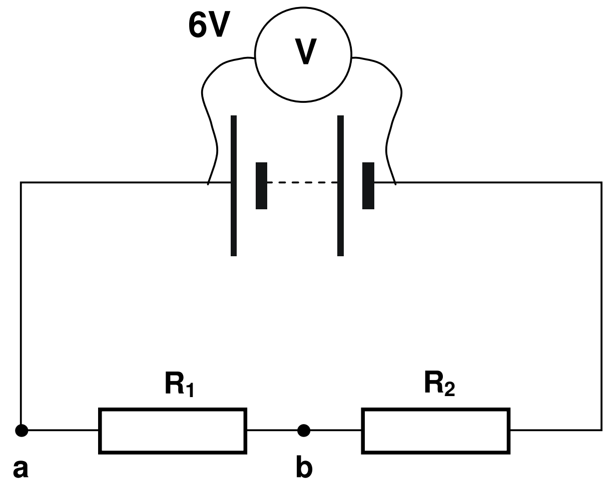
Choose one answer.

i	6V.
ii	Between 6V and 3V.
iii	3V.
iv	Between 3V and zero.
v	Zero.

(b) How would you explain this?

Qn 14

In this circuit, a 6V battery is connected to two resistors in series. The resistance of R_1 is **bigger** than the resistance of R_2.



Note: R_1 has a bigger resistance than R_2

(a) What is the potential difference (p.d.) between the points a and b?

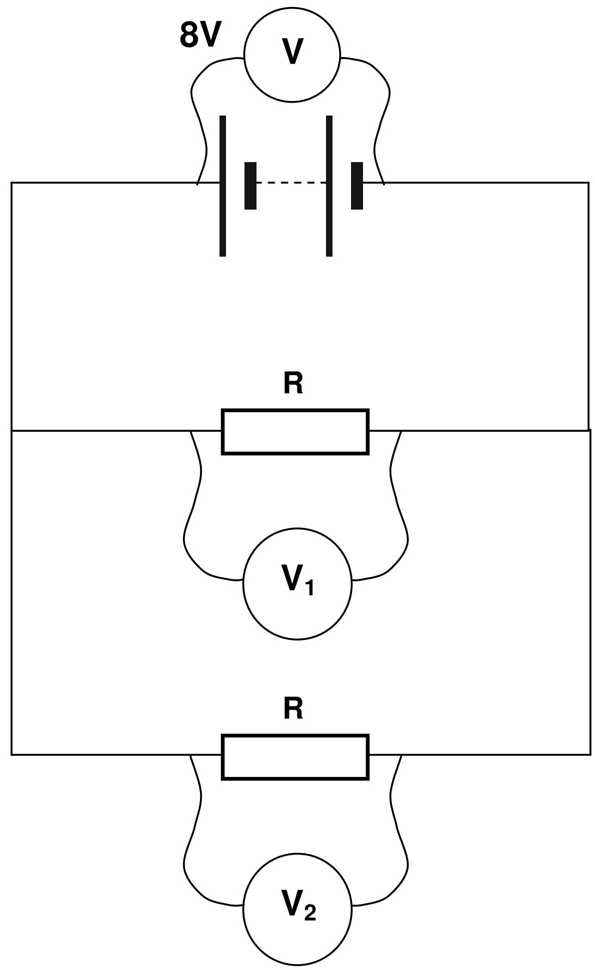
Choose one answer.

i	6V.
ii	Between 6V and 3V.
iii	3V.
iv	Between 3V and zero.

(b) How would you explain this?

Qn 15

The two resistors in this circuit are identical. The voltmeter connected across the battery reads 8V.



(a) What is the reading, in volts, on voltmeter V_1?

Use the answer sheet.

How would you explain this?

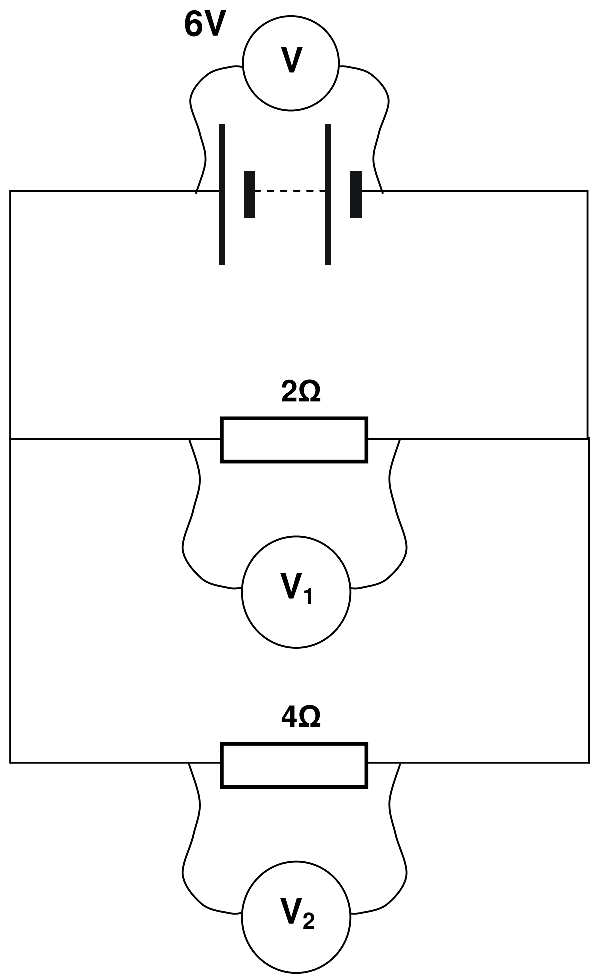
(b) What is the reading, in volts, on voltmeter V_2?

Use the answer sheet.

How would you explain this?

Qn 16

In this circuit, the voltmeter across the battery reads 6V.



(a) What is the reading, in volts, on voltmeter V_1?

Use the answer sheet.

How would you explain this?

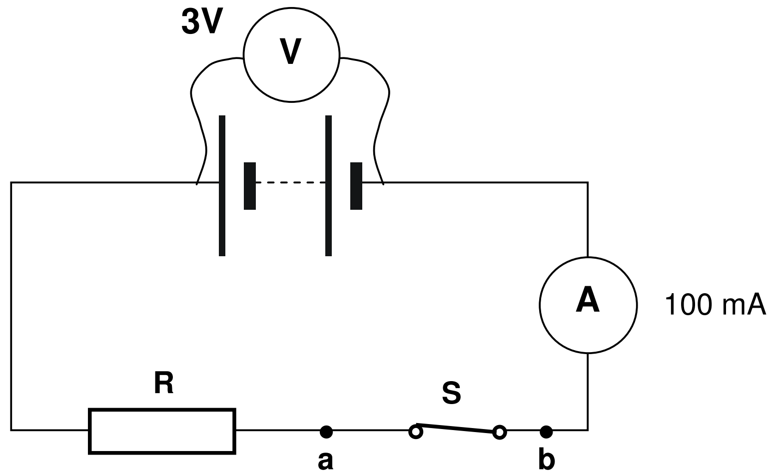
(b) What is the reading, in volts, on voltmeter V_2?

Use the answer sheet.

How would you explain this?

Qn 17

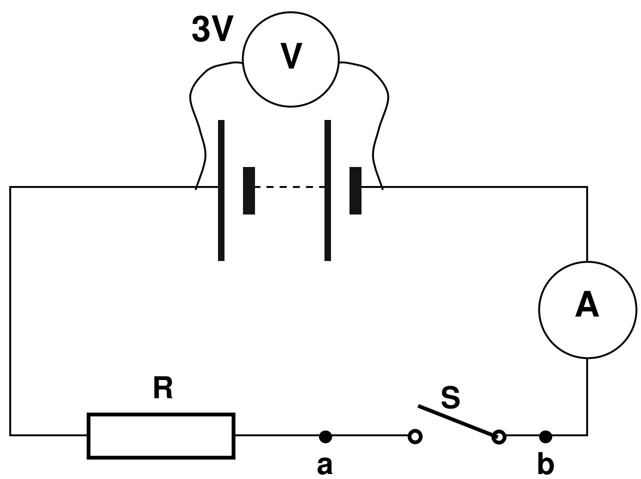
(a) This circuit consists of a 3V battery, connected to a resistor R and a switch S. The switch is **closed**. The ammeter reads 100 mA.



What is the potential difference (p.d.) between **a** and **b**?

Use the answer sheet.

(b) The switch S is then **opened**. The voltmeter across the battery still reads 3V.



(i) What is the reading on the ammeter now?

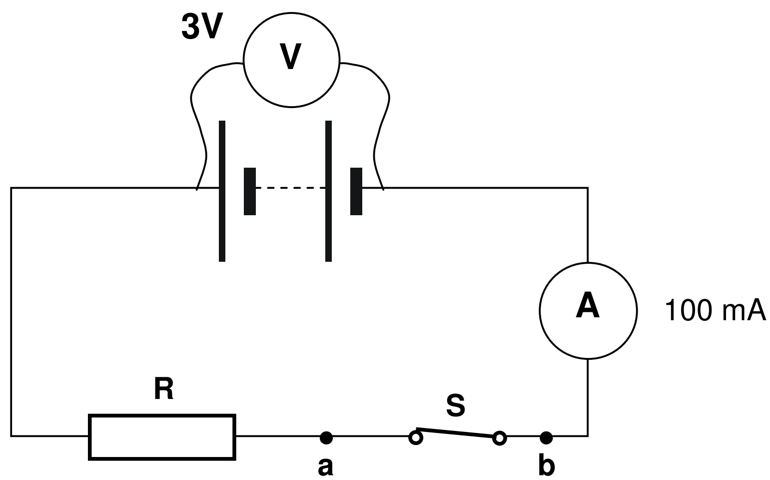
Use the answer sheet.

(ii) What is the potential difference (p.d.) between **a** and **b,** now?

Use the answer sheet.

Qn 17’

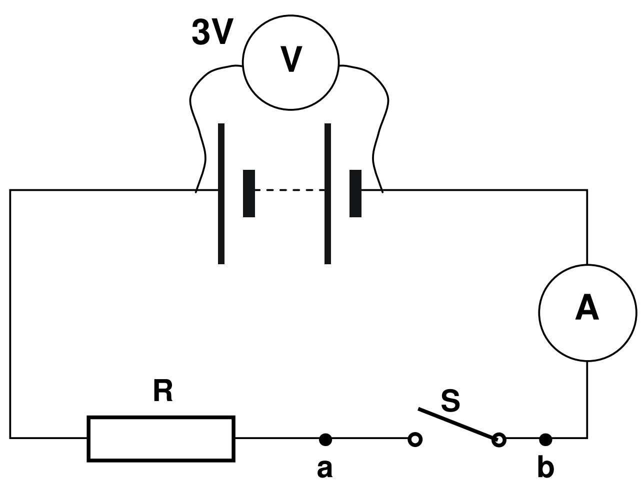
(a) This circuit consists of a 3V battery, connected to a resistor R and a switch S. The switch is **closed**. The ammeter reads 100 mA.



What is the potential difference (p.d.) between **a** and **b**?

How would you explain this? *Use the answer sheet*.

(b) The switch S is then **opened**. The voltmeter across the battery still reads 3V. The ammeter now gives zero reading.



What is the potential difference (p.d.) between **a** and **b,** now?

How would you explain this? *Use the answer sheet*.

Qn 18

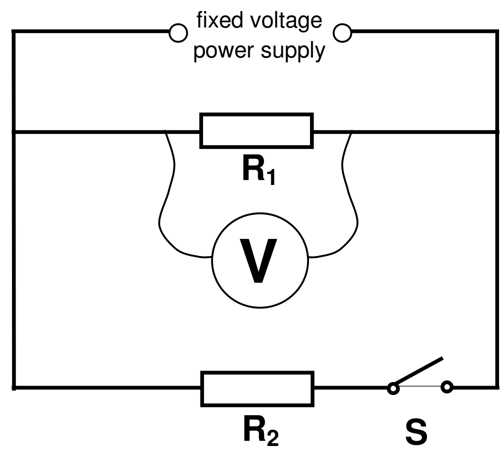
In this circuit, the power supply has a fixed voltage output.

The resistors R_1 and R_2 are connected as shown.

The switch, S, is open.

There is a reading on the voltmeter connected across R_1.

The switch is then **closed**.



(a) What happens to the reading on the voltmeter?

Choose one answer.

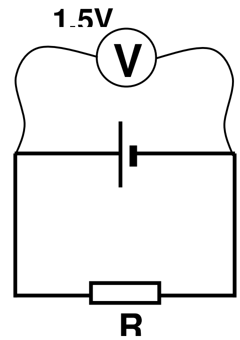
i	It gets bigger.
ii	It stays the same.
iii	It gets smaller.

(b) How would you explain this?

Choose one answer.

i	The voltage is now shared between the two resistors.
ii	R_1 is connected directly across the terminals of the power supply. So the voltage across it is always equal to the power supply voltage.
iii	The total resistance in the circuit is now bigger, so V increases (as V=IR).

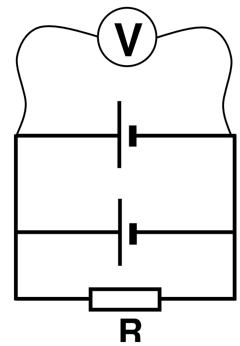
Qn 19



In this circuit, a battery is connected to a resistor R.

The voltmeter reads 1.5V.

A second identical battery is now added, like this.



(a) What is the reading on the voltmeter now?

Choose one answer.

i	3 V.
ii	1.5 V.
iii	0.75 V.
iv	Zero.

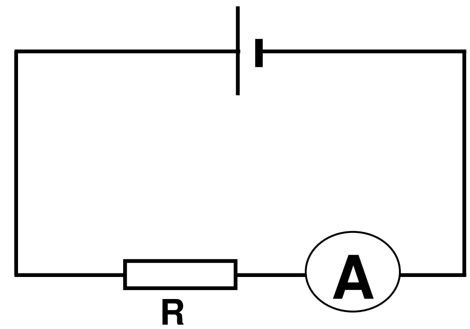
(b) How would you explain this?

Choose one answer.

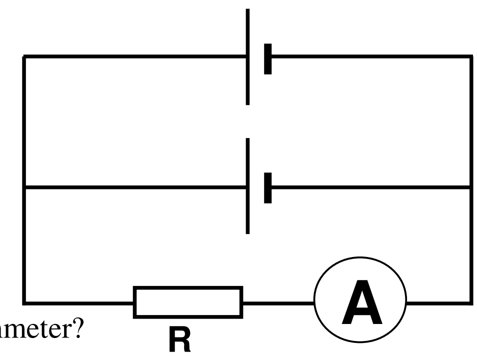
i	Two batteries 'push' harder than one on its own.
ii	The voltmeter measures the potential difference across each battery, which stays the same.
iii	The second battery pushes against the first one.
iv	The two batteries transfer more energy to the resistor every second.

Qn 20

In this circuit, a battery is connected to a resistor R. There is a reading on the ammeter.



A second identical battery is now added, like this.



(a) What happens to the reading on the ammeter?

Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller.

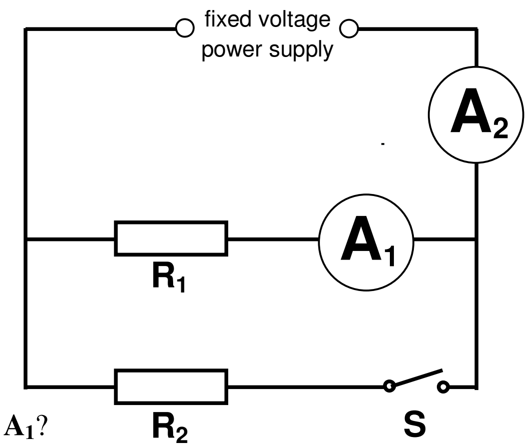
(b) How would you explain this?

Choose one answer.

i	Two batteries ‘push’ harder than one on its own.
ii	The potential difference across the resistor is still the same.
iii	The second battery pushes against the first one.
iv	Two batteries supply more energy every second.

Qn 21

Two resistors, R_1 and R_2, are connected as shown in the diagram. An ideal fixed power supply is used.



The switch S is open.
There is a reading on both ammeters.

The switch is then **closed**.

(a) What happens to the reading on ammeter $\mathbf{A_1}$?

Choose one answer.

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller.

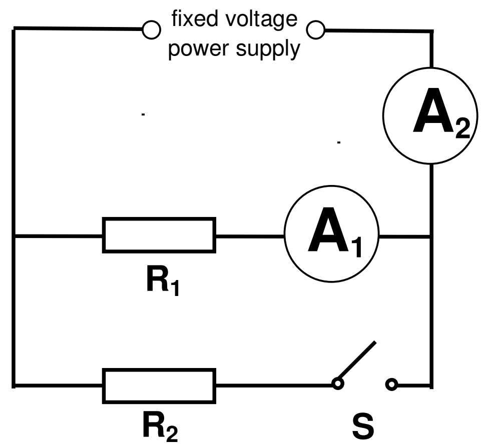
(b) How would you explain this?

Choose one answer.

i	Some of the current now goes through R_2, bypassing R_1.
ii	Two resistors need a bigger current from the power supply.
iii	The voltage across each parallel branch stays the same.
iv	The total resistance is now bigger, so the current gets less.

Note: This question continues on the next page.

The circuit below is identical to the one on the previous page.



(c) What happens to the reading on ammeter $\mathbf{A_2}$ when S is closed?

<u>*Choose one answer.*</u>

i	It gets bigger.
ii	It stays the same.
iii	It gets smaller.

(d) How would you explain this?

<u>*Choose one answer.*</u>

i	Some of the current now goes through R_2, bypassing R_1.
ii	Two resistors need a bigger current from the power supply.
iii	The voltage across each parallel branch stays the same.
iv	The total resistance is now bigger, so the current gets less.

Appendix 4 Reasoning Tasks

THE PENDULUM

Dietmar Küchemann
Research Fellow, Chelsea College
University of London

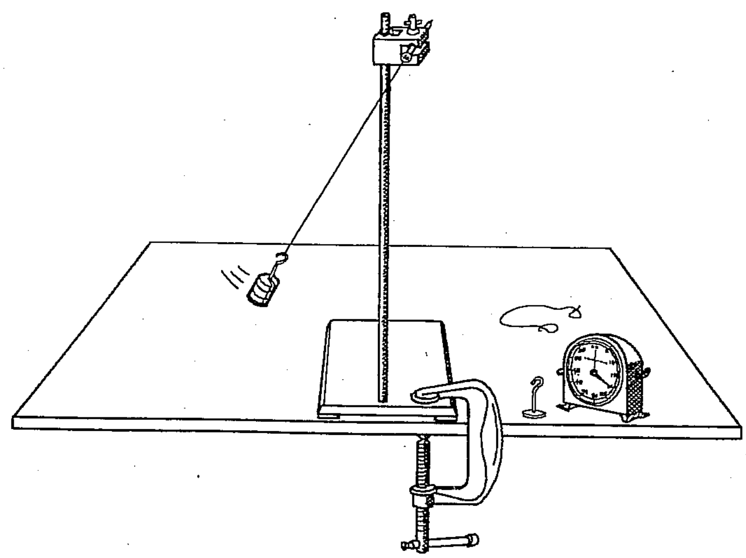
Introduction

This Task* is one of a series developed by the team 'Concepts in Secondary Maths & Science' at Chelsea College, University of London in the period 1973/78 in order to investigate the relationship between the optimum Piagetian level at which a pupil can function and the understanding of Science which he or she can achieve.

This Task investigates the pupils' ability to sort out the effects of three variables; how the Length, Weight, and Push of a pendulum determine the period of oscillation. Of course only the length is important, but the student has to overcome strong intuitive feelings in order to realise this. The Task is based on chapter 4 of Inhelder and Piaget's "The Growth of Logical Thinking," Routledge, London, 1958.
Allow about 45 minutes to complete the Task.

Equipment

Stopclock or watch with second-hand
2 weights (say 100 and 400 gram slotted weights on hangers)
2 strings looped at either end. (Loop to loop distances of 69 cm and 35 cm will give about 17 and 22 swings in half a minute. The numbers are not critical, but try to avoid lengths giving either 15 or 20 swings.)
Firm support to hang pendulum from.



*For information on the use, development, statistics etc. of this Task see Science Reasoning Tasks Booklet, NFER, Windsor.

EQUILIBRIUM IN THE BALANCE

Hugh Wylam and Michael Shayer
Research Fellows, Chelsea College
University of London

Introduction

This Task* is one of a series developed by the team 'Concepts in Secondary Maths & Science' at Chelsea College, University of London, in the period 1973/78 in order to investigate the relationship between the optimum Piagetian level at which a pupil can function and the understanding of Science which he or she can achieve.

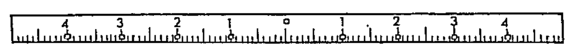
This Task based on chapter 11 of Inhelder and Piaget's "The Growth of Logical Thinking", Routledge, London, 1958, investigates the pupil's ability to recognise and use inverse proportions in a simple beam balance. Piaget says that the late formal thinker can understand the problem in terms of virtual work, so towards the end of the Task a work principle is introduced. However, most of the questions are at the concrete and early formal levels.

There is an annotated copy of the Task which gives all the cues you need during the administration, provided you have read this manual carefully first.

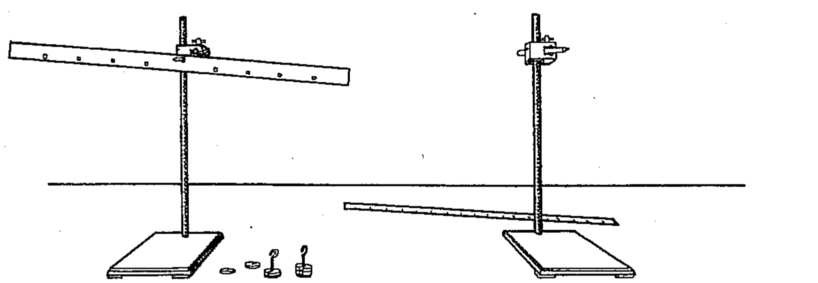
Allow about 35 minutes to complete the Task.

Equipment

2 metre rules, one with numbered holes every 10 centimetres



(It should balance by itself, if it does not add some "blu- tak")
At least six 100 gram slotted-weights and two hangers which fit holes
2 retort stands, 2 boss-head clamps
2 nails which fit easily through holes



*For information on the use, development, statistics etc. of this Task see Science Reasoning Tasks Booklet, NFER, Windsor.

Appendix 5 Test of Logical Thinking (TOLT)

Item 1: Orange Juice 1

Four large oranges are squeezed to make six glasses of juice. How much juice can be made from six oranges?

(a) 7 glasses
(b) 8 glasses
(c) 9 glasses
(d) 10 glasses
(e) other

<u>Reason</u>

1. The number of glasses compared to the number of oranges will always be in the ratio 3 to 2.
2. With more oranges, the difference will be less.
3. The difference in the numbers will always be two.
4. With four oranges the difference was 2. With six oranges the difference would be two more.
5. There is no way of predicting.

Item 2: Orange Juice 2

How many oranges are needed to make 13 glasses of juice?

(a) 6½ oranges

(b) 8⅔ oranges

(c) 9 oranges

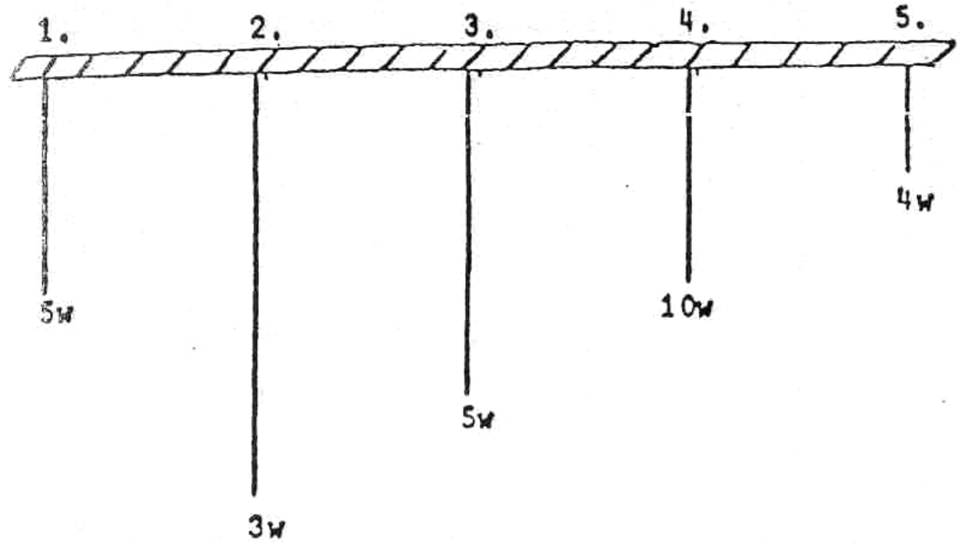
(d) 11 oranges

(e) other

Reason

1. The number of oranges compared to the number of glasses will always be in the ratio of 2 to 3.
2. If there are seven more glasses, then five more oranges are needed.
3. The difference in the numbers will always be two.
4. The number of oranges will be half the number of glasses.
5. There is no way of predicting the number of oranges.

Item 3: The Pendulum's Length



Suppose you wanted to do an experiment to find out if changing the length of a pendulum changed the amount of time it takes to swing back and forth. Which pendulums would you use for the experiment?

(a) 1 and 4

(b) 2 and 4

(c) 1 and 3

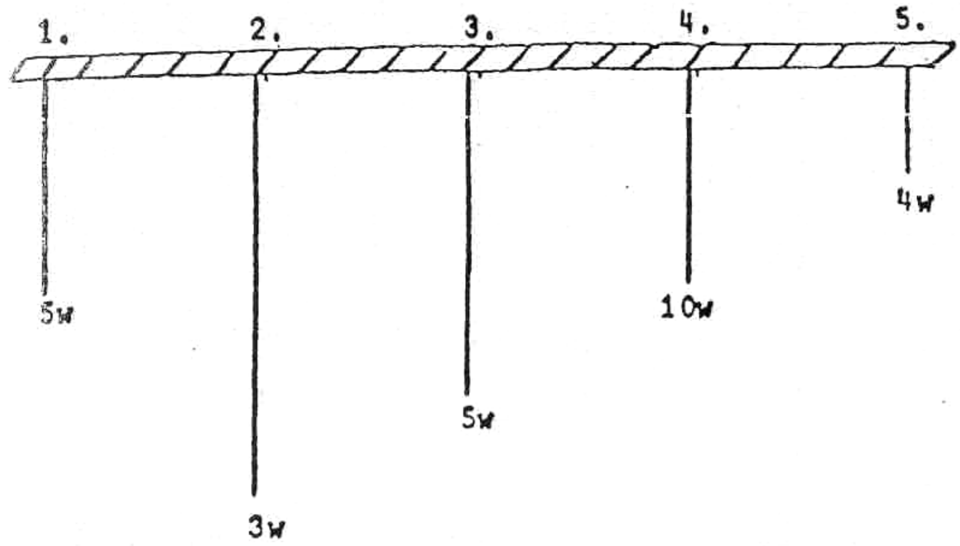
(d) 2 and 5

(e) all

Reason

1. The longest pendulum should be tested against the shortest pendulum.
2. All the pendulums need to be tested against one another.
3. As the length is increased, the number of washers should be decreased.
4. The pendulums should be the same length but the number of washers should be different.
5. The pendulums should be different lengths but the number of washers should be the same.

Item 4: The Pendulum's Weight



Suppose you wanted to do an experiment to find out if changing the weight on the end of the string changed the amount of time the pendulum takes to swing back and forth. Which pendulums would you use for the experiment?

(a) 1 and 4

(b) 2 and 4

(c) 1 and 3

(d) 2 and 5

(e) all

<u>Reason</u>

1. The heaviest weight should be tested against the lightest weight.
2. All the pendulums need to be tested against one another.
3. As the number of washers is increased, the pendulum should be shortened.
4. The number of washers should be different but the pendulums should be the same length.
5. The number of washers should be the same but the pendulums should be different lengths.

Item 5: The Vegetable Seeds

A gardener bought a package containing 3 squash seeds and 3 bean seeds. If just one seed is selected from the package, what are the chances that it is a bean seed?

(a) 1 out of 2

(b) 1 out of 3

(c) 1 out of 4

(d) 1 out of 6

(e) 4 out of 6

<u>Reason</u>

1. Four selections are needed because the three squash seeds could have been chosen in a row.
2. There are six seeds from which one bean seed must be chosen.
3. One bean seed need to be selected from a total of three.
4. One half of the seeds are bean seeds.
5. In addition to a bean seed, three squash seeds could be selected from a total of six.

Item 6: The Flower Seeds

A gardener bought a package of 21 mixed seeds. The package contents listed:

3 short red flowers

4 short yellow flowers

5 short orange flowers

4 tall red flowers

2 tall yellow flowers

3 tall orange flowers

If just one seed is planted, what are the chances that the plant that grows will have red flowers?

(a) 1 out of 2

(b) 1 out of 3

(c) 1 out of 7

(d) 1 out of 21

(e) other

Reason

1. One seed has to be chosen from among those that grow red, yellow or orange flowers.
2. ¼ of the short and $^{4}/_{9}$ of the tall are red.
3. It does not matter whether a tall or a short is picked. One red seed needs to be picked from a total of seven red seeds.
4. One red seed must be selected from a total of 21 seeds.
5. Seven of the 21 seeds will produce red flowers.

Item 7: The Mice

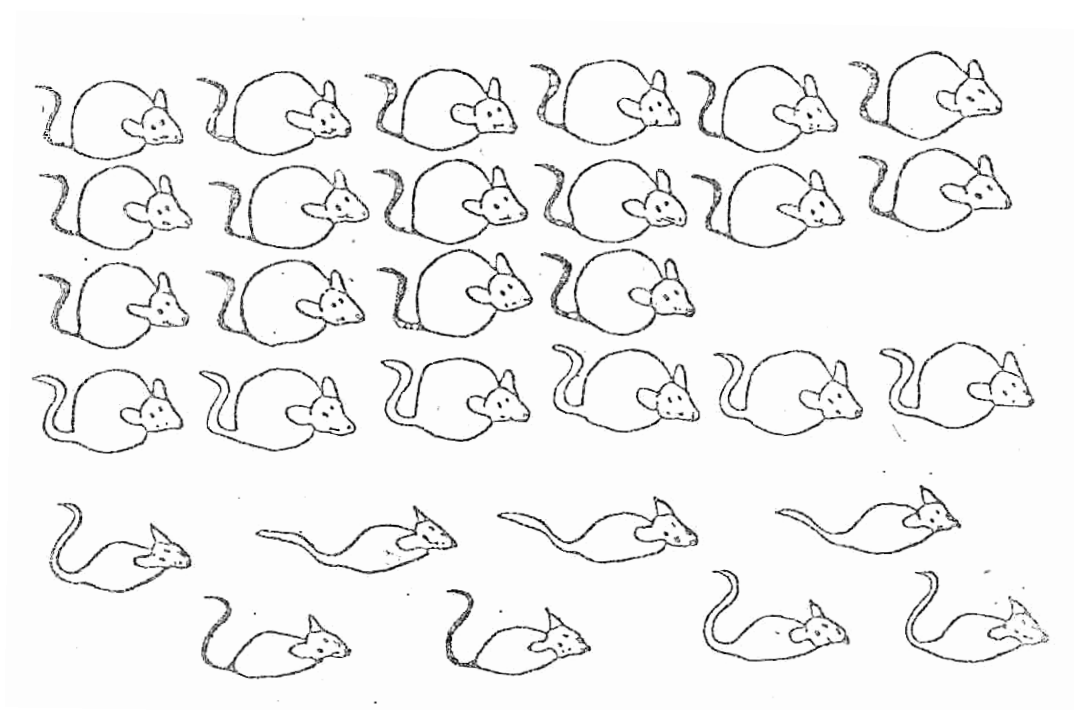
The mice shown represent a sample of mice captured from a part of a field. Are fat mice more likely to have black tails and thin mice more likely to have white tails?

(a) Yes

(b) No

Reason

1. $^{8}/_{11}$ of the fat mice have black tails and ¾ of the thin mice have white tails.
2. Some of the fat mice have white tails and some of the thin mice have white tails.
3. 18 mice out of 30 have black tails and 12 have white tails.
4. Not all of the fat mice have black tails and not all of the thin mice have white tails.
5. $^{6}/_{12}$ of the white-tailed mice are fat.



Item 8: The Fish

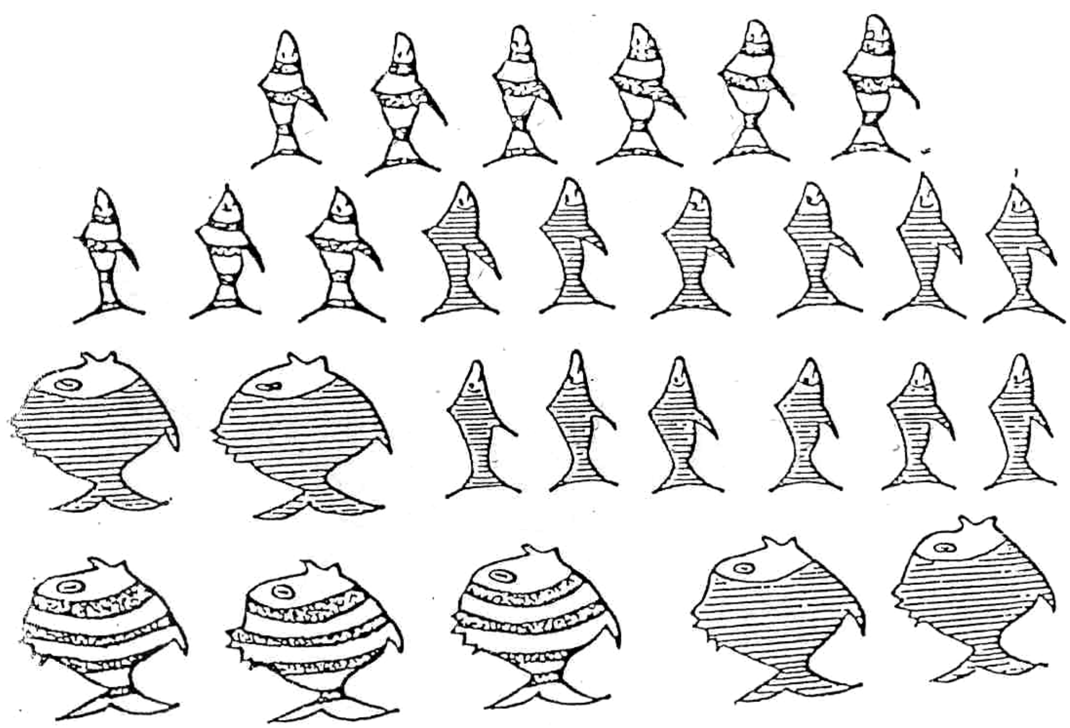
Are fat fish more likely to have broad stripes than thin fish?

(a) Yes

(b) No

Reason

1. Some fat fish have broad stripes and some have narrow stripes.
2. $^{3}/_{7}$ of the fat fish have broad stripes.
3. $^{12}/_{28}$ are broad striped and $^{16}/_{28}$ are narrow striped.
4. $^{3}/_{7}$ of the fat fish have broad stripes and $^{9}/_{21}$ of the thin fish have broad stripes.
5. Some fish with broad stripes are thin and some are fat.



Item 9: The Student Council

Three students from grades 10, 11 and 12 were elected to the student council. A three member committee is to be formed with one person from each grade. All possible combinations must be considered before a decision can be made. Two possible combinations are Tom, Jerry and Dan (TJD) and Sally, Anne and Martha (SAM). List all other possible combinations in the space provided.

STUDENT COUNCIL

Grade 10	Grade 11	Grade 12
Tom (T)	Jerry (J)	Dan (D)
Sally (S)	Anne (A)	Martha (M)
Bill (B)	Connie (C)	Gwen (G)

Item 10: The Shopping Centre

In a new shopping centre, 4 store locations are going to be opened on the ground level. A BARBER SHOP (B), a DISCOUNT STORE (D), a GROCERY STORE (G) and a COFFEE SHOP (C) want to move in there. Each one of the stores can choose any one of four locations. One way that the stores could occupy the four locations are BDGC. List all other possible ways that the stores could occupy the four locations.

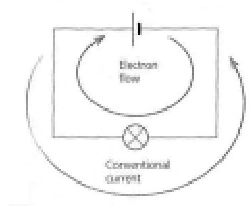
Appendix 6 Pilot Study Results for TOLT and Reasoning Tasks

Code	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Score on TOLT	TOLT Grade	Balance Task	Pendulum Task	TOLT Scheme	Balance Scheme	Pendulum Scheme
1	1	1	0	1	0	0	1	1	1	1	7	3A	3B	3A	3	4	3
2	1	1	1	1	1	1	0	1	1	1	9	3B	3A	3A	4	3	3
3	1	1	1	1	1	1	0	0	0	0	6	3A	3A	2B	3	3	1
4	1	1	1	1	1	1	1	1	1	0	9	3B	3A	3A	4	4	3
5	1	1	0	0	0	0	0	0	1	1	4	3A	2B/3A	2B/3A	3	2	2
6	1	1	1	1	1	1	0	1	1	1	9	3B	3A	3A	4	3	3
7	1	1	0	0	1	0	1	1	1	1	7	3A	2B/3A	2B/3A	3	2	2
8	1	1	1	1	1	1	1	1	1	1	10	3B	3A	3B	4	3	4
9	1	1	1	1	1	0	1	1	0	1	8	3B	2B/3A	3B	4	2	4
10	1	1	1	1	0	1	0	0	1	1	7	3A	3A	3A	3	3	3
11	1	1	0	1	1	1	0	0	1	1	7	3A	3B	2B/3A	3	4	2
12	1	1	1	1	1	0	0	1	0	1	7	3A	3B	3A	3	4	3
13	1	1	1	1	1	1	1	1	0	0	8	3B	2B/3A	3A	4	2	3
14	1	1	0	0	1	1	0	1	1	1	7	3A	3A	3A	3	3	3
15	1	1	0	1	0	0	1	0	1	0	5	3A	2B/3A	2B/3A	3	2	2
16	1	0	1	1	0	0	0	0	1	0	4	3A	3A	2B/3A	3	3	2
17	1	1	1	1	0	1	1	1	1	1	9	3B	3A	2B/3A	4	3	2
18	1	1	1	0	0	0	1	1	1	1	7	3A	2B/3A	2B/3A	3	2	2
19	1	0	1	1	0	0	0	1	0	1	5	3A	3A	3A	3	3	3
20	1	1	1	1	0	0	0	1	0	0	5	3A	3A	3A	3	3	3
21	0	0	0	0	0	1	1	0	0	0	2	2B/3A	2B	2B	2	1	1
22	0	0	0	0	0	1	0	0	0	0	1	2B	2B	2B/3A	1	1	2
23	0	0	0	0	1	0	0	0	1	0	2	2B/3A	2B/3A	2B/3A	2	2	2
24	0	0	1	1	1	0	0	0	0	1	4	3A	3A	2B/3A	3	3	2
25	1	1	1	1	1	1	0	1	0	1	8	3B	2B/3A	3A	4	2	3
26	1	0	0	1	1	1	1	1	0	1	7	3A	3A	2B/3A	3	3	2
27	1	0	0	0	1	1	1	0	1	0	5	3A	3A	3A	3	3	3
28	1	1	1	1	0	0	1	1	0	0	6	3A	3A	2B/3A	3	3	2
29	1	0	1	1	1	0	1	0	1	0	6	3A	2B/3A	3A	3	2	3
30	1	1	1	1	1	1	1	1	1	0	9	3B	3A	2B/3A	4	3	2
31	1	0	0	0	0	1	0	1	1	1	5	3A	3B	2B/3A	3	4	2
32	1	1	1	1	1	1	0	0	0	0	6	3A	3A	3A	3	3	3
33	1	0	1	1	0	1	1	1	1	1	8	3B	3A	3B	4	3	4
34	1	1	1	1	1	1	1	1	1	1	10	3B	3B	2B/3A	4	4	2
35	1	1	1	1	1	1	1	1	0	1	9	3B	3B	3A	4	4	3
36	1	1	1	1	1	1	0	0	0	0	6	3A	2B/3A	3A	3	2	3
37	0	1	1	1	1	1	1	1	0	1	8	3B	3B	3A	4	4	3

Appendix 7 PowerPoint Presentation

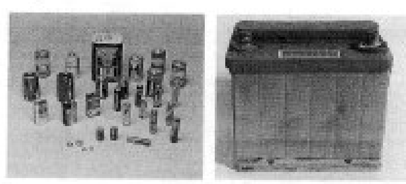
Current Electricity

A complete circuit is required for a current to flow.



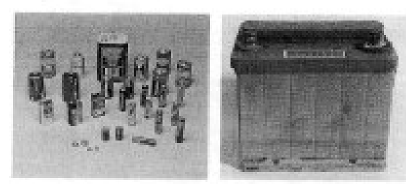
(Fullick, 2000)

The ‘push’ required to make electrons flow is supplied by the battery.



(Fullick, 2000)

It is not the shape or size of the battery that counts, but the potential difference across the terminals.



(Fullick, 2000)

An unusual source of potential difference

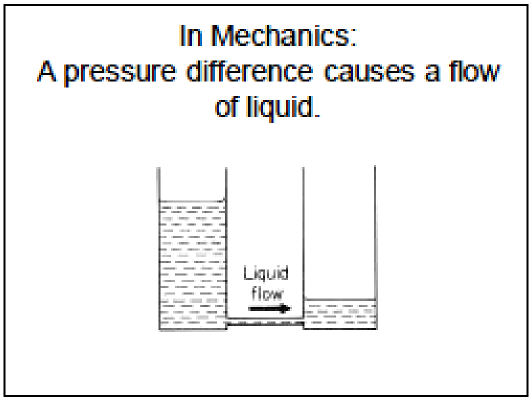
The pd between head and tail of the electric eel can be up to 600V.

(Hewitt, 2002)

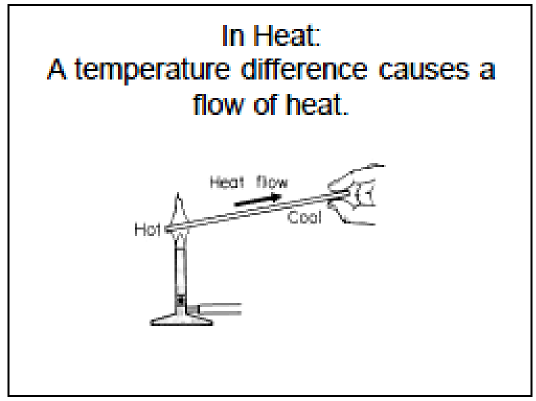
How to explain potential difference

Examples from:

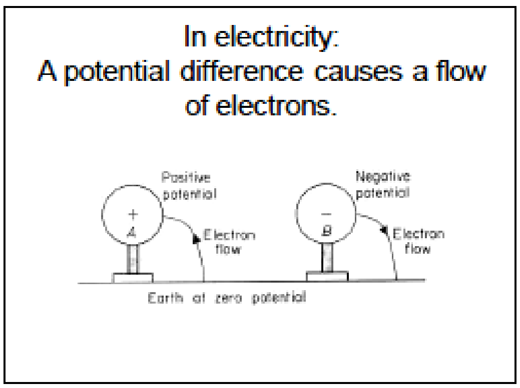
- Mechanics and
- Heat



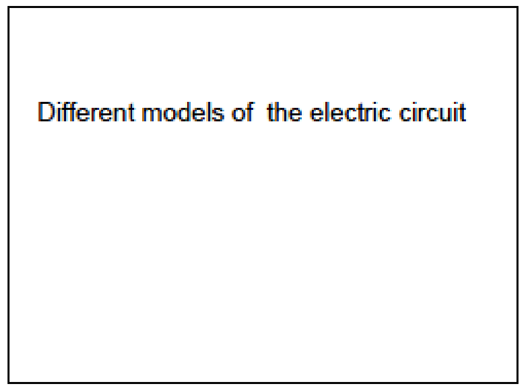
(Abbott, 1969)

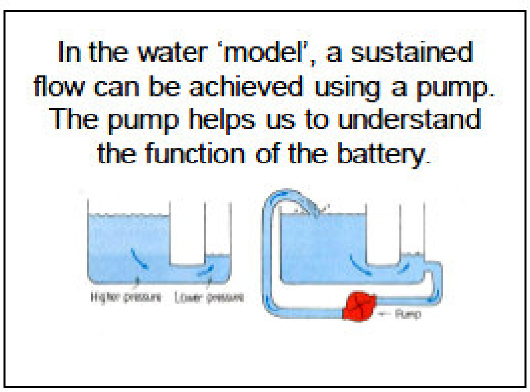


(Abbott, 1969)

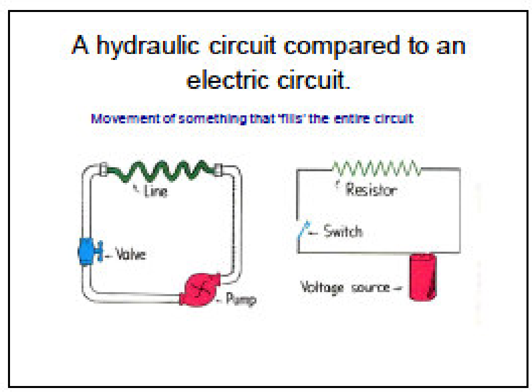


(Abbott, 1969)

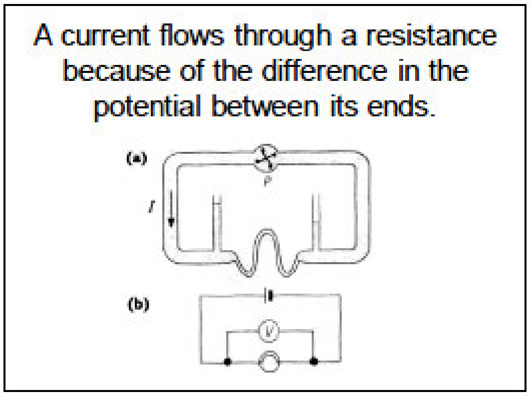




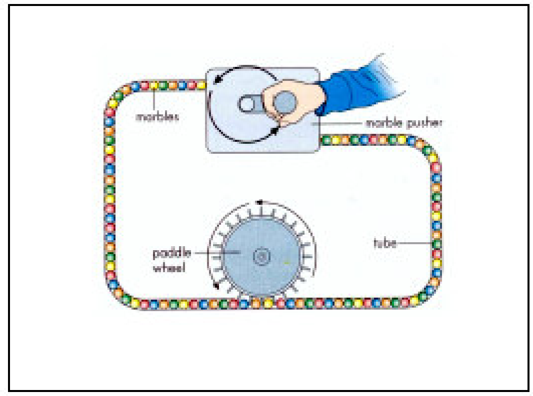
(Hewitt, 2002)



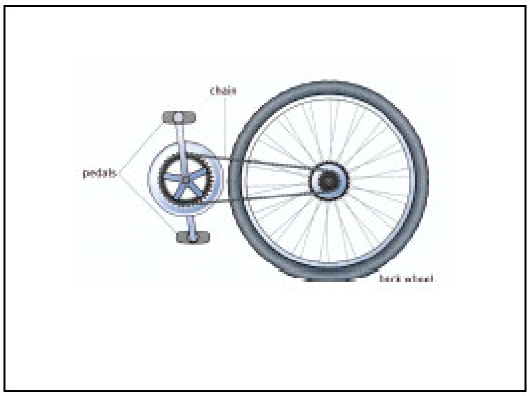
(Hewitt, 2002)



(England, Milward & Barratt, 1990)

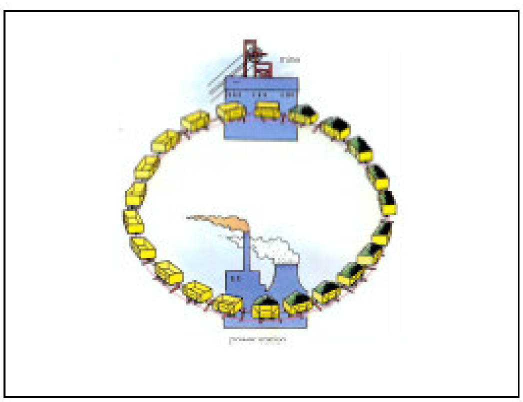


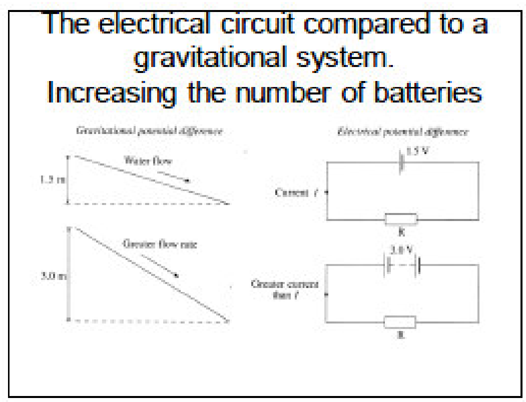
(Bradley, Gale & Winterbottom, 2001)



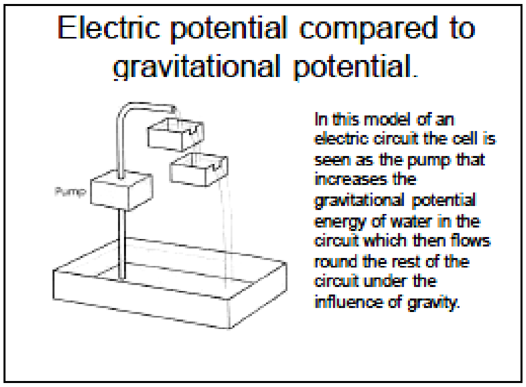
(Twenty First Century Science Project, 2003)

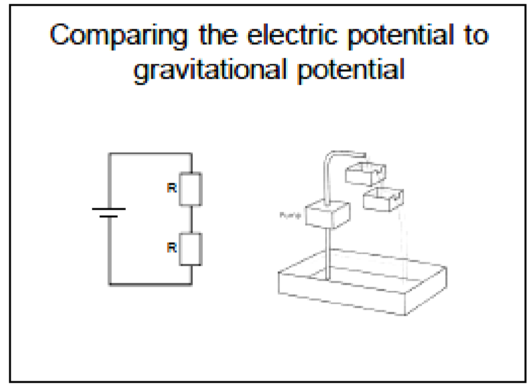
Something being carried round, and deposited at various points
('carriers and loads' models)


(Chapman, Musker, Nicholson & Sheehan, 2000)

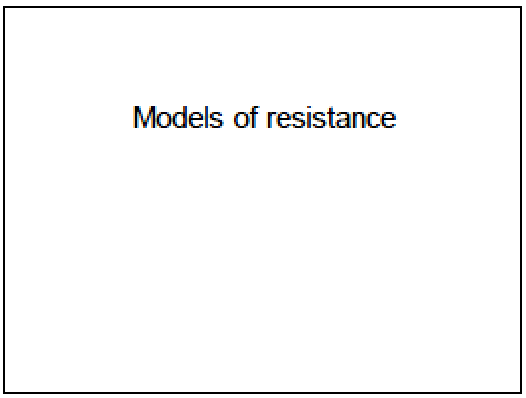


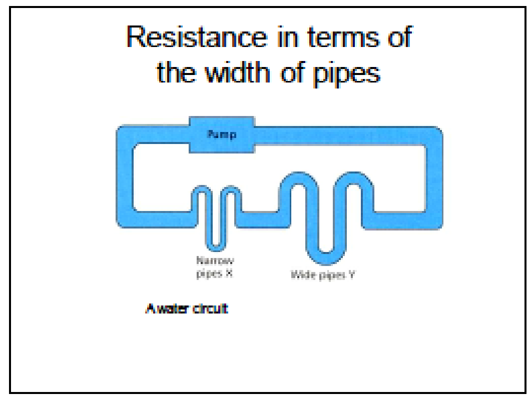
(Xuereb, 1999)



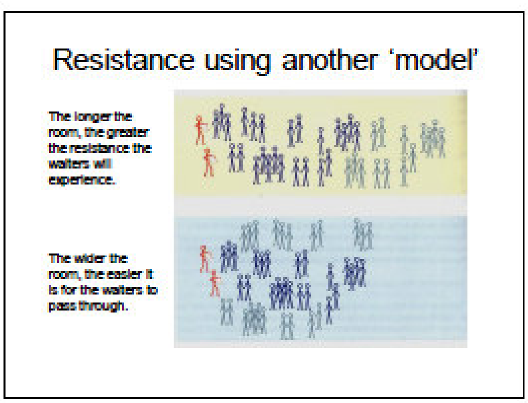


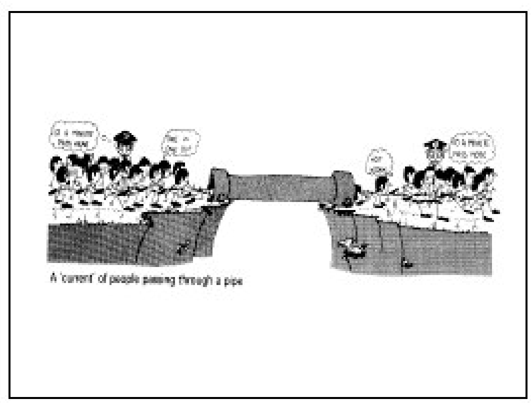
(Millar, 1989)





(Breithaupt, 2000)

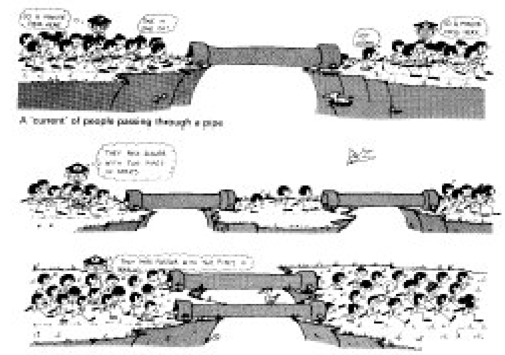




(Mee, Arnold, Crundell & Brown, 2000) (Warren, 1983)

Different types of
simple electric circuits:

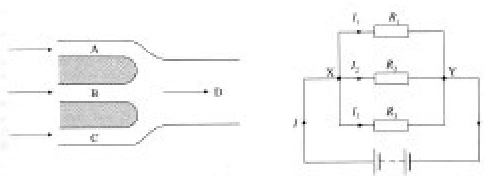
Series
and
Parallel



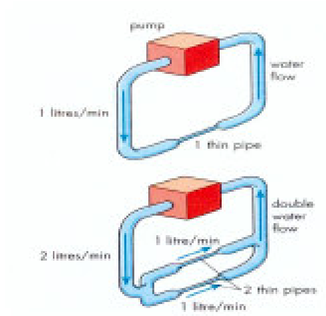
(Warren, 1983)

Resistors connected in parallel.

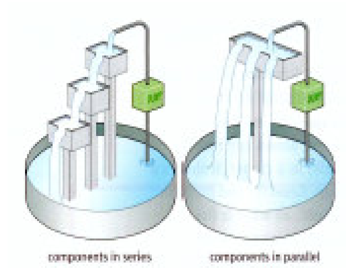
Same potential difference across each resistor.



(Xuereb, 1999)



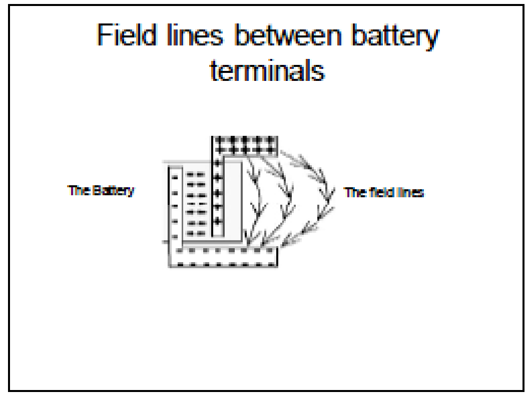
(Bradley, Gale & Winterbottom, 2001)



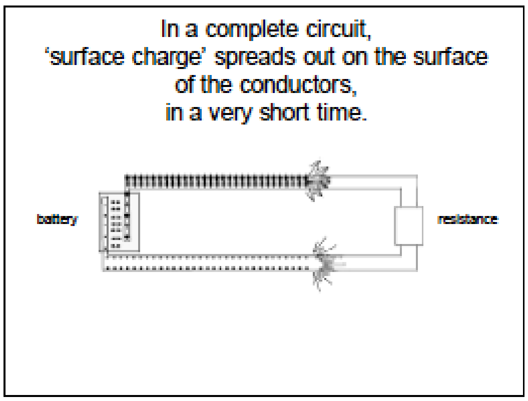
(Millar, 1989)

The presence and the effect of an
electric field

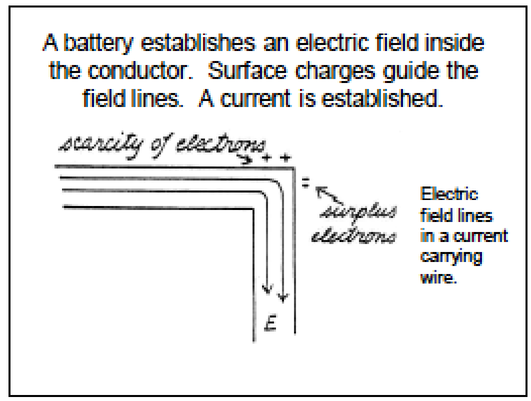
- An electric field is created because of the presence of a potential difference.
- The above is true, both in the case of static electricity and in current electricity.



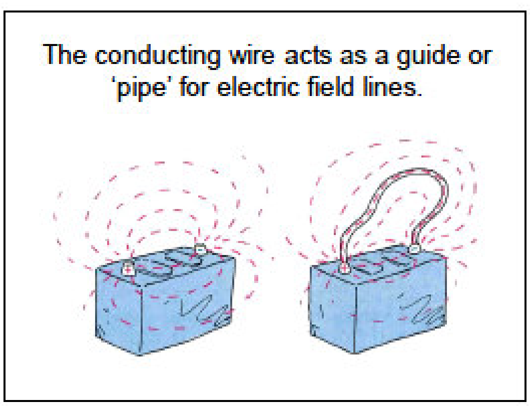
(Haertel, 1987)



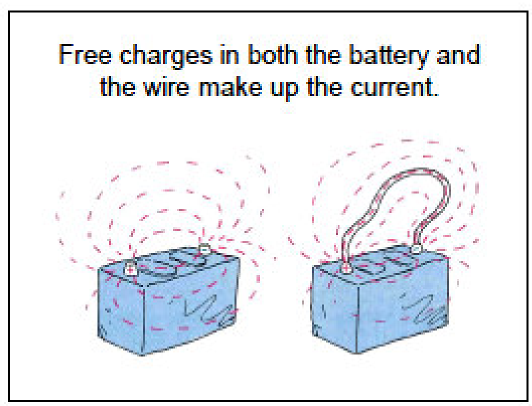
(Haertel, 1987)



(Swartz, 2003)



(Hewitt, 2002)



(Hewitt, 2002)

Appendix 8 Interview Schedules used with Cohort 1

1st Interview – Current in a simple circuit

The student will be thanked for accepting to be interviewed and told that the interview will take about an hour. It will be made clear that the researcher needs to get a better view of what the student understands about electric circuits. The student will be reassured that what the researcher is looking for is not necessarily correct answers but answers which reveal the student's ideas as learning and understanding are in progress.

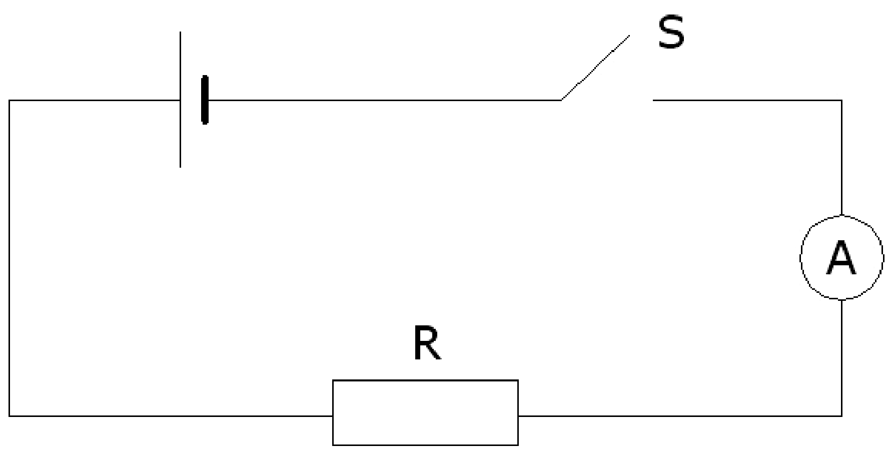


Figure 1: A simple circuit

The circuit diagram in Figure 1 will be shown to the student being interviewed. The student will be asked the following questions:

- Describe your mental picture of what is happening in this electric circuit when S is switched on.
- What affects the ammeter reading? Why?
- What do you imagine is happening within the circuit? What mental model do you have as you give this answer?

The student will be supplied with the necessary apparatus to construct the circuit. Help will be offered, if required. The interview will use the Predict-Observe-Explain technique to probe further into the models of current flow inferred by the student's answers. The student will be asked to predict what will happen when the circuit is switched on, giving reasons for the prediction, then to observe the result and finally to suggest reasons for any differences between prediction and observation.

The following questions will be asked:

- If you switch S on, what would you notice? Why?
- Will it make a difference to the ammeter reading if the position of the ammeter is changed and it is placed on the other side of the resistance? Why?

At the end of the interview the student will be thanked again and an appointment will be made to meet again during the following week.

2nd Interview – Resistances in series and in parallel

At the start of the 2nd interview, short questions based on the previous interview will be asked again in order to put the student at ease.

The student will then be shown the circuit diagram in Figure 2 and told that R1 and R2 are two equal resistors connected in series.

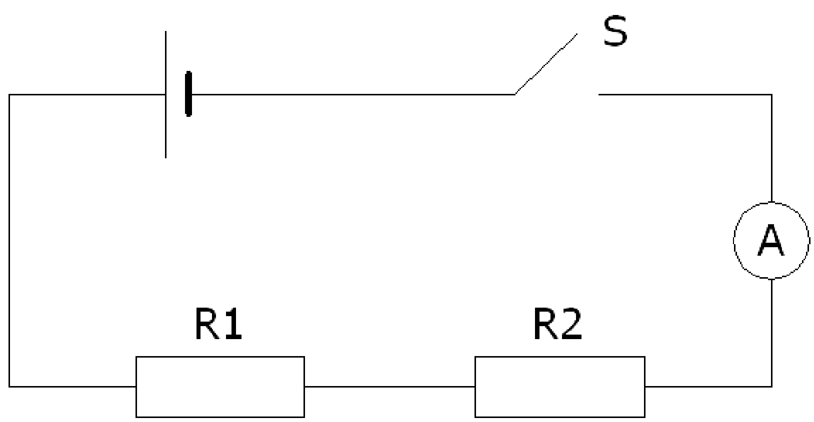


Figure 2: A series circuit

The student will be asked to assemble the circuit and help will be offered, if required. The student will be asked not to switch S on. The following questions will then be asked, before switching S on:

- In this circuit using two equal resistances, what happens when S is switched on? Why?
- Would the ammeter reading change if we change its position?

- In the same circuit, if we increase one of the resistors, what happens and why?

After predictions are made, the student will be allowed to observe the actual results and to comment about these, giving reasons for why the circuit works that way.

The student will then be shown the circuit diagram in Figure 3 and asked toconnect R1 and R2, the two equal resistances, in parallel.

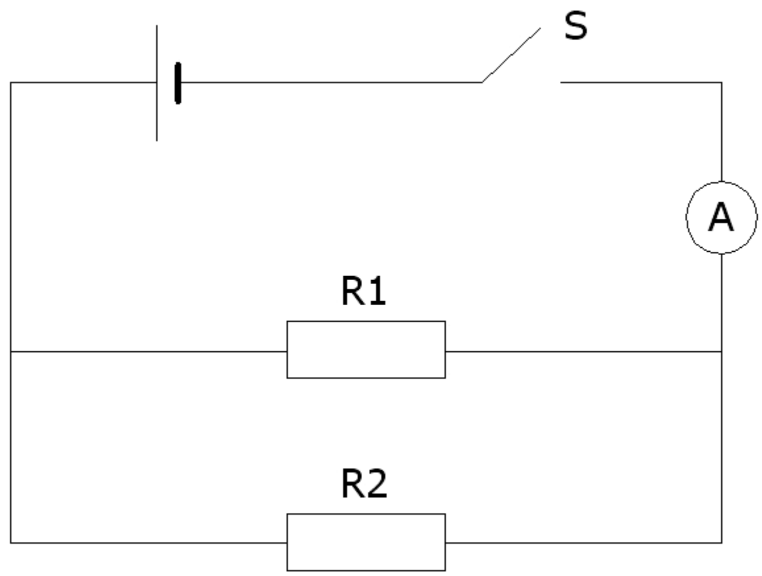


Figure 3: A parallel circuit

The following questions will be asked before S is switched on:

- What happens to the ammeter reading now, when S is on (comparing it to when the resistances were connected in series)? Does it increase, stay the same or decrease? Why?

After observing the results and commenting about predictions and observations, another question will be asked, thus:

- Can you describe <u>your</u> mental picture for why this is happening?

At the end of the interview the student will be thanked again and an appointment will be made to meet again during the following week.

3rd Interview – Part 1: Probing microscopic views

The student will be shown Qn 4 dealing with microscopic views of circuit (see Appendix 3) and her/his answers to the question in the pre-test. The student will be asked for reasons which prompted these answers, while at the same time she/he will be allowed to talk of the mental models of circuit which had guided the pre-test answers and also to describe how these models may now have changed because of the student's learning experience.

3rd Interview – Part 2: Meanings attributed to voltmeter readings

The student will be shown the circuit diagram in Figure 4 and asked to connect the series circuit using two equal resistances, without switching S on.

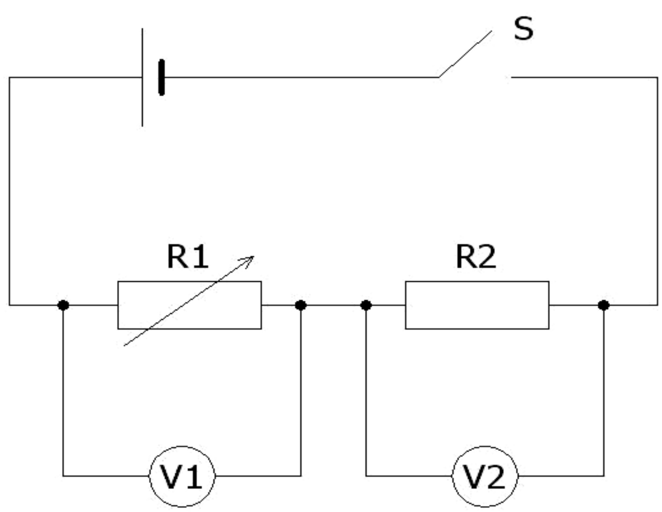


Figure 4: Voltmeter readings in a series circuit

The following questions will be asked to the student:

- What will the voltmeters read when the resistances are equal and S is closed? Why?
- What will the voltmeters read when one of the resistances is increased? Why?

The student will then be allowed to observe the actual results and will be asked to provide reasons for why the circuit behaves this way, with the aim of finding out what meanings the student gives to the voltmeter readings.

The student will then be asked to connect two equal resistances in parallel, as shown in Figfure 5.

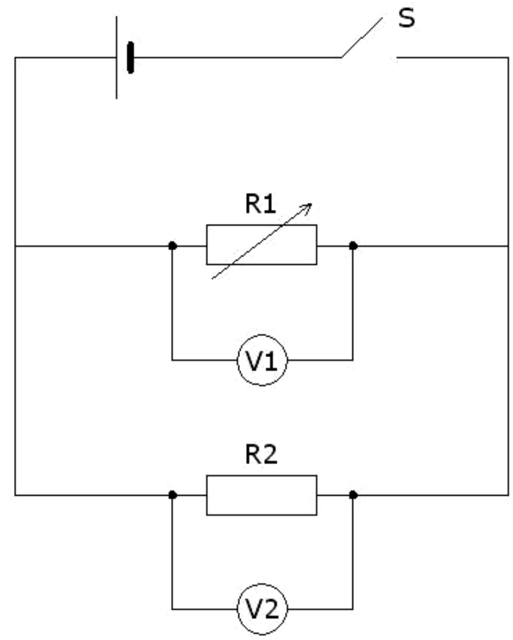


Figure 5: Voltmeter readings in a parallel circuit

The following questions will be asked before switching S on:

- What will the voltmeters read when the resistances are equal? Why?
- What will the voltmeters read when one of the resistances is increased? Why?

After observing the results, the student will be asked for reasons why the circuits behave this way.

At the end, the student will be asked a direct question about the voltmeter reading, thus:

- What does the voltmeter reading mean to you? Why?

At the end of the interview the student will be thanked again and an appointment will be made to meet again during the following week.

4th Interview – Differentiating between current and voltage

The circuit diagram in Figure 6 will be shown to the student and the student will assemble the circuit without switching S on and without connecting the voltmeters.

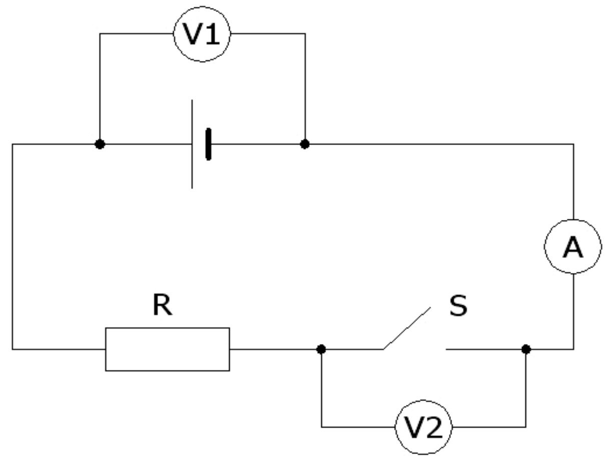


Figure 6: Voltmeters across the battery and switch

The student will be asked the following questions:

- Comment on what happens to the readings on voltmeters V1, V2, when connected as shown, and to the ammeter A, when S is switched ON? Give reasons for your answers.
- With S switched OFF, what can you say about the readings on V1, V2 and the ammeter A? Give reasons for your answers.

After predicting results giving reasons, the student will first be asked to switch S on and then to connect the voltmeters as shown. Reasons for any discrepancies between predictions and practical results will be asked for.

Results for the voltmeter and ammeter readings after S is switched off will be observed and reasons for why the circuit behaves this way will be asked for.

At the end of the interview, the student will be thanked for her/his contribution towards the research work being undertaken.

Appendix 9 Interview Schedules used with Cohort 2

The student will be thanked for accepting to be interviewed and told that the interview will take about an hour. It will be made clear that the researcher needs to get a better view of what the student understands about electric circuits. The student will be reassured that what the researcher is looking for is not necessarily correct answers but answers which reveal what the student's ideas are of how the circuit functions.

The student will be shown the circuit diagram in Figure 1, and then asked the following questions:

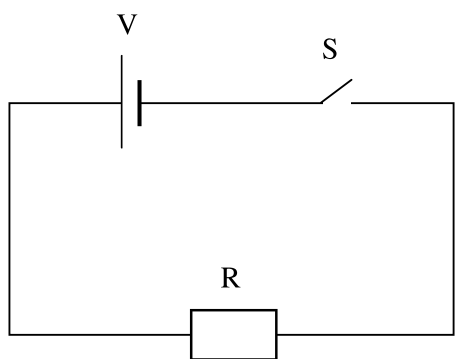


Figure 1: A simple circuit

- What is <u>your</u> mental picture of how the circuit works when S is switched ON?
- What models/ideas do you use to help you understand how the circuit functions?
- To what do you compare what goes on in the circuit so that you can help your understanding?

The student will next be shown Figure 2, and then asked the following questions:

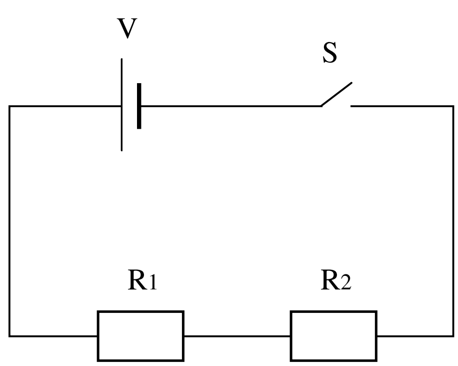


Figure 2: A series circuit

- When you see Figure 2, imagine that R_1 and R_2 are two equal resistances connected in series, how do you explain what goes on in the circuit?
- What do you 'see' or imagine is going on within the circuit?

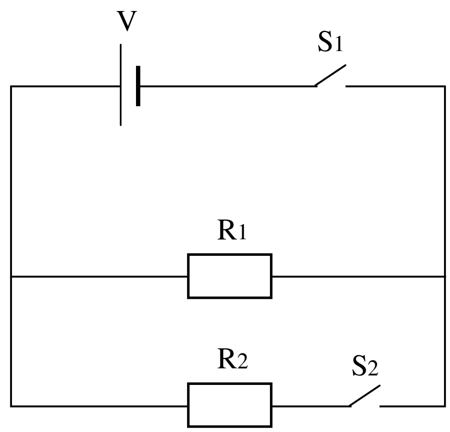


Figure 3: A parallel circuit

The student will then be asked to look at Figure 3. She/he will be told that S_1 is first switched on, making the upper part of the circuit the same as the circuit in Figure 1. The student will be told that now there is an added branch in the circuit which includes R_2 and S_2. The following questions will then be asked:

- What happens when S_2 is switched on? What picture do you imagine?
- Can you use your previous comparison, developing it further, to explain how you 'see' what is happening in this circuit?

<u>At this point, irrelevant of any comparison students may have made, and even if students have not mentioned any comparison at all, I shall introduce the water analogy myself to them, thus:</u>

- Now, I wish to ask you to give me your interpretation of how you see the circuit working in terms of water passing through pipes. Let us say that before S_2 was switched on, but with S_1 closed, $100cm^3/s$ of water was flowing through the circuit. What do you imagine happens when S_2 is switched on?
- In Figure 3, does the potential difference across the upper resistor (which is in the circuit already when S_1 is switched on) change when S_2 is switched on?
- How do you visualise this potential difference? What meaning does this potential difference have <u>for you</u>?

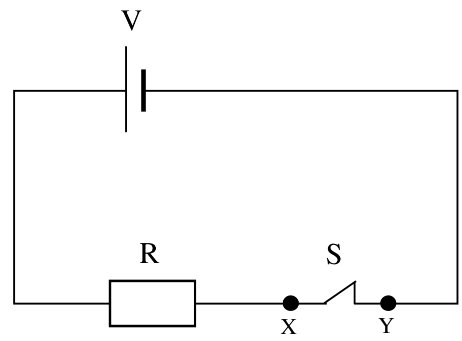


Figure 4: A simple circuit with S closed

The student is now shown Figure 4 and asked the following question:

- In Figure 4, what can you say about the potential difference across X and Y, when S is closed?

  Suggest a reason for your answer.

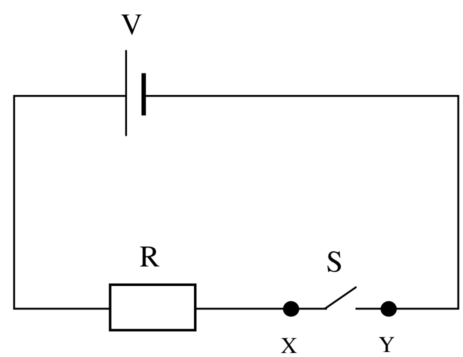


Figure 5: A simple circuit with S opened

Then the student will be shown the circuit diagram in Figure 5 and asked the following question:

- In Figure 5, what can you say about the p.d. across X and Y when S is open?

  Suggest a reason for your answer.

Appendix 10 An Extract from Dan's Transcript – The Interview with a Difference

Dan was a student in Cohort 2. He was a high ability student who was asked to be interviewed. The following transcript describes how Dan used the water analogy to understand and explain how he looked at resistors connected in parallel.

Dan: Now there are 2 paths for the electrons and these have a better chance to pass… They pass more easily. More of them pass.

I: More of them move?

Dan: In fact, the battery gets drained more easily. In fact, when the R is less, more electrons flow. If the battery is short circuited, then R=0 and the battery is used up immediately. Here there is a lower R, the battery is used up quicker and the electrons move and separate out more easily.

I: So can you try and visualize the situation in terms of some comparison within another context?

Dan: There are many things you can compare it with. Water, say. You can consider the battery as a tank which is placed high up so that you can create the p.d. You put the tank high up and a pipe lower down. In this case you are using 2 pipes since there are 2 resistances in parallel. The 2 pipes are in parallel. The water comes out of the tank more quickly from 2 pipes instead of 1. More water comes out, because if there is just 1 pipe, a certain amount of water is released, but if you open another outlet there will be 2 pipes. The pipes have to be the same width if the resistances are the same and more water comes out.

I: And if you were to imagine a certain amount of water flowing, say $100cm^3$ /s, flowing when you only had one resistor?

Dan: This is the 'current' in terms of water flow. Now with electrons the current is electrons per second. In fact current is charge transfer per unit time.

I: So now, how would you imagine the situation when switch 2 is switched on?

Dan: Now the rate will be increased. It will be doubled. Double what it was before, since a new path has been introduced. They both have the same pressure, these pipes, since the voltage remains the same. The 2 pipes will have the same pressure of water through them, because the pressure is the same and you've opened a larger flow of water. So now you have an extra $100cm^3$ /s. Now you have $200cm^3$ /s.

I: From where?

Dan: Going out of the battery and reaching it again. So if we consider it as water, I mean that from the tank to the ground, $200cm^3$ /s have come out and have reached the pipes.

I: And how much would be passing through switch 2 and the first R?

Dan: $100cm^3$ /s

I: So you see it that way. Do you find the comparison you made with water …because you came up with it after all… do you find it useful for you?

Dan: Very much so. You can imagine new pathways, extra pipes for water to pass through. You have a complicated system and you can see it better with this comparison. It depends though. If you have 4 or 5 resistors, then you have to imagine different widths, lengths…. But in terms of the concept, it is always the same.

I: So do you see that there are difficulties when you compare, but that it helps you at the same time?

Dan: It depends. 4 ohms and 5 ohms it will be difficult to imagine, but in terms of the concept it is the same. The equations may be used in both. But through an exam or in solving problems you cannot take the area of the pipe …etc. Then it becomes more complicated. Then you start working on the circuit directly. But, just to imagine what is really happening, it works. You don't see the electrons, you only see the result.

I: Has there been any time when you realized it is helpful but you also noticed that there were situations when the comparison had its limits? Do you recognize these limits?

Dan: Recognise these limits?! If it works, I mean it is ok. It is almost all the same. In one case it is the electrons which move, in the other case it is water. Both can be seen in terms of particles. It is the size which is different. I think that it always works. That is what I think. If you want to see it, instead of the ammeter and voltmeter in circuits, you use the flow-meter and the pressure-meter in water. The latter would indicate the voltage but it would calculate pressure. The flow-meter works like the ammeter, seeing the current flow through it.

I: By the way, did you always use this comparison?

Dan: At the start, you start trying to understand it, then you start seeing the electrons moving. You start saying that the electrons move in the same way as the water does. Then you start not using so much passages and pipes, because you get used to the way the concept works. Because all it is, is passages and paths through which water and electrons pass.

I: But since when did you use this comparison? Has it been since a long time ago or did you just start using it here at the college?

Dan: Even since I was young I used to use these ideas. I used to go to our garage and play with switches and batteries. I always tried to understand what was happening in terms of water. Then when we covered the topic of capacitors at the college, the teacher asked us to compare and use this tank analogy and I started to agree more with what I had been thinking. So I continued along this way of thinking.

I: So this was at the college.

Dan: I went on further to agree with what I knew already… what I had been comparing before.

I: And one more thing about this circuit, before we go to something else. If I were to ask you how you visualize voltage across this resistor, if switch 2 is open…?

Dan: V across the first resistor.

I: And when you switch it on?

Dan: V also. No change. It will be the same voltage for both resistors. It is the same wires.

I: So you think there won't be a change.

Dan: I see it like pressure in the water. Yes, exactly so. It varies according to the resistance, that is depending on how the pipe is and depending on how much flow there is in it.

[And later on during the interview]

I: Do you remember the PowerPoint presentation which I showed you in class, and the DVD?
Dan: The one with the ducks!
I: Which one was that?
Dan: When you had 2 pipes with ducks going through. Just the same as for water. When you open 2 paths, it is the same.
I: Did you like that presentation?
Dan: Everything helps. It was the same as the water analogy. I saw everything linked with each other.
I: So you made more comparisons?
Dan: Yes.
I: And do you suggest that it be shown to other people?
Dan: Yes, very much… for those people especially who do not know what electricity is, it would be really helpful.
I: Did it help you also?
Dan: Yes, because I could agree and clear my doubts.

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